Levi, Andrew (COMM)

From: Willis Mattison <mattison@arvig.net>
Sent: Monday, July 10, 2017 10:37 PM
To: MN_COMM_Pipeline Comments
Cc: MacAlister, Jamie (COMM)
Subject: Comments by Willis Mattison on Line 3 DEIS - Docket numbers CN-14-916 and PPL-15-137
Attachments: Dybdahl Report (2).pdf; Perspectives_for_the_Energy_Transition_2017.pdf; Willis Mattison comments PUC.pdf; Final Version- Willis Mattison Line 3 DEIS Comments w Cover letter.doc

July 10, 2017

Ms. Jamie MacAlister, Environmental Review Manager
Minnesota Department of Commerce
85 7th Place East, Suite 280
St. Paul, MN 55101-2198

(Transmitted via email to: Pipeline.Comments@state.mn.us)

Re: Public Comments of Willis Mattison on the DRAFT ENVIRONMENTAL IMPACT STATEMENT FOR ENBRIDGE PROPOSED LINE 3 PIPELINE PROJECT Docket numbers CN-14-916 and PPL-15-137

Dear Ms MacAlister,

Enclosed (attached) are my comments on the subject Draft Environmental Impact Statement (DEIS). Thank you for the opportunity to review and submit comments on the DEIS. I look forward to your and your Department's consideration of my suggested changes and additions to the document.

I respectfully request that the Draft Final EIS acknowledge each of these comments and provide responses and indication of their ultimate disposition.

I trust that you will find my suggestions helpful in making the final EIS a more comprehensive but concise and informative document for the Public Utilities Commission's and other permitting decisions on this project in the broader and long range public interest.

Sincerely,

Willis Mattison, Volunteer Citizen Advocate/Advisor
42516 State Highway 34
Osage, Minnesota 56570

Final Version

July 10, 2017

Ms. Jamie MacAlister, Environmental Review Manager
Minnesota Department of Commerce
85 7th Place East, Suite 280
St. Paul, MN 55101-2198

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Public Comments on the
DRAFT ENVIRONMENTAL IMPACT
STATEMENT FOR ENBRIDGE PROPOSED LINE 3 PIPELINE PROJECT
Minnesota Public Utilities Commission Docket numbers:
CN-14-916 and PPL-15-137
by
Willis Mattison
42516 State Highway 34
Osage, Minnesota 5570
July 10, 2017

Introduction

My education and professional career experience and qualifications for making the observations, criticisms and recommendations in these comments can be found in Appendix A of this document. I will only summarize those qualifications here by stating that I am presently retired but remain a practicing natural scientist (ecologist) and an experienced environmental review practitioner of over forty years.

A significant portion of my 28 year career with the MPCA involved reviewing and preparing official agency critiques and comments on dozens of environmental assessments and impact statements at the local, state and federal levels. I have continued to regularly review and prepare detailed comments on major local, state and federal environmental review documents.

I take special pains to summarize my qualifications in the paragraph above and to provide a more complete version in Appendix A to clearly establish my credentials for make the comments I do here in this document. I believe it is important to demonstrate that I have exceptional knowledge, skill and experience at natural resource condition assessment and have applied resource management methods to large tracts of land in order to achieving certain eco-function goals.

And I am quite familiar with both the aspirational policies and goals of the Minnesota Environmental Policy Act as well as the intricacies of the Rules and guidance used to administer that Act. I have considerable experience

Accordingly, I encourage the responders to my comments to view my critique of the DEIS in light of my professional credentials to do so, especially with regard to my criticisms of the data sets selected and the methods of analysis used as they reflect on the validity of conclusions reached in the DEIS

Purpose and Conclusion of this Review

By order of the Minnesota Court of Appeals, the Line 3 pipeline project was found to have significant potential to cause pollution, impairment and destruction of Minnesota's human and natural environment. Therefore, by law the project must undergo the extraordinary high level of scrutiny required in an environmental impact statement (EIS).

For over forty years now, environmental review has performed a vitally important function for Minnesotans. Environmental review is required to help Minnesotans answer a simple rather straight forward question about this project: "Are the benefits to society from a proposed project worth the harm the project is likely to cause? The EIS itself does not answer that question but it is the instrument used to gather and analyze the all the information necessary to find that answer.

To do this the EIS must clearly describe all the various types and places this project is likely to cause "pollution, impairment and destruction" and also establish the significance of this environmental harm in plain objective terms ordinary citizens can understand

In turn, public review and comment is intended to help determine if a draft EIS actually accomplishes this task and if it does so clearly, completely and in plain language. If not, the DEIS is unacceptable must be revised sufficiently to adequately accomplish this task.

My review of the draft environmental impact statement led to the conclusion that this DEIS fails to accomplish this vital task and must be significantly amended and revised for the following reasons:

1. The DEIS is far too long and complicated for citizens or policy makers to fully understand and the executive summary is far to brief and shallow to serve its purpose;

2. The benefits to be derived from the project in terms of what important societal need would be met was not described at all but instead was deferred to a later "needs" process.

3. The purpose of the project was defined in narrow terms that were self-serving to the project proposer and that prematurely eliminated less polluting or less harmful alternatives;

4. The information used and the analysis performed was incomplete and/or inappropriate;

5. The significance of potential harm to the environment caused by the project or its alternatives could not be established because the assignment of relative resource values, an essential element for determining significance of impacts is missing.

The detailed review and comments below are offered in support of these conclusions.

Overarching Issues That Altered Normal Approach to Review & Comment

The DEIS was far too lengthy, too complicated, too repetitious and was largely based on several broad assumptions that were weak, unwarranted or unsupported. Consequently that I found a complete reading and preparation of a point by point critique of the DEIS not only impossible but unnecessary.

For time constraint and other reasons developed later in these comments, I necessarily truncated the more complete review I had originally had intended for this document. A complete review would have involved developing detailed comments on a page by page, section by section basis. Normally, this has been my preferred method for providing complete and thorough review and comment on a DEIS.

So first off, the DEIS fails to meet one of the first essential tests for MEPA adequacy in EQB Rules 4410.2300.

> **4410.2300 CONTENT OF EIS.** *An EIS shall be written in plain and objective language. An RGU shall use a format for an EIS that will encourage good analysis and clear presentation of the proposed action including alternatives to the project*

One parenthetical point is pertinent here that will help explain my decision to go into far greater detail providing arguments and references in support of comments made here. Because the opportunities for meaningful public participation in the EIS process were severely limited by the meeting formats offered the public has not had full access to important information. The robust dialogue and debate that could have provided the necessary technical foundations for many of these comments was not allowed to happen in a public forum.

So the, more expansive comments are provided here to make some of this background information available to the public when they review these comments and the responses the RUG provides in the DFEIS.

As my review progressed through the document it became increasingly apparent that the criticisms I was developing were consistently traceable to a list of persistent underlying assumptions, assumptions that were either weak, unsupported or unsupportable. Therefore I shifted my primary comments to focus on these root sources of problems in the DEIS and relate them to the myriad other issues that cascade from these core assumptions throughout the document.

These are major foundational deficiencies in the DEIS that I contend must be better supported or corrected before the DEIS can be scientifically and functionally adequate.

Moreover, it is standard practice in environmental review as it is for practicing science in general to identify what assumptions are made, why the assumption made and the effect the assumption had on the reliability of the analysis being performed. And not all assumptions are equal in strength or are they universally accepted. Professional scientists often disagree.. Finally, in cases where there was significant differences of professional opinion on team or with other contributing agencies the implications of applying the particular assumption should be reflected in any conclusions that are reached based on the assumption.

This is vitally important to the overall credibility of this particular DEIS because the recent public record on pipeline projects is replete with significant differences of opinion and critical comments from various state agencies and from the public. On a highly controversial project such as this, the authors of the DEIS cannot afford to ignore these criticisms. A key way the authors can strengthen the FDEIS is to fully acknowledge catalogue and respond to these substantive critiques in a transparent way.

More specifically, the public is well aware of major recommendations for use of various data sets and specific methodologies for use in the DEIS as well as substantive criticisms of made in MPCA and MDNR letters to the Department of Commerce. Most of these letters are posted in the eDocket system either for the Sandpiper or the Line 3 project so are already in the public record. There were additional letters from other agencies like the Departments of Health and Agriculture that were not as publically available. Reference is made later in these comments to several of the state agency recommendations and criticisms that do not appear to have been resolved in the draft.

Revision of the DEIS should include a special section devoted to dealing with the substantive issue raised and recommendations made in these agency comment letters. This section should include discussion of how the issues were resolved.

<u>Core Assumptions Requiring Full Disclosure, Re-examination, or Revision</u>

The core assumptions found in the DEIS that have major implications for conclusions reached in the DEIS and need to be clearly acknowledge, better supported or more fully addressed in the DFEIS include:

1. Assumption that major relevant government policies can be excluded from consideration throughout the DEIS in spite of Statutes and Rules requiring consideration and that some relevant policies can be can be expressly excluded by caveat including climate change policy, green house gas reduction policy, civic engagement policy and environmental justice policy.

2. Assumption that the PUC's Certificate Need process necessarily proceeds on a "project by project" basis which some how excuses the EIS from addressing the broader policy level issues of future fossil fuel use and how degree of society's reliance on fossil fuels may be impacted by this or other energy projects.

3. Assumption that while future pipeline corridor implications of this project are real these implications not need to be addressed in this document as a reasonably foreseeable future impact of this project.

4. Assumption that project purpose can be stated or assessed only in terms of applicant's needs and that this industry need can only be met by a limited number of project design options;

5. Assumption that the issues of project need are separable from issues suitable to be addressed by environmental review. And that issues of need could only be addressed by the PUC in a separate decision making process, a process based not only on the information not available for inclusion in the EIS;

6. Assumption that because the need for the project could not be "determined" by the EIS, project need did not have to be addressed at all in the DEIS;

7. Assumption that comparisons of route alternatives that do not have the same start and end points can objectively reflect route impact differences and that simply acknowledging the bias resolves the problem and does not adversely affect the outcome of the analysis.

8. Assumption that the term "energy type" as used in Certificate of Need Criterion must be narrowly interpreted as meaning only crude oil excluding consideration of other types of energy such as renewables;

9. Assumption that MEPA does not require a project benefit analysis on the broader basis of what pubic need is served or public benefit is provided by a project. This assumption prevents the informed balancing of public benefit against potential loss or damage to resources that may result from the project.

10. Assumption that information necessary to fulfill requirements of Certificate of Need Criteria cannot be fully developed in the DEIS and that trade secret information alone determines project need;

11. The assumption that shipment of crude oil either by rail or by truck from new terminals at the Canadian border and near Superior were actually reasonable and prudent alternatives to the proposed project.

12. Assumption that a proper significance of impacts can be made without establishing weighted values for potentially impacted resources;

13. Assumption that micro scale assessment methods can credibly capture macro level (ecosystem level) impacts and that a simple summing of acres potentially impacted is the appropriate metric of significance for many those impacts.

14. Assumption that issues of climate change, was an issue too large to factor into final decisions on project;

15. Assumption that the quantity and distribution of public meetings are the appropriate metric for expressing the quality of public participation and involvement in the EIS process.

16. Assumption that System Alternative SA-04 as proposed by citizens should be treated as an inflexible centerline rather than represent a broader initial search corridor within which refinements could and should be made;

17. The assumption is made that the narrower construction zone width used for the applicant's preferred route through wetlands and certain water bodies was equal to and therefore offset by wetland areas omitted from footprint of SA-04.

It is requested here that each of these assumptions be individually addressed and greater support for them be provided in the DFEIS.

Names and Qualifications of DEIS Authors and Contributors 2432-1

The education and professional experience qualifications of the DEIS authors is not properly disclosed in the DEIS. This information is essential to the credibility of the DEIS.

So essential is this information to the integrity and public acceptance of environmental review that it is actually required by rule. Minnesota Administrative Rules 4410.2300 part D. requires inclusion of the names and qualifications of the persons responsible for preparing the EIS itself or for those preparing significant background papers.

This requirement would include the list of all contributing consultants, their qualifications and previous work experiences on projects of this nature and the clients for which this work was prepared. This is important information, not only to assure the quality of expertise that went into the DEIS but also to disclose potential conflicts of interest and sources of potential bias that may be reflected in the draft document.

To be fair it is acknowledged that conflicts of interest and other sources of bias on the part of the authors and consulting contributors can never be completely avoided or eliminated. But the influence of these sources of bias can be managed. To do this the full disclosure of these potential sources of bias that can influence the integrity of the DEIS and the measures taken to counteract these influences must be transparent to the reviewing public. This is also an important consideration for the decision-makers who ultimately rely on the EIS.

This information must be provided in the DFEIS indicating which persons or consultant firms prepared each portion of the DFEIS.

Loss of Public Confidence and Trust in Government

This is a discussion section that must be added to the DEIS in some detail given the history, the contentiousness and controversy surrounding pipeline projects nationally and here in Minnesota given the growing levels of citizen distrust for government institutions in general and for pipeline projects in particular.

The public, the applicant and the Public Utility Commissioners (PUC) themselves are well aware of this troubled history. This DEIS does not emerge into an historical vacuum. Therefore, for purposes of full disclosure the DEIS should be amended to recount the path by which the Sandpiper pipeline project was reviewed by Department of Commerce (DOC) staff and how that review culminated in the Department's recommending Sandpiper, as proposed by the applicant for PUC approval.

This discussion should discuss the history of how the Sandpiper pipeline was a predecessor to the Line 3 project proposed by the same applicant for the same exact corridor and in the very same environmental setting. The DOC, acting as agent for the PUC was the lead agency that prepared the high level environmental report for the Sandpiper pipeline certificate of need. It was that high level review that determined there were no significant differences in impact between the applicant's preferred route (APR) and any of the other alternative routes considered in the review including the alternative route SA-04, a route that is now an alternative route for Line 3 as well.

The DOC's original finding of no significant difference between these alternative routes prevailed through the Certificate of Need (CON) process for Sandpiper and led to the PUC's ultimate decision to approve it. While that decision was overturned by a court the original findings in the Sandpiper review now stand as potential source of prejudice that must be properly addressed in this document to assure there is no biasing influences carried over into review of Line 3.

It is fully understandable and significantly worrisome to skeptical outside observers that the DOC is once again in charge of comparing the merits of the same alternative routes for this project as it did for Sandpiper.

This request for disclosure is not made to embarrass the Department but to encourage them to exhibit the degree professional integrity required of any other RGU that found themselves in a similar situation. The acknowledgment of a previous analytical study and report by a researcher on the same subject would not be accepted for publication by any reputable journal without an accounting and review of all previous works. The conclusions of the previous work should also be presented along with the methods used to reach those conclusions. Critical reviews of previous work should be disclosed and how those criticisms were taken into account in subsequent work of the same nature.

Methodologies used by other researchers to assess and analyze impacts from similar projects should also be reviewed (possibly in an appendix to the DEIS) to demonstrate what methods were considered and either accepted, rejected or modified. The rationale for choosing or not choosing historically used methods should follow.

<u>Citizen Efforts to Neutralize, Minimize Sources of Professional Bias or Prejudice</u>

The following history is offered here as suggested topic to be considered for amending into the DFIES and that is written from the perspective of citizens who participated in the process outlined here.

In response to citizen lawsuit the Minnesota Court of Appeals found that the CON environmental review process as administered by the DOC for Sandpiper was inappropriate and the court ordered the preparation of the current full EIS instead. Many citizens believe there existed obvious cause for, if not evidence of, corporate agency regret and resentment for the judicial rebuke of their alternative environmental review efforts. What was even more apparent in the Sandpiper process was the loss of public trust for the DOC's ability to fairly and objectively prepare a new environmental review document for Line 3 that was not pre-destined to confirm the original findings of the previous CON analysis for Sandpiper.

For this very reason this author, supported by numerous citizen and Tribal organizations appealed to the Environmental Quality Board (under EQB rules allowing such appeals) to reassign RGU responsibilities for the Line 3 EIS to the Minnesota Pollution Control Agency(MPCA) and the Department of Natural Resources (MDNR). Appellants asserted these agencies were more capable, and objective because they were less likely to affected by the adverse Court Ruling. While the citizen appeal was ultimately denied on split vote the informal finding of the EQB Chairperson was that the Department of Commerce had obviously lost the public trust and that the Department was well advised to take special measures during preparation of the Line 3 DEIS to reestablish this public trust.

This author along other willing groups and individuals formed an ad hoc group of citizens and Tribal members who volunteered to work with the Department of Commerce, to find fair and effective ways to alleviate the public-trust problem. Over the next fifteen months through a series of email exchanges, telephone conversations and direct meetings with agency representatives citizens proposed a wide array of methods for doing so. (The full file and records of these exchanges is available to anyone upon request made to this author).

The shared goals, operating principles and group norms were set out and memorialized in the following document prepared for the first meeting of the group.

<u>RESTORING PUBLIC TRUST IN MINNESOTA'S PIPELINE EIS PROCESS</u>

SHARED GOALS, PRINCIPLES, ASSUMPTIONS, STRATEGIES AND NORMS

<u>Goal</u>: To Identify, develop and implement plans and strategies to restore the public's trust in Minnesota's current and future environmental review and permitting of petroleum pipeline projects.

<u>Guiding Principle</u>: Citizens have a fundamental right to be meaningfully involved in important government decisions that affect their lives.

<u>Shared Assumptions</u>:

Public Trust has been lost and once lost extraordinary measures are required to restore it; simple adherence to minimums of required public involvement process will be inadequate.

Participation in this meeting by all parties indicates a willingness and capacity to take extraordinary measures to restore the public trust through mutual cooperation affirmative actions and open communications.

<u>Primary Strategic Categories</u>:

1. Effective Methods for Improving Meaningful Public Participation
2. Employing Proven Methods for Ensuring Scientific Integrity of Process and Final Products

<u>Operational Norms</u>:

At all times we conduct our selves in a manner of mutual respect, dignity and cooperation focusing on strategic principles while avoiding other personal agendas.

Because our shared goal is to restore the public trust by improving the EIS *process*, we focus our attention on those strategic process elements thus avoiding discussion of project specific issues. (Possible exceptions allow for citing anecdotes but only to better define certain procedural issues not to debate the issue.)

(End of document)

The ad hoc citizen group and representatives of DOC, MPCA, and MDNR attempted several trust-building strategies in several subject areas focusing on EIS preparation procedures while avoiding project specific issues. Discussions focused on the traditional government accountability strategies of accessibility, transparency and civil engagement and accountability.

Published studies which were shared with the participants consistently show that participatory governance and social accountability require two key elements:

1. Capacity to monitor government and service providers (access and transparency); and

2. An communication system which acts as an effective ‘feedback mechanism’ between government and its citizens (usually facilitated dialogue).

(Sources: *International Association for Public Participation* and *“Accountability and Responsiveness of the State and Society* –GSDRC Applied Knowledge Services at:

http://www.gsdrc.org/topic-guides/voice-empowerment-and-accountability/supplements/accountability-and-responsiveness-of-the-state-and-society).

Specifically, citizens presented DOC with a number of mechanisms by which the EIS process would be more transparent, where citizens have access to the information and be afforded feedback mechanisms to the EIS drafting process. These proposals are listed below with the ultimate outcome for each proposal shown in parenthesis:

1. Reasonable level of access to meetings and communications with DEIS writing team including MDNR and MPCA staff contributions; (rejected)

2. Early disclosure of selected data and methodologies to be used for EIS; (promised but not delivered until DEIS released);

3. Disclosure of names and qualifications of EIS writing team; (Some team names but no qualifications ever revealed);

4. List of potential conflicts of interest and other bias sources; (promised but not delivered then nor are they in the DEIS)

5. Mechanisms to be used for neutralizing conflicts of interest and bias in the DEIS; (None provided then, none are shown in DEIS);

6. Feedback mechanisms on effectiveness of Tribal Consultations; (not acknowledged or provided);

7. Provisions for internal and external peer review; (No external peer review, public access to MPCA and MDNR staff input to EIS eliminated by Interagency MOU);

8. Effective feedback mechanisms including special EIS Issue forums; (None were accomplished);

9. Access to meetings and other documentation about State/Federal Coordination; (Not granted nor were subjects or minutes of joint meetings or correspondence disclosed.);

10. Appointment of a Citizen's Advocate, a person who would be proactive disseminating information rather than simple reactive to requests; (Reactive Ombudsman appointed in place of usual Citizen Advisor; not a pro-active position);

11. Professionally facilitated civic engagement format be used for all public information and comment meetings rather than using Open House or traditional timed-testimony formats. (Open houses were held instead, followed by a limited amount of "moderated" timed-speaker sessions);

12. Column to be added spreadsheet in Final Scoping Document listing all comments tracking final disposition of substantive comments through to the DEIS; (Citizens were aware this spreadsheet had been prepared but it was not made available to them);

13. A more detailed explanation of how the issue of "need" would be defined for purposes of the DEIS (Citizens were informed that "need" would not be addressed in the EIS.)

There were only two positive outcomes from this trust-building effort and each was of minimal benefit for achieving the stated goals:

1. DOC's designation of an "ombudsman" position (a substitute title for Public Advisor a position routinely established for CON projects) to respond to citizen EIS inquiries and.

2. DOC's creation of a new Line 3 DEIS website for posting preparation status and a Q & A page.

None of the other requested EIS citizen monitoring, communications, documentation or other integrity assuring mechanisms listed above was meaningfully granted by DOC.

The trust-building process was formally abandoned early in 2017 on the finding that little more was likely to be gained by further efforts.

Conclusions on Public Trust-Building Effort

In spite of respectful, persistent and sincere efforts on the part of this ad hoc citizen committee public for meaningful civic engagement in the EIS process public trust remains a major unresolved issue and in some ways the trust issue may have actually worsened.

DOC's unwillingness to employ civic engagement methods especially facilitated dialogue for public meetings on the DEIS is especially noteworthy in light of Governor Dayton's Executive Order for all agencies employ civic engagement strategies in state government. The 2016 State Civic Engagement Plan lays out specific goals for more effective engagement of citizens in state government and the Environmental Quality Board's expressed intent and special meeting to promote civic engagement in environmental review activities.

Many of the disputes that may arise again now at the eleventh hour in the EIS process might have been avoided or significantly ameliorated with meaningful civic engagement.

The revised DEIS must contain a detailed explanation as to why the citizen's good-faith trust-building and civic engagement requests could not or would not be honored in any meaningful way. This response in the DFEIS should take special note of the Governor's and EQB Civic Engagement Policies and also make reference to the applicable provisions of Minnesota Civic Engagement Plan in responding to this comment.

Environmental review is a participatory exercise designed to serve the greater public good. The public cannot meaningfully participate when they are treated like mere spectators cheering from the sidelines hoping someone will notice.

Why is this so important now? Because citizens, the RGU (PUC and DOC), the applicant, state legislators, Governor Dayton and possibly the courts may now find themselves in a predicament that might well have been avoided had legitimate civic engagement been embraced by DOC staff. The applicant has a right to expect due process, the citizens have a right to participate meaningfully, legislators have rights to expect the executive branch to function efficiently and the Governor can expect state agencies to perform with integrity and dispatch, all this to serve the greater public interest.

However, good efficient decision-making serving the broader public interest seldom flow from poor quality or incomplete environmental review.

After the lawsuit citizens entered into the EIS process with far greater hopes for open and meaningful dialogue with key agency officials but, as is outlined above, nearly all these efforts failed rather badly.

Now, it remains to be seen whether the process can be salvaged through revisions the DFEIS or in subsequent proceedings before the PUC. If not, each of the entities listed above may feel obliged to mete out various remedies within their power to do so.

This author remains gravely concerned for the potential outcome of those remedies.

Independent Internal and External Peer Review

Citizen's early and persistent requests for outside, independent peer review of the data sets selected and analytical methods applied during the DEIS preparation were steadfastly denied by the DOC raising suspicions that scientific integrity issues were going remain problem areas for the DEIS. Now, review by this author and other qualified professional scientists have found significant reason to challenge the fundamental scientific methodologies in the DEIS. The basis for some of these challenges is outlined in the list of assumptions above and others will be developed further in comments below.

Basically, citizens were concerned that the very same flawed assessment methods used in DOC's analysis of the Sandpiper project would also be used in the Line 3 DEIS. These methods were highly and credibly criticized as flawed and unreliable by professional scientists and experienced practitioners of environmental review.

For example, in open comment letters to the DOC other more effective methods of analysis and more appropriate data sets or sources were offered by the MDNR and MPCA were rejected or ignored by the DOC for the Sandpiper CON review. No more than passing acknowledgement these agency recommended data and methods appear in the Line 3 EIS and few if any were actually used.

Many of citizen's doubts about the scientific integrity of the Sandpiper high level CON review were born out by these MDNR and MPCA letters of comment. But, the public no longer has access to MPCA or MDNR staff inputs or critiques of the Line 3 DEIS as it did for Sandpiper. A memorandum of understanding (MOU) entered into by these state agencies with DOC has thrown a cloak of secrecy on the one remaining transparent peer review mechanism that had been so useful to citizens.

It was citizen's understanding of the PUC's recommendation for more direct involvement in the DEIS by these agencies through negotiations of a memorandum of understanding (MOU) was to ensure adequate funding would be available for the extra staff time needed for more substantial contributions by sister these agencies. We do not believe the PUC's is aware that the MOU has effectively subsumed the MPCA and MDNR technical staff making their role in the Line 3 DEIS secret and out of sight and unavailable to the public.

To restore the previous level of transparency and instill some semblance of internal peer review to the DEIS, the complete record of interagency correspondence, documents exchanged and records of team meetings be disclosed as an appendix to the DFEIS in an organized fashion to subject if possible. If that is not possible, a chronological ordering of these documents would be helpful to the reviewers.

Where significant differences of opinion and professional judgment developed between DOC and the MPCA or MDNR the outcome of any such differences should be described and the rationale for the final choice of outcome provided in the appropriate sections of the DFEIS.

External Peer Review

The need and urgency for independent and objective peer review of this document is clear and growing. Many of the questionable assumptions listed earlier in these comments and raised by other professional commenters could be effectively and efficiently vetted by external peer review. DOC's rejection of early requests to incorporate outside peer review on the basis they lack the time and resources rang hollow then and ring even more hollow now. Citizens are concerned that substantive comments criticizing the scientific integrity of the DEIS, even from the most credible and objectives sources will once-again be ignored or preemptively rejected as irrelevant. Other critical comments may be simply dismissed as partisan opposition to the project.

Reputable scientists acknowledge blindness to their own bias and how, while still imperfect, they utilize multiple and sophisticated techniques to combat it. Peer review, replication and double blind studies are common place in scientific work. The example of seeking an independent second opinion for serious medical diagnosis is helpful to point out that even the public understands the value of peer review and uses it frequently in important health crises.

The DOC is challenged here to expose their data selection and analytical methods in this DIES to independent peer review and make improvements recommended by such review. Citizen review and comment does not substitute for expert, outside peer review as all public comments can be seen as partisan.

No scientist can hope to have their work published in reputable journals without proper vetting of their work by their peers. DOC's steadfast and persistent resistance to outside objective review of their work draws only more and more reason for citizens to be skeptical and demand accountability. As outlined in comments above and throughout the process, the potential long-term consequences of possibly approving project are far too grave for DOC to get it wrong in this EIS.

Coordination with Federal and Neighboring States

MEPA Statute and Rule require RGU's to "the fullest extent possible" coordinate environmental review with other entities that have jurisdiction, sources of information and expertise for reviewing a project. Yet it is apparent in the DEIS that this coordination, if it occurred, was not transparent or effective. The fact that certain Federal and state protected species data and reviews were not complete and therefore not considered in this DEIS is a matter of concern. The fact that vital information on the environmental setting for alternative routes in North Dakota, Iowa and Illinois or extensions of existing pipeline routes beyond Superior Wisconsin was not available for use in this DEIS is regrettable and was avoidable. Valid route comparisons cannot be made with out consistent and uniform sets of data.

An interagency and interstate data gathering and assessment team should have been assembled at the outset of this effort to assure adequate quantity and data of uniform quality were used.

Federal permits requiring federal environmental assessments will be required for any pipeline projects that move into permitting phase following this review. Because DOC did not perform this interagency coordination the applicant and the public will have to maintain their vigilance protecting their interests through the subsequent federal review process. This could have been avoided had there been joint state/federal review.

The revisions to the DEIS should expand on the nature and substance of federal or other neighboring state involvement in the EIS process. Summaries of their interactions with the EIS team should be inserted in a new section of the DFEIS and all correspondence with these other government agencies and documents they submitted should be appended to the DFIES for public review.

Methodology and Metric for Independent Risk Assessment

Human, property and natural resource risks are quite difficult to assess and quantify. Recently some insurance industry tools have become available that can shed light on and even quantify environmental risks in terms the general pubic can readily grasp, risk insurance. The attached April 8, 2015 report entitled: *"An Insurance and Risk Management Report On the Proposed Enbridge Pumping Station*", was prepared for The Dane County Wisconsin Zoning and Land Regulation Committee by: David J. Dybdahl Jr, CPCU American Risk Management Resources Network LLC.   In this report Mr. Dybdahl describes the distinct difference between the types of insurance needed to cover the unique nature of incidents that are associated with crude oil pipelines.

The DEIS should be revised to include consideration of these concerns insofar as pertains to the Line 3 here in Minnesota. Hazard Insurance Premium rate differentials present a useful metric for assessing risks and comparing relative risks of various energy types and various pipeline routes.

This risk assessment by insurance standards performed by independent experts would illuminate discussions of long-term financial assurances necessary to protect public interests should any of the facilities become stranded assets of bankrupt owners. These socio-economic aspects of pipelines would seem very appropriate for exploration in revisions to the DEIS. If other assessment tools are more suitable for hazard insurance and financial assurance proposes in the DIES they should be identified and the appropriate assessments made.

<u>Need for Fossil Fuel</u>

The DEIS author's attempt to absolve the EIS process of any responsibility for assessing this project relationship to society's long range need fossil fuels or alternative types of energy is baffling. There would seem no better instrument that this EIS in which to expose these relationships between the public's need to break its addiction to fossil fuel and seriously examine alternative types of energy sources.

The DEIS should clearly outline all the pertinent international, national and state policies and goals for reducing the climate change impacts of greenhouse gases and fossil fuels. Broad policy statements from Minnesota's Next Generation Policy Act; Minnesota's 2025 Energy Action Plan, the Global Climate Leadership Memorandum of Understanding (MOU) recently signed by Governor Dayton and the Governor's formal commitment to goals of the Paris Climate Accord and any other polices should be quoted in this section. The contribution to greenhouse gases from the operation of Line 3 and from the consumption of the fossil fuel it will deliver to the world are quantified in the DEIS.

A clear analysis of whether and how this project or alternative to this project would conform to or conflict with the goals of these important and relevant policies is extremely important in the DEIS. What's more, it is clearly a requirement of this EIS under MEPA statute and rule.

This project and other pipelines proposed to ship tar sands to domestic or foreign market should be cumulatively assessed in context with projections for society's need to reduce it consumption of fossil fuel and green house gas emissions.

A simple graphic should be added to the DEIS showing the declining slope of Minnesota, the United States and World fossil fuel use necessary to conform to projected green house gas reductions needed over the next fifty years (the life of this project). The graphic should reflect the green house gas reduction goals in each of these climate change policies mentioned above. Superimposed on that graph should be the projected growth in crude oil shipping capacities represented by each of these new pipelines.

The attached Joint Report by the International Energy Agencies and International Renewable Energy Agency entitled; **"***PERSPECTIVES FOR THE ENERGY TRANSITION - Investment Needs for a Low-Carbon Energy System*", (electronic PDF copy attached) includes similar graphics projecting fossil fuel use declines necessary to meet greenhouse gas reduction goals. These reports go on to describe the potential economic drag on regional and world economies represented by existing and planned future fossil fuel infrastructure when these facilities become stranded assets.

The Joint IEA/IRENA report one of the first widely accepted and highly reputable reports published that attempt to capture and put into perspective the levels of world investments needed (and investments not needed) if society has any hope of reaching the safe, clean energy future Minnesota and the planet needs.

With simple graphic representations like this Minnesota's potential role for becoming a major fossil fuel addiction enabler to the world by approving this pipeline project would come into stark relief. And the real question before the PUC would be entirely reframed to ask: "How is it in the public interest of the citizens of Minnesota to enable the increasing global glut of one of the dirtiest fossil fuels on the planet by approving this project?" Since individual states have primary (and singular) up or down approval authority over pipeline projects such as this, the Public Utilities Commission must have the project assessed from this global perspective in the final EIS.

Minnesotans and the PUC, acting on their behalf cannot be lulled or deceived into thinking that this "single pipeline" project doesn't matter in the national or global level. All the little fossil fuel parts matter. Like rivets falling out of an airplane wing, one rivet at time. No single rivet's can be said to be responsible for the ultimate and dire outcome but collectively and cumulatively every individual rivet mattered. This pipeline matters.

This DEIS would be extremely inadequate to achieving its assigned task under MEPA if this important issue were to be arbitrarily swept aside by the discretionary proclamation of the DOC. This is one of the major issues that both NEPA and MEPA require RGU's to take that long hard look at and project the significant implications for each of the alternative courses of action facing the PUC. This fossil fuel and climate change topic should be included for thorough review under cumulative potential effects.

Overall Scale of Review and Analysis

Large linear infrastructure projects crossing international and multi-state boundaries require a high level landscape or macro perspective to grasp some of the most important potential impacts and determine their significance. These overarching ecosystem level impacts can be lost if a close-up micro examination of individual impacts is used without a method for aggregating these individual effects.

In Minnesota alone the proposed project and its alternative routes cross at three major global ecosystems (larger ecosystems called biomes). We sometime are aware of differences between prairie, hardwood forests and boreal forests. But, we may not be so aware of the various subdivisions of these major ecosystems and how they may differ from one another. Because we live here and see them all the time we are often not aware of their distinctive features, how their boundaries merge into one another and how different groups or communities of organisms perform what ecologist call trophic level functions transforming energy in and out and transporting water and nutrients through endless looping cycles.

Ecologists study how each organism or group of organisms each play vital roles in larger communities and ecosystem level functions and how these groups rely on one another to each perform their functions well. They know from study and experience that if any one group is stressed by forces from within or forces from with, all the vital functions will be influenced to some degree whether measurable to human beings or not. The science of ecosystem stressor identification and significance assessment is a complex and complicated one, a field of science requiring a high level of expertise. But ecologists have appropriate tools for aggregating impacts on landscape, natural community or ecosystem levels

A thorough reading of the methods used in the DEIS reveal little or no ecosystem level assessment was performed. This is just one of many reasons why it is important to disclose the professional qualifications of the EIS contributors. If there were no qualified professional ecologists on the team or if their work was not included in the DEIS that fact could explain the absence of this level of analysis.

It is a fundamental principle of impact assessment to use a systematic approach appropriate to the scale of the project under review and the scale of impacts involved.

Ecosystem stressor impact magnitude must be described in terms of intensity, duration, frequency (if repetitive) area impacted and the sensitivity and resilience of the target resource to this specific stressor. This characteristic of the stressor can be aggregated 2432-2
and ranked relative to all other stressors assessed and assigned numerical impact ranking scores. Then the natural community or ecosystem potentially under stress is ranked in terms of is value (rarity or use importance for example) when compared to other communities or ecosystems under examination. Significance of various impacts on the several target resources becomes the product of stressor magnitude when multiplied by relative target resource value. (Note to reader: Please excuse my attempt to write this outline strictly by recall in a matter of minutes, there are plenty of reference manuals for doing this to fact check my representation of the principles here.).

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In the DEIS, beginning with the description of the natural setting for the project and its alternatives in Chapter 5, natural resources are segregated into convenient subsections (boxes) such as of wetlands, surface waters, groundwater, fish and wildlife etc. and placed into a matrix of repetitive and serial qualitative impact descriptions. For the most part the mechanisms of impact quite well sourced and seem fairly accurate. But because impacts are not grouped into levels of significance (area, intensity, duration, and sensitivity etc. multiplied by ranked resource value) the aggregate impacts are lost in organizational maize in the DEIA that confounds even the most experience reviewer.

The summary charts for each resource impact attempt to collate all these qualitative impacts but minor, moderate and high impacts all get lost. No credible attempt is made in the DEIS to integrate these individual resource impacts into ecosystem levels of significance.

The matrix developed in the DIES would be far more useful as a first level screening for impacts needing further analysis, and inventory of impacts rather than as a final assessment. In fact that is what the DEIS actually appears to be. It is as though time ran out and the team had to publish the first level inventory of impacts and resources without full assessments being completed. That is understandable and an unfortunate consequence of political compression of time frames for performing adequate reviews of large scale projects such as this one, but I digress.

The impacts from this first level screening inventory should then be combined with others in a new list of potentially significant impacts to be carried forward into the second level. At this second level these impacts on specific ecological areas or sub areas (targets) could than be converted to a scale (based on intensity, duration, and target sensitivity) which could be multiplied by a value ranking of the ecological target area potentially impacted. Cumulative scores derived by this method would begin to aggregate into significance of impact system level impact rather than accumulate as “acres” of impact as is attempted in the DEIS. Additional details of this method are developed later in thes comments.

<u>Habitat (or Ecosystem) Fragmentation</u>

With large scale linear projects such as pipelines, power lines, roads and highways one of the primary stressors needing assessment is fragmentation not only of local habits but for entire ecosystems. The DEIS mentions the mechanism of fragmentation in discussing certain wildlife populations but, as was described above, without assessing this stressor on the larger landscape the significance of this large scale fragmentation is lost.

A discussion of the broader ecosystem level impacts from fragmentation can easily be found in literature readily available on the topic and can used for amending into the DEIS. A newer and important aspect of fragmentation should also be included in this discussion, and that is the phenomenon of ecosystem migration, the slow collective movement (In Minnesota this is a retreat north and east) for entire ecosystems in response to climate change. Linear facilities can present continuous migration barriers to certain species communities that are unable to bridge the gap. This applies to many species of animals but is of growing importance to the plant communities that support animal communities. Animals may be physically able to cross the barrier but unless the plant community that forms their habitat can migrate with them, the animal migration is also blocked.

The natural settings for the pipeline alterative routes differ in dramatic ways that make contrasting and comparing fragmentation impact assessment of the project at ecosystem level impact more straight forward than for some other impacts. From various data sets the RUG can assemble and construct an inventory of fragmenting facilities in the region of interest. The density of individual facilities can be expressed in a common ratio or indicator indeces (used by the U. S. Forest Service and the Fish and Wildlife Service among others) in terms of miles of linear fragmentation per square mile. There are more steps needed here but the concept is quite clear. This type of analysis should be completed and included in the DFIES and applied as a GIS data layer (see description of GIS later in these comments).

Degree of road saturation is additional component in fragmentation assessment can be used to compare alternative routes as an indicator of accessibilty to leak or spill sites by response crews. The MPCA developed a route comparison criterion based on access to streams below pipeline crossing points which works for spills that may reach streams. This criterion could augmented to gauge ease of access to any spill site along a route whether the spill to place on land or near water. Road density indices could be developed as a data layer also for use in GIS Route Optimization described elsewhere in these comments.

Other Broad Landscape Characteristics Useful for Route Optimization Assessment

In comment letters from the MDNR (and possibly the MPCA) as well as from the general public pointed out contrasts between landscape settings for the APR and SA-04 that are rather obvious but these criteria were not developed or used in the DEIS. The Red River Basin is flat, with tight clay soils and has its natural ecosystems highly altered by agriculture and development (cities, roads, etc.). There are few natural native plant or animal communities remaining that have not been highly altered. The Upper Mississippi Basin is quite the opposite, characterized by greater slopes, courser soils, and a much less altered native plant and animal community and large ecosystems are largely still relatively intact. 2432-3

SA-04 would cross a large number of the rivers encountered in their lower reaches where they are highly impacted by hydraulic destabilization due to agricultural and urban drainage and replacement of natural vegetative cover with cultivated crops. Using either MDNR or MPCA biotic integrity scores to contrast upper and lower reaches of these streams reveal how impacted and altered these aquatic ecosystems are. A relevant biotic integrity pattern emerges that would be useful when comparing routes. (see more on that below). It would be reasonable to infer that this pattern holds true for tributary streams both sides of the Red River and for streams in Southwest and even Southern Minnesota as well even were biotic assessments may not have been performed.

2432-3 Cont'd

Highly altered crop and urban lands support a relatively simple ecosystem with few available niches and many niches occupied by cultivated species, urban plantings or invasive species. Such an ecosystem is highly manipulated and natural succession is in a constant state of reset which encourages and sustains ecosystems at the pioneer species level. Trophic level hierarchies are rather simple with a narrow list of primary producers consisting of uniform monocultures of cropped species. Large expanses of cultivated lands are occasionally interrupted by corridor forest or prairie like ecosystems along rivers, streams and roads. Other important landscape characteristics like these should be developed further into GIS data layers for analysis the revised DEIS.

The relatively unaltered landscape that characterizes the APR is quite diverse especially forest and wetland types found there and the wide diversity of associated plant and animal communities that exist there. The DEIS describes the existence and locations of many of these natural landscapes but the method of analysis used on the mirco level fails to describe the significance of large, intact ecosystems such as these and the potential impacts a pipeline can have on these ecosystems by disrupting the normal flow of energy and the cycling of water and nutrients throughout the system including ecosystem migration describe above.

Major streams in this part of the state, most of which are tributaries to the Mississippi River, including the Mississippi River itself have their headwaters in these fully functioning forest and wetland ecosystems. High biotic integrity scores extend much farther down stream than is documented for Red River Basin and Western Minnesota streams. The route of the proposed pipeline crosses many of these streams in these zones of high biotic integrity that indicate fully functioning aquatic ecosystems are in place.

Many more useful indicators of the full extent of the ecosystem settings for each of the two routes can be developed by ecology experts than can be listed and described here. But this needs to be done for the DEIS revisions to fairly and accurately assess impacts that exhibit at this higher ecosystem level that objectively characterize the significant difference between the alternative routes.

<u>Consequences of DOC's Improper Framing of the Project Must be Corrected</u>

My preference for using the term "large energy project" rather than "a crude oil transportation project" is reflective my strong objection to the biased framing used throughout this process and the serious consequences of this framing. When framed as a pipeline project ostensibly "needed" by the proposer to transport crude oil, it automatically and powerfully shifts the public and regulatory focus and debate into a question of how to perform the transportation of crude oil function rather than posing the question: "Is this project providing the type and quantities of energy *society* needs. Thus, the prejudicial framing of the project as a crude oil transportation project has a powerful slight of hand effect that leaps over the initial decision points and prematurely limits the array of available alternatives considered. The fact is that by improper framing of the project purpose the debate has leapfrogged over the first and primary choices of "energy type" that should be considered first.

This subtle but powerful re-framing of the project purpose alternative ways for transporting crude oil from point "A" to point "B" rather than choices of alternative form of "energy" is crippling to the EIS process. However, framing the project as a large energy facility project has a distinct functional advantage for administrative and environmental review because this framing would allow for proper application of the PUC's CON criteria for determining "need".

Fossil fuel projects like pipelines facilitate and create certain consumer incentives for fossil fuel "type" of energy as opposed to other "alternative" types of energy sources.

Renewal and expansion of a major component of the world's fossil fuel transportation infrastructure constitutes a major long-term commitment of resources (public, private and natural resources) to a fossil fuel "type" of energy that has been proven not to serve society's need for cleaner energy. Influence of this long term infrastructure commitment must be included in the DEIS revisions

This demonstrates the awesome and coercive power of "framing" and how improper framing has detracting from the larger public policy questions that are actually at issue. Framing can create powerful bias of perspective that not only shapes public's and elected officials opinion but can influence and even bias the many discretionary options regulatory agencies have to make on energy projects.

My comments below will show that the public, our political leaders, and government decision-makers, and most importantly the Public Utilities Commission in particular are precariously close to being misled as a result of this improper framing of this project. In the DEIS and throughout the remaining certificate of "need" deliberations on this project. State agencies, especially RGU's (or agents of RGU's) have moral as well as policy and regulatory obligations to properly frame the project as an energy project rather than a crude oil transportation project.

Environmental review documents are the perfect instrument to perform this "re-framing" exercise but this reframing must be done by the, authors of the EIS (the RGU). To do this requires fierce and objective independence on the part of the Responsible Government Unit (RGU) charged with preparing the EIS. The RGU must not be encumbered by past practice or so heavily influenced by other energy projects like power lines and other pipelines that they do not see new opportunities and bold alternatives where none were thought to exist before.

As EQB staff point out in their guidelines on this topic project proposers and supporters will (for obvious reasons) try to frame the project and its purpose in self-serving terms to intentionally eliminate further consideration of alternatives. That's understandable and even predictable. And it is self-serving on the part of the proposer.

But these attempts at improper framing must be successfully overcome for environmental review to be successful. In fact, the improper framing of the purpose for proposed projects is so common and yet so pivotal to proper environmental review that the EQB staff devotes several paragraphs to this topic in it guidance to RGU's.

> One of the main purposes of an EIS is to examine potential impacts of project alternatives. Unlike with an EAW, the impacts analyzed are not limited to environmental impacts. The statute calls for the EIS to evaluate "*economic*, employment and sociological impacts" as well. The RGU should observe the following when selecting an appropriate range of alternatives.
>
> ***Alternatives may be excluded only if they meet one (or more) of the following criteria:***
>
> *a) underlying need for or purpose of the project is not met;*
>
> *b) significant environmental benefit over the proposed project is not provided; or*
>
> *c) another alternative is likely to be similar in environmental benefits but will have less socioeconomic impact.*

The EQB staff expands on the proper application of the exclusion criteria in their guidance to RGU's by stating:

> "In applying exclusion criteria, the RGU must not be overly restrictive in defining the project's purpose and need. Occasionally, an RGU will claim desirable but nonessential elements as part of the project's purpose or need, thus eliminating alternatives that should be included. In many cases, these are cost-related factors and, while important, they cannot overrule environmental considerations."
>
> "The RGU must take a hard look at the basis for prior decisions to make sure that environmentally superior alternatives were not eliminated without sufficient justification based on the rule's three criteria. Eliminated alternatives should be discussed in the EIS and noted in the scoping decision document. Prior decisions to eliminate options may need to be revisited in the EIS if insufficient consideration was given to environmental impacts." -
>
> (Excerpts above from Guide to Minnesota Environmental Review Rules May 2010 by EQB)

Framing the purpose or need for a product or service is a subtle but powerful and persuasive art of marketing that plays on the human psyche. Because the importance of this framing exercise can not be over emphasized and out of concern EIS writers will not take it seriously I offer the following classic example:

> *Henry Ford Quote: "Any customer can have a car painted any color that he wants so long as it is black."*

Henry Ford issued this statement in 1909. He did so, not because he thought people shouldn't have a choice of color. He had something else in mind. He made this decision at the same time he decided that his plant would only produce one model of car, the "Model T."

*Ford's reason for making these decisions was profound. Ford wanted to greatly expand car ownership. To do so, he needed to make the car as affordable and reliable as possible. He did this by **limiting variation** in the production of cars. Lots of people objected, particularly his sales force who wanted lots of models with lots of variety. They predicted he would go out of business. In the end, he achieved his objective.*

Henry Ford's motivation for limiting his Model "T" color "variations" (aka alternatives) was obvious but by stating it in a humorous quip, he was able to mask his ulterior motive which was his desire for a profoundly greater profit margin. He successfully "framed" the narrowing of public choices in self-serving terms that benefitted him financially. In this case, the general public also enjoyed the collateral benefit of Ford making private transportation more affordable.

This analogy is especially useful in the current "energy project" situation because it also illuminates and differentiates between a corporate "purpose and need" and the public's "purpose and need".

The analogy helps understand how framing the need for the Line 3 project in alternative limiting terms like Henry Ford did it comes out sounding like this: *"Society can have any type of energy you want so long as its fossil fuel".*

It also helps identify how private industry needs can be balanced against public interest needs in mutually beneficial terms that are measurable but this balancing must be explicitly described for purposes environmental review.

The public comments in the record for both the Sandpiper and the Line 3 dockets time and time again ask the Commerce Department to make a clear re-statement of the purpose and need for this energy project within the plain meaning of MEPA, EQB rules.

Early Notices of Public meetings and hearings published by the DOC repeatedly used the applicant's framing of the purpose and need for this project in self-serving language supplied by the applicant. When confronted at one public meeting in Park Rapids held for scoping both the Sandpiper and Line 3 EIS, DOC staff conceded that the language used was inappropriate, they promptly rescinded it, revised it and reprinted the Public Meeting information documents on the spot. Public statements at subsequent public EIS scoping meetings (as transcripts of these meetings would show) included a specific announcement that the purpose and need statement that were being used were "drafts", subject to change in the DEIS scoping document based on public input. No such clear statement of public "purpose and need" has appeared in subsequent DOC or other scoping documents or in this DEIS.

Now, in Chapter 1 of the DEIS the Department of Commerce proposes to make the "need" determination for this energy project on the basis of "market forces" as judged by the validity of "shipper demand" for crude oil. In so doing a public agency places itself (and the potentially the PUC) in Henry Ford's "corporate need" frame of mind primarily considering the corporate profit motives and whatever competitive advantages the company might gain by routing a pipeline in one location or another between predetermined Points A and Point B (*any color so long as its black*).

Once again, and the purpose and need statement reverts to the old paradigm using only self-serving and private profit motivated language. Paraphrasing (and reframing with italicizing) for clarification the project purpose statement from page 2-4 in Chapter 2 of the DEIS. This (think **black** Model "T") particular project's purpose is:

1. To replace *their* failing Line 3
2. To save *them* money (repair and inspections)
3. To meet a demand for *their* type of energy *they* claim *exceeds* their current capacity;
4. To reduce *their* "curtailment" of service to *their* shippers and improve *their* operational flexibility;
5. To improve the energy efficiency of *their* pipeline system.

The applicant's purpose of the project is clearly described here but it is very significant that the word "need" does not appear here. The definition and determination of "need" are precluded from further discussion in the DEIS with this misleading declaration in Section 1.4.1.1; under the heading *Need for This Project*): "The EIS Does Not **Determine** the Need for **THIS** project." (bold emphasis added)

This is quite true but misleading. An EIS it is supposed to describe evidence whether a project will provide a needed socio-economic benefit that would somehow balance the actual environmental harm (or threat of future harm) predicted to occur if the project moves forward. As EQB staff explains the MEPA process:

> "One of the main purposes of an EIS is to examine potential impacts of project alternatives. Unlike with an EAW, the impacts analyzed are not limited to environmental impacts. The statute calls for the EIS to evaluate "***economic***, employment and sociological impacts" as well.

In the case of the current pipeline project if there is a beneficial economic and sociological need for the “type” of energy this pipeline facility will deliver it is the RGU’s responsibility to clearly identify and quantify that need in the DEIS.

And this must be done within the arena of a MEPA compliant EIS rather than transfer and delay that debate for some other arena such as the contested case hearing on the CON as is apparently proposed in the DEIS. It is this reviewer’s contention that the EIS process can be used to fully inform that other CON arena of deliberation. As will be shown below, each of the Certificate of Need Criteria are genuine fodder for and fall well within the scope of the EIS process.

The CON arena cannot be allowed, as DOC suggests, to claim special preemptive jurisdiction or to assemble a different body of facts or in any other way constrain the definition of “purpose and need” that would interfere the functions of the MEPA process by hobbling the EIS.

There are certain aspects of shipper demand for the type of energy (tar sands crude oil) that are declared proprietary information (trade secret) and the strict procedural confines of a contested case hearing may be where this information is properly taken into account. But this cloak of legal protection cannot be thrown over the entire body of socio-economic need information necessary for weighing these benefits against potential public harm in the DEIS. Societies obviously need energy and the project proposes to deliver fossil fuel type energy. And that energy need and the optional ways society can get that or any other type of energy can be fully developed in the DEIS without disclosing any of this trade-secret information.

When closely examined the PUC’s Certificate of Need Criteria are quite consistent with the type and scope of information required under MEPA. And the PUC criteria for pipeline routing pipelines are not inconsistent with MEPA requirements.

Compatibility of PUC Certificate of Need Criteria with MEPA

A review of PUC Certificate of Need Criteria for large energy projects cast in the frame of society’s purpose needs rather than the applicant’s purpose and need stated in the DEIS is shown below with the author’s comments in blue font enclosed in parenthesis.

PUC Need Criteria: 7853.0130 CRITERIA.

A certificate of need shall be granted to the applicant if it is determined that:

A. the probable result of denial would adversely affect the future adequacy, reliability, or efficiency of energy supply to the applicant, to the applicant's customers, or to the people of Minnesota and neighboring states, considering: (The term energy is used here, not crude oil. The applicant’s customers need not, in fact should not, be defined as “shippers” because these shippers are simply partners in transporting or processing (refining) crude

oil before it reaches its ultimate consumer. To lump other shippers or refiners into the same category as energy users consumers in Minnesota and neighboring states is a stretch because it lumps transporters and processors with end user of th energy. The ultimate customers are the consumers of the energy, not other transporters or processors who actually don't actually use the energy, they represent the middle men. It is also important to note that energy demands of foreign countries are not included in this need criterion. If "customer demand" is defined by shipper demand foreign based consumers are hidden but actually counted as legitimate customers along with Minnesota and neighboring states.)

(1) the accuracy of the applicant's forecast of demand for the type of energy that would be supplied by the proposed facility; (Again, crude oil shipper demand is not ultimate consumer energy demand and again masks export with domestic demand. This criterion requires the applicant to make a showing that this "type" of energy (fossil fuel) will continue to be in demand as energy type of choice for domestic customers. And this future demand should be extended through the expected life of the proposed project - 50 yrs or more.)

(2) the effects of the applicant's existing or expected conservation programs and state and federal conservation programs; (Enbridge claims to have reduced its energy needs for operating its pipeline system through conservation measures and has made significant shifts securing renewable types of energy for powering its pumping stations thus reducing the applicant's demand for fossil fuel type energy. State and Federal energy conservation programs have also significantly reduced fossil fuel type energy demands in Minnesota and in neighboring states. This is an important indicator of a decreasing need for fossil fuels regionally that is driven by the applicant and its customer's conservation programs and shifts to alternative energy types.)

(3) the effects of the applicant's promotional practices that may have given rise to the increase in the energy demand, particularly promotional practices that have occurred since 1974; (Big oil companies have lobbied Congress for years and finally succeeded in lifting the ban on exporting crude oil from the U.S. thus increasing the world market opportunities, especially for heavy tar sands type crude. Domestic refineries are tooled for lighter crude so it seems will likely serve emerging foreign rather than domestic energy demand where fossil fuels may still be the energy type of choice.

(4) the ability of current facilities and planned facilities not requiring certificates of need, and to which the applicant has access, to meet the future demand; and (The applicant has access to renewable energy sources within the state and in other states, specifically North Dakota wind energy that do not require certificates of need. Other renewable sources not requiring certificates of need could be assessed for capacity to meet future demand with energy types that conform to global, national and state energy policy.)

(5) the effect of the proposed facility, or a suitable modification of it, in making efficient use of resources; (The effect of a pipeline project for making efficient use of resources can be addressed in the EIS.)

B. a more reasonable and prudent alternative to the proposed facility has not been demonstrated by a preponderance of the evidence on the record by parties or persons other than the applicant, considering: (The existing record is replete with proposals for alternative renewable energy facilities and the DEIS could be used to develop these in detail meeting all the subsections below)

(1) the appropriateness of the size, the type, and the timing of the proposed facility compared to those of reasonable alternatives;

(2) the cost of the proposed facility and the cost of energy to be supplied by the proposed facility compared to the costs of reasonable alternatives and the cost of energy that would be supplied by reasonable alternatives;

(3) the effect of the proposed facility upon the natural and socioeconomic environments compared to the effects of reasonable alternatives; and (The EIS process is particularly well suited for gauging impacts and comparing fossil fuel type energy to renewable types)

(4) the expected reliability of the proposed facility compared to the expected reliability of reasonable alternatives; (The EIS can be used to compare reliability of renewables to fossil fuel type energy)

C. the consequences to society of granting the certificate of need are more favorable than the consequences of denying the certificate, considering:

(1) the relationship of the proposed facility, or a suitable modification of it, to overall state energy needs; (State policy declares that its

citizens must reduce its energy needs and switch to renewables reducing use of fossil fuel types. The relationship of the proposed fossil fuel energy project to the state's needs as determined by policy can be developed in the EIS.

(2) the effect of the proposed facility, or a suitable modification of it, upon the natural and socioeconomic environments compared to the effect of not building the facility; (This no-action alternative is also required under MEPA rules and the effects of not expanding Line 3 or abandoning it altogether can be assessed in the EIS)

(3) the effects of the proposed facility or a suitable modification of it, in inducing future development; and (Since the market for fossil fuel energy is not "developing" domestically but foreign markets apparently are developing the EIS could be used to assess the global effects this project would have for inducing greater dependencies of these foreign consumers on fossil fuels.)

(4) socially beneficial uses of the output of the proposed facility, or a suitable modification of it, including its uses to protect or enhance environmental quality; and (This is one of the most important criteria that defines project need in social terms, rather than in the applicant's terms. The "output" of the proposed project is crude oil and using this crude oil has few if any environmental protecting or enhancing prospects. The ones that do exist could be placed in direct contrast to the negative environmental effects from using fossil fuels in the EIS.)

D. it has not been demonstrated on the record that the design, construction, or operation of the proposed facility will fail to comply with those relevant policies, rules, and regulations of other state and federal agencies and local governments. (Since the EIS must not only include ultimate use of the fossil fuel the pipeline transports the amount of green house gases release must be compared to rates established in all other state policies including MEPA, the Next Generation Energy Act, the State Climate Action Plan, and the Governor's commitments to the Paris Climate Accord, the Global Climate Leadership Memorandum (The Under 2 MOU) and all other applicable policy statements on climate change.

If DOC found any other conflict between MEPA requirements and PUC Need Criteria for addressing energy need from the societal perspective there is clear guidance from the Legislature in MEPA on what statutes and rules are to take precedence and guide state agencies caught in this kind of dilemma. The language here is clear and needs no further explanation.

Minnesota Statutes 116D.03 - ACTION BY STATE AGENCIES.

Subdivision 1. **Requirement.** The legislature authorizes and directs that, to the fullest extent practicable the policies, rules and public laws of the state shall be interpreted and administered in accordance with the policies set forth in sections 116D.01 to 116D.06.

Subd. 2. **Duties.** All departments and agencies of the state government shall:

(1) on a continuous basis, seek to strengthen relationships between state, regional, local and federal-state environmental planning, development and management programs;

(2) utilize a systematic, interdisciplinary approach that will insure the integrated use of the natural and social sciences and the environmental arts in planning and in decision making which may have an impact on the environment; as an aid in accomplishing this purpose there shall be established advisory councils or other forums for consultation with persons in appropriate fields of specialization so as to ensure that the latest and most authoritative findings will be considered in administrative and regulatory decision making as quickly and as amply as possible;

(3) identify and develop methods and procedures that will ensure that environmental amenities and values, whether quantified or not, will be given at least equal consideration in decision making along with economic and technical considerations;

4) study, develop, and describe appropriate alternatives to recommended courses of action in any proposal which involves unresolved conflicts concerning alternative uses of available resources;

(5) recognize the worldwide and long range character of environmental problems and, where consistent with the policy of the state, lend appropriate support to initiatives, resolutions, and programs designed to maximize interstate, national and international cooperation in anticipating and preventing a decline in the quality of the world environment;

(6) make available to the federal government, counties, municipalities, institutions and individuals, in-formation useful in restoring, maintaining, and enhancing the quality of the environment, and in meeting the policies of the state as set forth in Laws 1973, chapter 412;

(7) initiate the gathering and utilization of ecological information in the planning and development of resource oriented projects; and

Conclusion: It seems clear that project need can and must be addressed in revisions of the DEIS in light of the CON criteria interpretations above. For convenience of the reviewer these revisions can be organized the fashion of CON need criteria as shown above. There may little or no need to consider shipper contracts or shipper demand when developing the need information sufficient to satisfy both MEPA and PUC CON criterion. Shipper market forces are simply the wrong indicator of societies needs for alternative types of energy and therefore are irrelevant to the current review.

Extraneous Alternatives Unnecessarily Complicate the DEIS

EQB guidance on selection of alternatives also warns RGU's against a common practice of intentional complicating an EIS by including exhaustive consideration of illogical and extraneous alternatives. This admonition is vitally important for a numbers of reasons. First an EIS is intended to consider only "reasonable and prudent" alternatives. And, secondly an EIS, in order to be "adequate" for its intended purpose, must be concise and tease out only issues that are really significant. To do otherwise is to weaken and underming some of the most useful purposes of an EIS, to aid and inform government decisions intended to serve the greater public interest. EQB guidance states:

> "At the same time, the RGU should not examine extraneous alternatives just to make an EIS more complicated."

Earlier in these comments it was observed that reviewing rail and truck transport of crude oils certainly made the DEIS more (and unnecessarily complicated. The request to remove these impractical and unreasonable alternatives from the DFIES is renewed here.

BIASED AND PREJUDIAL FRAMING OF ALTERNATIVE ROUTE SA-04

Throughout the DEIS the assessment of route SA-04 is significantly skewed in consistently negative ways. This methodology is inconsistent in unjustifiable ways and produces biased results.

Comparing Apples to Apples

SA-04 is routed to deliver crude oil over the entire distance of approximately 1,550 miles from Neche, N.D. directly to Joliette, Illinois the ultimate destination hub for the bulk the oil proposed for shipping in Line 3. This alternative is said to suffer greater aggregation of potential adverse impacts simply by virtue of it being significantly longer than the Applicant's preferred route (APR).

APR would also deliver crude oil some 1,550 miles also to Joliet Illinois from Neche, N.D. via Superior Wisconsin but does so by connecting with existing pipelines at Superior that extend to Joliet. Construction impacts of the Superior to Joliet leg of the APR have already taken place along the Superior to Joliet leg of this route the operations, maintenance and potential for leaks and spill impacts continue along this leg and are similar to that SA-04. Some temporary impacts will have dissipated over time as construction scars on the landscape heal. But even those impacts are still considered potential cumulative impacts of the APR must be counted in present terms when comparing alternatives, these are past impacts added to present, and reasonably foreseeable future impacts.

But some of the more significant ecosystem level impacts are ongoing along the Superior to Joliet leg such as the habitat fragmentation and ecosystem migration barrier effects. Invasive species distribution, predator prey relationship changes still exist and increased public access to remote natural areas along the pipeline corridor are also on-going.

For consistency purposes the impacts of two routes for delivering the same amount of oil from the same point of origin to the same destination must be assessed equally.

Another potentially cumulative impact must also be added to the APR side of the ledger and that is the prospect for having to expand pipeline capacity between Superior Wisconsin and Joliet to accommodate increased volume demands caused by expansion of Line 3 or other pipelines to Superior.

And, the recent order by the Michigan Attorney General possibly shutting down Enbridge's line 5 out of Superior to Canadian refineries may also result in crude oil being diverted to the Superior to Joliet leg of the extended APR. This may qualify as a reasonably foreseeable future impact and therefore potentially cumulative.

Unequal Opportunity for Center Line Refinements

APR's centerline has undergone several years of refinement weaving side to side avoiding higher value resources and areas of greater sensitivity which undoubtedly lowered the aggregate resource impact score by the method used in the DEIS. No such refinement of SA-04 was conducted in spite of alterative routes selection rules (Administrative Rule 7852.1900 for pipeline route selection) that require refinement to ensure all potential impacts proposed routes are minimized before final route selection is made. Several of the major impacts identified along SA-04 including areas of kasrt topography may well have been greatly reduced if not eliminated altogether had the route been adjusted (refined). 2432-4

7852.1900 CRITERIA FOR PIPELINE ROUTE SELECTION.

> *Subp. 2.Standard. In determining the route of a proposed pipeline, the commission shall consider the characteristics, the potential impacts, and methods to minimize or mitigate the potential impacts of all proposed routes so that it may select a route that minimizes human and environmental impact.*

The DEIS seems to assert that the route selection rule cited above does not apply until after the CON process is complete insofar SA-O4 is considered unless it emerges as the preferred alternative after the CON phase. In this case the DEIS acknowledge that the route SA-04 could be "refined" to circumvent sensitive resources but would be refined only if Enbridge applies for permitting of that route.

Under MEPA that sequential application of routing criteria rule after CON screening is not allowed. If a superior alternative route exists, the RGU must evaluate that alternative at its finest level of refinement. It cannot be presented at a disadvantaged level of refinement for one level of review and than at higher level of refinement later.

In this first ever attempt MEPA and PUC criterion must be allowed to reasonably merge constructively and fairly in the spirit and letter of MEPA when identifying the best available alternatives that would allow for the least adverse impacts.

Mitigation Prematurely Factored into APR Reducing Wetland Impacts

In Chapter 5 wetland impact methodologies on p. 5-110 the DEIS explains that APR incorporates measures to avoid or minimize wetland impacts but that these impact mitigations were not similarly applied to SA-04. This is a highly unusual method because mitigation is normally not factored into original impact assessment. If it is, it is done equally to avoid biasing of results. 2432-5

There also appears to be a discrepancy in construction and/or operation zone width for the two routes for wetland crossings that is not clearly explained or justified. Unequal application of wetland impact mitigation measures or unequal foot print width for wetland impact would seem to skews the results in favor of APR.

If this unequal application of impact mitigation or wetland foot print width was intended to counter balance lack of estimated wetland impacts for additional temporary work areas, roads pipe yards etc thought to be needed along SA-4 it is not made clear. The FDIES should further explain if, why and to what overall extent this counter-balancing was done and compare totals derived with and without these adjustments.

If these adjustment cannot be justified the wetland impacts should be recalculated.

Conclusion: The overall analysis of resource and oil release impacts for APR and SA-04 should be redone comparing these routes on more equal unbiased basis in the DFEIS.

Pipeline Route Optimization Methodologies

In preparing the comments below, an internet search of alternative routing methods was conducted. No examples of the unique method used in the DIES were found. However, many examples of Optimum Route Selection by GIS, the very method suggested in previous public comments were found in the search and all of the sites that included method evaluations affirm its superior characteristics, its practical utility for intial routing and for route comparisons. Most articles also describe just how universal this method has become in the industry. A comparison of the standard GIS Route Optimization for Pipeline methods found in this search to the unconventional method used in the DEIS is presented in the following two sections of thes comments.

The DEIS does not name the special method used but for convenience of discussion here, I have assigned a descriptive title to it: “Impact Assessment by Proximity to Selected Resources of Unranked Value” or IAPSRUV.

GIS Route Optimization

With the advent of computerized data base mapping (geographic information systems or GIS), invented by Dr. George Tomlinson for the Canadian government in the 1960's land use decision making was revolutionized. With this tool, that could be used to store and analyze information, private and public land use and natural resource management decision making entered the computer age. Its very first application in Canada was to help determine *"land use capability"* of a specific geographic study area to withstand certain potential environmental and cultural stresses introduced by a proposed development or project. This is the very same question that is at the very heart of pipeline routing issue in the DEIS.

And in this very first application of this method assessment of "land use capability" depended on certain social value judgments, a factor for rating relative resource value considerations was added.

See the history, the evolution and innovative applications GIS and geospatial analysis can be found on Wikipedia at:

https://en.m.wikipedia.org/wiki/Geographic_information_system

And one very important point needs emphasis here for reasons discussed in further detail in the section that follows comparing this conventional method to the DOC's selected IAPSRUV method.

That point is that from its very first application in the 1960's its inventor found it necessary to add a rating classification system to various soils, agriculture, recreation, wildlife, waterfowl, forestry and land use parameters to assist decision-makers in making ranked value based judgment comparisons between various types of land use options and alternative locations. Below is an excerpt from the GIS history page on the Wiki site above describing the very first application of the technology to government land use problems:

> **"The year 1960 saw the development of the world's first true operational GIS in Ottawa, Ontario, Canada by the federal Department of Forestry and Rural Development. Developed by Dr. Roger Tomlinson, it was called the Canada Geographic Information System (CGIS) and was used to store, analyze, and manipulate data collected for the Canada Land Inventory – an effort to determine the land capability for rural Canada by mapping information about soils, agriculture, recreation, wildlife, waterfowl, forestry and land use at a scale of 1:50,000. A rating classification factor was also added to permit analysis." (Highlighting added to emphasis earliest application of ranking)**

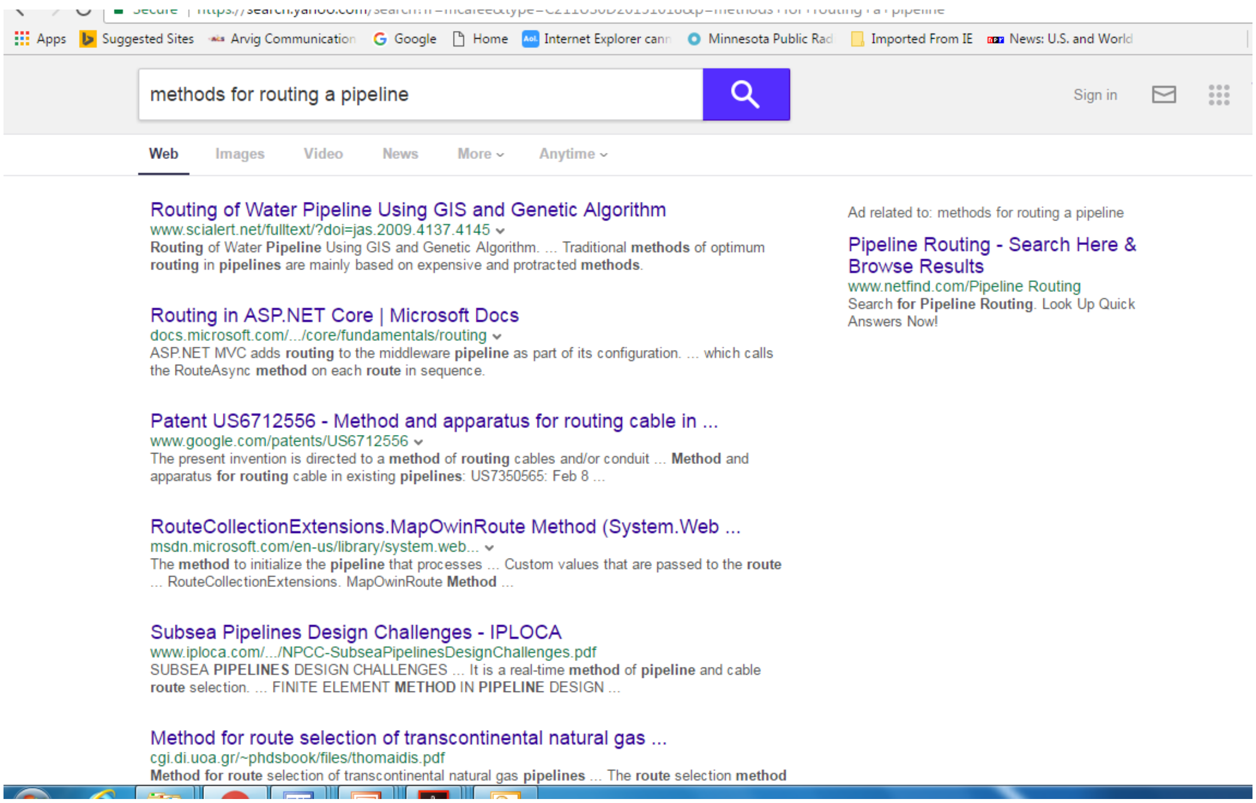
So powerful, so flexible and convenient is this technology that this GIS optimization system is now considered the gold standard of available technology for land use decision-making.

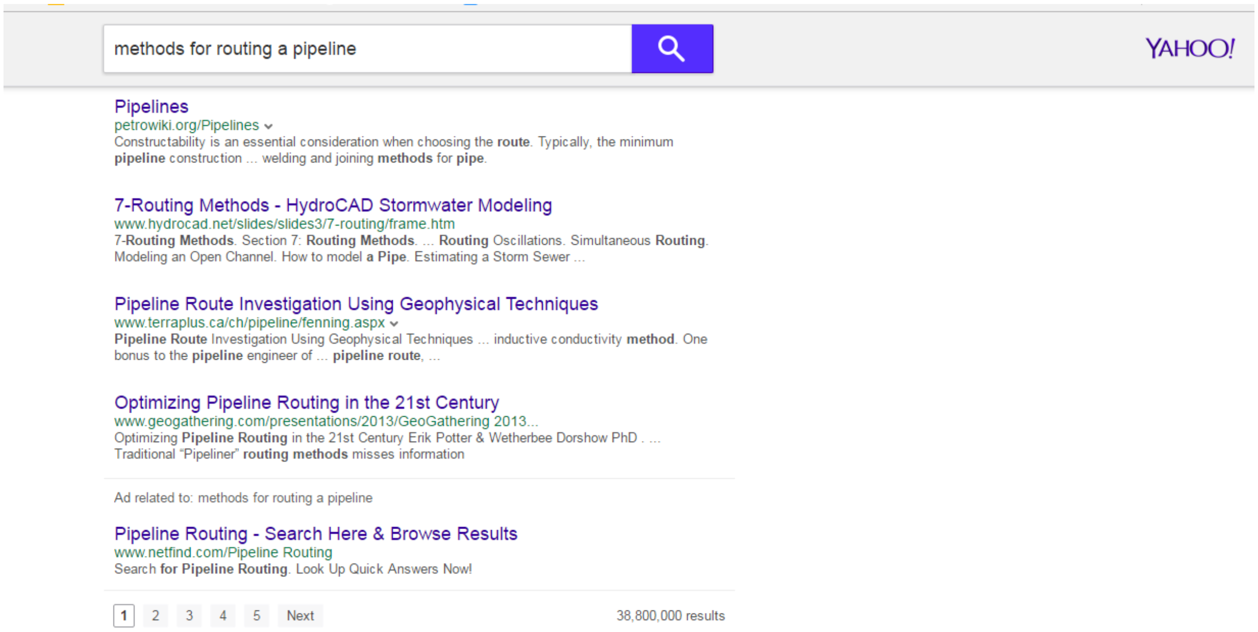
Furthermore, the method produces maps that are readily understandable by the lay public because the maps synthesize and compress so much useful but highly technical information into a map picture that nearly everyone can relate to. The numerical social values assigned to various land, water, cultural or other resources are easily displayed and available for critical reviewers to see and adjust if the general consensus so dictates. Adjustment to value weighting criteria can be applied to see if lowest cost routes by one set of criteria differ significantly if other weights are applied.

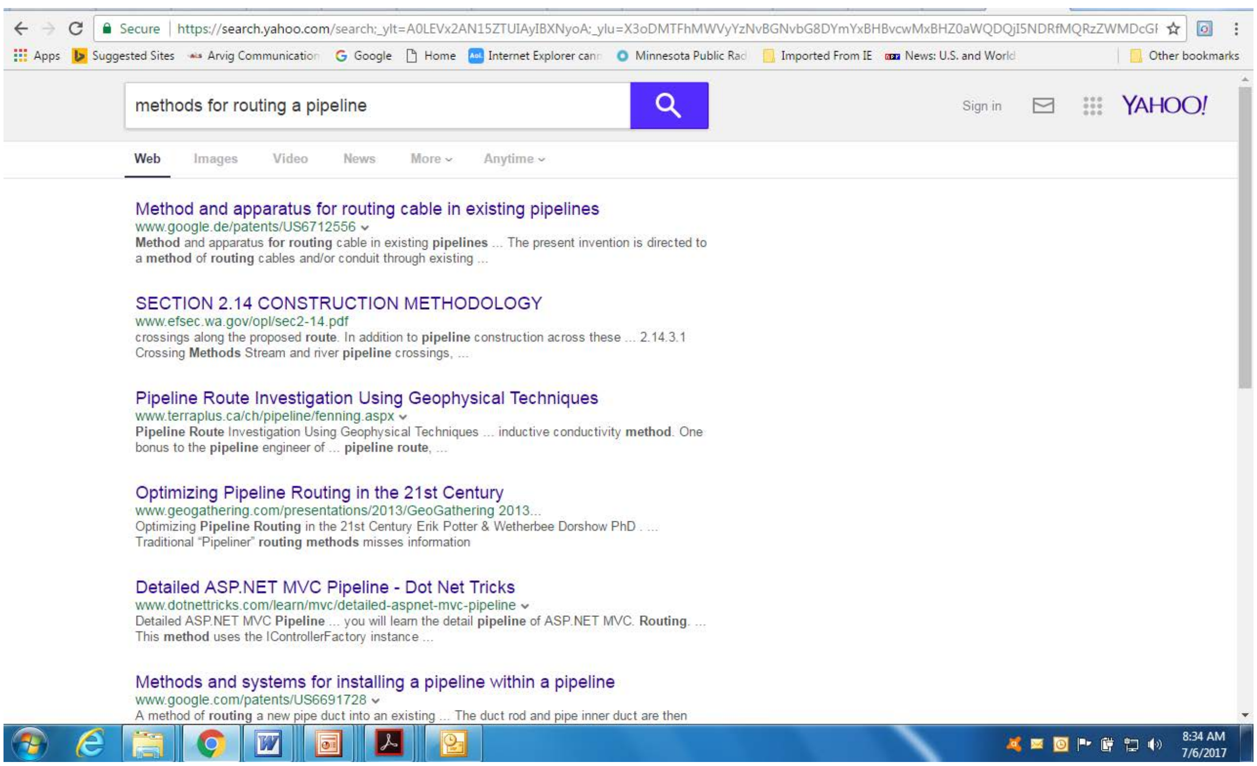
In the literature this is often called the “Least Cost Path” method, a term that will be used again in another cited paper to explain the essential steps in the process.

This consensus building attribute of this methodology is one of its strongest selling points for helping to resolve contentious land use issues. So much so that it is now the “go-to” technology for routing pipelines of all kinds and for other linear utility facilities like highways, internet cable service and even something as simple as a walking path or sidewalk.

A simple Google or Yahoo search on “methods for routing pipelines” yields a large number of theoretical and practical applications of the technology and critiques of it use and misuse as well. Here are the first three pages (in screen-shots) of my search results that serve as evidence of the methods wide acceptance in the industry.



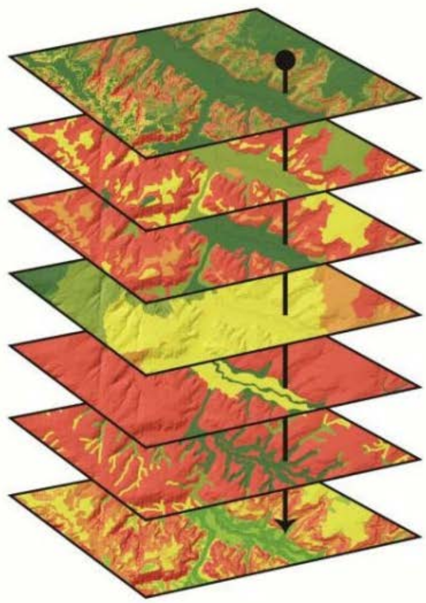




One of these search results sites: "*Optimizing Pipeline Routing in the 21st Century*" at:

http://www.geogathering.com/presentations/2013/GeoGathering%202013%20Pipeline%20Routing_M3Midstream.pdf has a graphic that is virtually self-explanatory insofar as how useful, understandable and flexible this technology can be for analyzing broad landscape level impact from large projects and their alternative locations.

Cost Surface Creation



Rank	Criteria	Weight
1	Side Slope Avoidance	10%
2	Slope	10%
3	RTE and Cultural Resources	8%
4	Surficial Geology	8%
5	Protected Areas	8%
6	Leases (No Data)	0%
7	Proximity to Proposed Wells (No Data)	0%
8	Existing ROW Proximity	7%
9	Existing Pipeline Corridor (no Data)	0%
10	Wetlands	5%
11	Parcel Size	4%
12	Dwelling Density	5%
13	Transportation	2%
14; Partially Restricted	Landowner Issue Avoidance	2%
15	Hydrology Avoidance	6%
16; Restricted	Rooftop Presence	9%
17; Partially Restricted	Mining	8%
Total		100%
*Restricted cells will not be traversed by SmartFootprint Route		

SmartFootprint cost surface rasters have pixel values ranging from zero to five, where a score of zero indicates the absence of constraints on pipeline project implementation success and a score of 5 indicates the presence of a very significant constraint on pipeline project implementation success.

One of the most essential consensus building components common to all standard GIS route optimization methods is the application addition of “pixel values” to determine the “significance” of any individual and collective impacts based on the relative value of the resource potentially impacted. And finding and using an analytical method for determining “significance” of impacts of a pipeline project is the essential element of any environmental impact statement

Assignment of a *“rating classification factor to permit analysis”* was recognized as one of the most important attribute of Dr. George Tomlinson’s original application of this technique over 50 years ago.

It is readily apparent that assignment of different level of importance (significance) to various human or natural resource assets along a pipeline or any other linear facility can be quite contentious. And unless consensus of the interested parties is achieved, the outcome of any analysis will likely be even more contentious as it as become with pipelines here in Minnesota and across the entire nation.

But this need not be so because this problem has also had a long-standing and consensus-building solution that is well documented in the literature. And, to be consensus building the method must be participatory for stakeholders.

In his paper entitled: "*Optimal Path Analysis and Corridor Routing: Infusing Stakeholder Perspective in Calibration and Weighting of Model Criteria*" available on line at:

http://www.innovativegis.com/basis/present/geotec04/gis04_routing.htm

Joseph K. Berry, University of Denver's Geography Department states:

> *"The use of the Least Cost Path (LCP) procedure for identifying an optimal route based on user-defined criteria has been used extensively in GIS applications for siting linear features and corridors. Whether applications involve movement of elk herds, herds of shoppers, or locating highways, pipelines or electric transmission lines, the procedure is fundamentally the same— 1) develop a discrete cost surface that indicates the relative preference for routing at every location in a project area, 2) generate an accumulated cost surface characterizing the optimal connectivity from a starting location (point, line or area) to all other locations based on the intervening relative preferences, and 3) identify the path of least resistance (steepest downhill path) from a desired end location along the accumulated surface."*

> *"The ability to infuse different perspectives into the routing process is critical in gaining stakeholder involvement and identifying siting sensitivity. It acts at the front end of the routing process to explicitly identify routing corridors that contain constructible routes reflecting different perspectives that guide siting engineer deliberations. Also, the explicit nature of the methodology tends to de-mystify the routing process by clearly identifying the criteria and how it is evaluated."*

And Mr. Berry goes on to explain:

> *"In addition, the participatory process 1) encourages interaction among various perspectives, 2) provides a clear and structured procedure for comparing decision elements, 3) involves quantitative summary of group interaction and dialog, 4) identifies the degree of group consensus for each decision element, 5) documents the range of interpretations, values and considerations surrounding decision criteria, and 6) generates consistent, objective and defendable parameterization of GIS models."*

The paper goes on to describes the use of modified Delphi and Analytical Hierarchical Process (AHP) techniques for quantitatively establishing calibration ratings and data layer weights similar to that displayed in the graphic above from the Optimizing Pipeline Routing in the 21st Century**"** on-line article.

Critique of Method Selected by RGU for Route Analysis

For this discussion the method applied in the DEIS to compare alternative routes has been titled: “Impact Assessment by Proximity to Selected Resources of Unranked Value” or IAPSRUV. The internet search for “methods for routing a pipeline” described above revealed no methods similar to the IAPSRUC method as having been published in industry literature, scientific journals or as having applied to the routing or comparative routing analysis for a specific pipeline project. It appears to be an entirely new creation developed for this DEIS.

To be fair, there are circumstances under which available more conventional methods such as Route Optimization or Least Cost Path methods are inappropriate for a given task and these conventional methods are either modified as needed to fit the new more challenging situation or an entirely new method must be developed as was done for the DEIS.

However, there is a professional obligation on the part of the authors of any technical report such as this DEIS to explain why a non-conventional method was thought necessary for this particular application. The source of this non-conventional method should be provided and why this alternate method was thought better than the available conventional methods. This explanation is normally presented the methodology section of a report but no such acknowledgment or explanation is presented in the DIES.

The selected IAPSRUV method used in the DEIS suffers from several important weaknesses of assumption which will be assessed later in these comments. But the primary failing of the methods used throughout Chapter 5 and elsewhere in the DEIS is that it actually fails to “analyze” significance of impacts. As stated above, determination of “significance” is the primary function of environmental review.

Without serving this essential function of describing for decision-makers the significance of impacts from this projects and comparing these impacts to those of project alternatives the DEIS fails to perform its intended purpose under MEPA and therefore DEIS condemns itself by admitting its own inadequacy.

The principle authors (DOC staff) of the DEIS not only refuse to use appropriate analytical tools in the DEIS for determining relative impact significance the authors even refuse to acknowledge these tool actually exist.

It should be noted here that this author and others recommended these or very similar methods during public comment periods for Sandpiper (nearly three years ago) and again more recently for the Line 3 process (copies of those comments are attached to and made part of these comments PDF Willis Mattison Comments to PUC, prepared for FOH).

Then the authors actually declare their abdication and turn that responsibility back to the PUC, the very entity that delegated the burden of responsibility to the DOC in the first place.

In section 1.4.2.2 Resource Prioritization DEIS provides this astonishing explanation for “only presenting facts” in the EIS but then excuses itself from actually analyzing the significance of these facts through the normal process of “prioritizing the value of one resource over another”.

> *1.4.2.2 Resource Prioritization*
> *The EIS Establishes Facts and Does Not Prioritize Some Resources over Others*
>
> *“The EIS assesses potential impacts on a wide range of resources and provides quantitative and qualitative descriptions of the nature, magnitude, and duration of these impacts. In addition, the EIS compares the nature, magnitude, and duration of impacts on a given resource across various alternatives. While the presentation of impact data in the EIS highlights tradeoffs across the differential alternatives so that decision-makers and other stakeholders can work from a common set of facts, the EIS does not prioritize one resource over another, nor does it prescribe how impacts on different types of resources should be weighted. The analysis in the EIS may show, for example, that some alternatives would result in greater impacts on human settlement and fewer impacts on natural resources, or more impacts on pristine waters and fewer impacts on waters that already are stressed by pollution. Decisions about whether and how to prioritize avoiding populated areas over undisturbed natural areas, and whether to concentrate infrastructure in already disturbed watersheds or spread the burden to other areas are part of the Commission’s charge and are not prescribed by the EIS.”(Highlights added for emphasis)*

In the DEIS, DOC acknowledges that the Pubic Utilities Commission has the “charge” of deciding “whether or how to prioritize” resource values, but seems to imply that this prioritization will be done later by the Public Utilities Commissioners themselves and possibly by some other unnamed method. The DOC by preparing the DEIS is acting as the technical agent for the PUC. A finding of significance impact is a technical process, using proven methods with input of value weighting judgments from stakeholders in a transparent and iterative way. Prioritizing Resources is just such a value judgment, a necessary stop on the road to finding significance.

In making this statement in the DEIS the Department of Commerce staff seems to display a fundamental misunderstanding of the MEPA process and for the gravity of the Appeals Court Order calling for preparing this EIS in the first place. The EIS was ordered on the Certificate of Need portion of pipeline review.

It also appears to reflect a willing abdication of the responsibility the PUC Commissioners delegated to DOC with for performing the heavy analytical lifting required in any environmental review process. Both the MEPA statute and EQB

Administrative Rules explain the very purpose of an EIS is to perform the necessary analysis in order to find the significance of impacts, and should such methods no be readily available to for explore (and find) appropriated methods for doing so. In MEPA (Minn Statues 116D) we find:

> **116D.03 ACTION BY STATE AGENCIES.**
>
> Subd. 2. **Duties.** All departments and agencies of the state government shall:
>
> (3) identify and develop methods and procedures that will ensure that environmental amenities and values, whether quantified or not, will be given at least equal consideration in decision making along with economic and technical considerations;

And in EQB Administrative Rules we find:

> **4410.2000 PROJECTS REQUIRING AN EIS.**
> Subpart 1. **Purpose of EIS.** The purpose of an EIS is to provide information for governmental units, the proposer of the project, and other persons to evaluate proposed projects which have the potential for **significant** environmental effects, to consider alternatives to the proposed projects, and to explore methods for reducing adverse environmental effects.

If the Commerce Department staff felt unqualified or unauthorized to perform the analysis required for environmental review they had many reasonable courses of action available to resolve this problem in a timely and efficient manner including:

1. Hiring of a consultant that had the expertise and experience in applying the necessary analytical methods;

2. Requesting PUC Commissioners perform the appropriately modified Delphi and Analytical Hierarchical Process (AHP) described in the Berry and Tomlinson papers cited above;

3. Establishing "*advisory councils or other forums for consultation with persons in appropriate fields of specialization so as to ensure that the latest and most authoritative findings will be considered*" as provided for in the MEPA cite above;

4. Proposing a set of resource weighting criteria based on the modified Delphi and Analytical Hierarchical Process (AHP) as part of the Draft Scoping process for the DEIS for public comment. This approach would have had obvious public and applicant consensus advantages.

5. Advising the PUC and the public of they lacked the necessary skills or resources to prepare the EIS and requested to be excused from this environmental review burden;

Conclusion: The sections of the EIS that fail to assign the weighting values to potentially impacted resources and derive objective levels of significance for these impacts must be completely revised to include this essential step. Without this final determination of significance the analysis is incomplete and comparisons of alternative routes produced by this incomplete assessment process cannot be used in the DFEIS. 2432-6

The pipeline route optimization method described earlier in these comments is highly recommended for completing the route comparisons. The modified Delphi and Analytical Hierarchical Process (AHP) techniques for quantitatively establishing calibration ratings and data layer weights should be utilized to determine significant differences in cumulative scores for each alternative route.

Crude Oil Leaks and Spills

Chapter 10 on this subject needs a thorough revision to include realistic worst case leak and spill scenarios in high value resource areas. The spill scenarios provided are far too limited by model boundaries such as downstream travel in 24 hrs. The lack of crude oil release volumes which were withheld by the applicant as trade secret prevent critical peer review of spill scenarios presented including revelation of what other limiting or biasing assumptions were used in the model runs. 2432-7

Several worst case sites along SA-04 should be modeled for use in comparing routes assessed in the DEIS.

And the leak/rupture scenarios should be more fully developed for the DFIES in terms of:

1. Exposure – the physical mechanisms by which aquatic organisms would become exposed to the spilled product;

2. Transport and fate – the distance down stream the toxic components would travel down stream before dissipating, degrading or diluting below applicable water quality standards for each or most important chemical constituent of the product spilled;

3. Exposure - Response – A full analysis of the product for all toxic components, list of state and federal water quality standards for these chemicals and laboratory methods used to simulate water column concentrations of each chemical of concern;

4. A review of analogous spills into likely receiving water types including isolated lakes, lake chains, high or low quality streams, wetlands of different types should be used to ground truth model results;

5. Risk Characterization –comparing exposure levels to toxicological benchmark levels, duration of risks, actual spill histories including

2432-7 Cont'd

potential for remediation and recovery of spilled product, site specific factors and overall weight of evidence; and

6. The Range of Uncertainties in each of these pieces of evidence.

A long term pin-hole leak scenario should be modeled for a major unconfined shallow sand aquifer such the Straight River aquifer in Hubbard County. This aquifer has been studied extensively so data needed to perform the model run should be readily available. This site may appear similar to the USGS Pinewood Study site but it represents a similar aquifer under influence of high rate pumping wells that would significantly increase groundwater velocities and flow directions. The number of municipal drinking water supply wells, industrial water supply wells and irrigation water supply wells is high and the aquifer is vertically complex with inter aquifer leakage common.

The significance of a major volume leak or spill on this site could then be compared to the most sensitive high value aquifer found along SA-04.

Need to Edit Entire DEIS Text to Eliminate Biased Language

Need to cleanse the DEIS of self-serving, project justifying language. There are many instances where statements are qualified or nullified causing them to lose objectivity. 2432-8
Many instances where potential for significant impacts are described the DEIS has sentences or whole paragraphs describing the applicant's intentions to minimize or mitigate a potential impact. Minimizing word like "only" or "seldom" or "minimal" should be used appropriately. .

In several locations in the DEIS the applicant promises to seek advice from certain other sources, usually some government agency, on how some impacts could or should be mitigated. Fracking fluid additives, for example are to be none other than MPCA approved additives with no indication whether MPCA makes or has authority for such approval or that they would grant approval for any of the available fluid additives.

The most common example is where paragraphs describing mitigation measures are misplaced in the discussion of impacts on a particular resource, especially if the section was describing an impact from the proposed project or APR. All such descriptions of mitigation should be moved to the section reserved for that information.

An independent copy editor may have to be retained to scour and cleanse the entire document for this biased language.

Need for Extended Review of a Revised DEIS Before a Draft Final is Prepared

Due to the extensive revisions that will be necessary to correct the major errors, deficiencies and omissions in the current DEIS and the that the summary will have to be changed dramatically as a result it is suggested that the DOC approach the PUC requesting a major time extension during which a revised DRAFT EIS can once again be put out for public review and comment rather than a draft FINAL EIS. Such major revisions can not be made in the short time period normally allowed. The PUC has already been put on notice that extended time will be needed just to review and respond the comments on this version. The pubic will need a similar extended time in which to review major revisions that result.

End of Comments-

APPENDIX A
Qualifications of the Author
Willis Mattison
42516 State Highway 34
Osage, Minnesota 56570

Education and Special Qualifications for performing this review:
I earned a Biology and Broad Science Degree from Bemidji State University with a minor in Chemistry and Master's of Science Degree with course emphasis and Master's Thesis in Ecology from St. Mary's University in Winona.

Career Experience
I have spent professional career time in the four major regions of greater Minnesota beginning with a career performing as a research biochemist at the Mayo Clinic, teaching Biology, Chemistry and Environmental Science in Tracy Minnesota, and as MPCA Regional Director for a twenty three county area in Southeast Minnesota while stationed in Rochester and for 28 counties in Northwestern Minnesota as MPCA Regional Director in Detroit Lakes and for seven counties in Northeastern Minnesota on a temporary mobility assignment as Regional Director Duluth.

Experience Performing and Reviewing Environmental Assessments and Impact Statements
I am a presently retired but remain a practicing natural scientist (ecologist) an experienced environmental review practitioner of many years. A significant portion of my 28 year career with the MPCA involved reviewing and preparing official agency critiques and comments on dozens of environmental assessments and impact statements at the local, state and federal levels.

I have continued to practice the applied ecological sciences in both my private life and public life staying current in the advancing methodologies used to address the ever increasing complexities and challenges involved in environmental issues and natural resource management. I own and have managed several hundred acres of forested land in Minnesota's Central Hardwood Forest in eastern Becker County. My private forest management goals, developed in accordance with provisions of the Minnesota Sustainable Forest Incentive Act and approved by the Minnesota Department of Natural Resources Forestry Division include protecting, restoring and enhancing the native plant communities on my private property. I also have a U.S. Department of Agriculture; Natural Resources Conservation Service approved Conservation Stewardship Plan with approved practices for forest wildlife habitat restoration and enhancement with a special focus on pollinator habitat. I have taken Department of Natural Resources courses for identifying and classifying Native Plant Communities and for applying these criteria toward achieving forest management goals. I’ve also taken University of Minnesota Extension classes in identification and control measures for terrestrial invasive species. Each of these subject areas, Native Plant Communities and Terrestrial Invasive Species are pertinent in this DEIS.

I was a principle author on several highly controversial environmental review documents such as for the U.S. Army Corp of Engineers Upper Mississippi Navigation Channel Maintenance (dredging) program, a major Mississippi River Lock and Dam Environmental Impact Study, several major hog feedlots in S.E. Minnesota, Red River Flood Control Impoundments in NW Minnesota and citizen petitioned EAW’s for proposed potato irrigation projects in north central Minnesota.

I received U.S. Environmental Protection Agency and Corps of Engineer’s in-service training on various complex aspects of the National Environmental Policy Act including proper methods for assessing cumulative environmental impacts and for effective civic engagement & group dynamics and facilitation for environmental review. I have provided testimony at public and legislative hearings on environmental issues in general and on specific projects with emphasis on various aspects of environmental impact. In my official capacity with the MPCA and in my private life since retirement I have served as an expert witness with regard to scientific data and analytical methods for environmental review.

My career assignments in four major outstate regions of Minnesota provided me with extensive opportunities to familiarize myself with the ecological conditions and assess the overall impacts of human development in the major biomes of the state and employ a number of ecological assessment criteria for both terrestrial and aquatic ecosystems. The specific ecosystem assessment methodologies I’ve worked with having direct applicable to the current Line 3 Pipeline include Index of Biotic Integrity (IBI for fish and macroinvertebrate and Native Plant Community Assessment.

I currently serve on a special EQB Advisory Panel assigned the task of modernizing the state’s environmental review program including the making recommendations for improving the administrative rules for environmental review and the guidance documents designed to assist Responsible Government Units in preparing MEPA compliant assessments and impact statements.

<u>Experience With Accidental Pollutant Release Incidents (ruptures, leaks and spills)</u>
During my career with the MPCA I served as first responder and performed as incident remediation oversight manager role for several large pipeline leaks and ruptures including

the 1979 Enbridge (then Lakehead) pipeline rupture near Pinewood just east of Bemidji. A leak site used as a reference in this DEIS. I am familiar with various studies done on the Pinewood spill site by the U.S. Geological Survey and other researchers examining the ultimate fate and transport of the large amount of unrecovered crude oil that remains on and in the groundwater beneath this site.

I also served as MPCA project manager for dozens of leaking underground storage tank (LUST) sites. I was first responder and lead project manager for system failure analysis following a large anhydrous ammonia storage tank release in Barnesville Minnesota that caused significant human health effects and damage to natural resources in the vicinity.

Familiarity and Experience with Optimal Site Analysis & Linear Path Analysis for Corridor Routing

As a volunteer with the North Country National Scenic Trail Association I have practical experience applying the preferred U. S. Park Service's Optimum Location Review (OLR) methodology for routing of this hiking trail, a linear facility routing procedure employing methods similar to those least-cost corridor routing software programs applicable to pipelines. I also have lead project manager experience applying the principles of "Limits of Acceptable Change" (LAC) to the Round Lake Wild Forest Recreation Area proposed for Becker County. LAC a well established planning system adopted by the U.S. Forest Service and designed to limit human impacts on natural resource protection areas to sustainable levels with the goal of protecting the essential ecological functions and aesthetic values of the planning area.

2432

PERSPECTIVES FOR THE ENERGY TRANSITION

Investment Needs for a Low-Carbon Energy System

About the IEA

The International Energy Agency (IEA), an autonomous agency, was established in November 1974. Its primary mandate was – and is – two-fold: to promote energy security amongst its member countries through collective response to physical disruptions in oil supply, and provide authoritative research and analysis on ways to ensure reliable, affordable and clean energy for its 29 member countries and beyond. The IEA carries out a comprehensive programme of energy co-operation among its member countries, each of which is obliged to hold oil stocks equivalent to 90 days of its net imports. The Agency's aims include the following objectives:

- Secure member countries' access to reliable and ample supplies of all forms of energy; in particular, through maintaining effective emergency response capabilities in case of oil supply disruptions.
- Promote sustainable energy policies that spur economic growth and environmental protection in a global context – particularly in terms of reducing greenhouse gas emissions that contribute to climate change.
- Improve transparency of international markets through collection and analysis of energy data.
- Support global collaboration on energy technology to secure future energy supplies and mitigate their environmental impact, including through improved energy efficiency and development and deployment of low-carbon technologies.
- Find solutions to global energy challenges through engagement and dialogue with non-member countries, industry, international organisations and other stakeholders.

About IRENA

The International Renewable Energy Agency (IRENA) is an intergovernmental organisation that supports countries in their transition to a sustainable energy future, and serves as the principal platform for international co-operation, a centre of excellence, and a repository of policy, technology, resource and financial knowledge on renewable energy. IRENA promotes the widespread adoption and sustainable use of all forms of renewable energy, including bioenergy, geothermal, hydropower, ocean, solar and wind energy, in the pursuit of sustainable development, energy access, energy security and low-carbon economic growth and prosperity. www.irena.org

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Executive Summary

Authors: International Energy Agency and International Renewable Energy Agency

Scope of the study

Investment is the lifeblood of the global energy system. Individual decisions about how to direct capital to various energy projects – related to the collection, conversion, transport and consumption of energy resources – combine to shape global patterns of energy use and related emissions for decades to come. Government energy and climate policies seek to influence the scale and nature of investments across the economy, and long-term climate goals depend on their success. Understanding the energy investment landscape today and how it can evolve to meet decarbonisation goals are central elements of the energy transition. Around two-thirds of global greenhouse gas (GHG) emissions stem from energy production and use, which puts the energy sector at the core of efforts to combat climate change.

Against this backdrop, the German government has requested the International Energy Agency (IEA) and the International Renewable Energy Agency (IRENA) to shed light on the essential elements of an energy sector transition that would be consistent with limiting the rise in global temperature to well below two degrees Celisius (2°C), as set out in the Paris Agreement. The overarching objective of this study is to analyse the scale and scope of investments in low-carbon technologies in power generation, transport, buildings and industry (including heating and cooling) that are needed to facilitate such a transition in a cost-effective manner, while also working towards other policy goals. The findings of this report will inform G20 work on energy and climate in the context of the 2017 German G20 presidency.

The analyses in this report are framed by several key questions which include:

- How can the energy sector achieve a transition to a decarbonised, reliable and secure energy sector at reasonable costs?
- What are the investment needs associated with the energy sector transition and how do investment patterns need to change to reach a low-carbon energy system?
- What are the co-benefits for other energy policy objectives that could result from an energy sector transformation?
- Assuming a timely and effective low-carbon energy sector transition, what is the outlook for stranded assets? What is the impact for stranded assets if action is delayed and the transition is sharper?
- How does the trend of declining costs for renewables and other low-carbon energy technologies, as well as acceleration of efficiency gains, support the decarbonisation? How can policy accelerate this development?
- What are the roles of carbon pricing and the phase-out of fossil fuel subsidies in ensuring a cost-effective decarbonisation of energy systems?
- What are the roles of more stringent regulations, better market design and/or higher carbon prices for the energy sector transition?
- What is the role of research, development and demonstration, and how can early deployment of a broad array of low-carbon technologies support an efficient and effective energy sector transition?

In order to address these questions, the IEA and IRENA separately have examined the investment needs for energy sector pathways that would foster putting the world on track towards a significant reduction in energy-related GHG emissions until the middle of this century. Each institution has developed one core scenario that would be compatible with limiting the rise in global mean temperature to 2°C by 2100 with a probability of 66%, as a way of contributing to the "well below 2°C" target of the Paris Agreement. Both the IEA and IRENA analyses start with the same carbon budget for the energy sector. But the pathways to reaching the goal differ between the two analyses: the modelling analysis conducted by the IEA aims at laying out a pathway towards energy sector decarbonisation that is technology-neutral and includes all low-carbon technologies, taking into account each country's particular circumstances. The analysis conducted by IRENA maps out an energy transition that stresses the potential of energy efficiency and renewable energy sources to achieving the climate goal, while also taking into consideration all other low-carbon technologies.

While IEA and IRENA base their energy sector analyses on different approaches and use different models and/or tools, there are similarities in high-level outcomes that support the relevance for a pathway and framework for a timely transition of the global energy sector. In the following sections, key findings from the analyses of each organisation are presented.

Carbon budget

The average global surface temperature rise has an almost linear relationship with the cumulative emissions of carbon dioxide (CO_2). This useful relationship has resulted in the concept of a remaining global "CO_2 budget" (the cumulative amount of CO_2 emitted over a given timeframe) that can be associated with a probability of remaining below a chosen temperature target.

The Paris Agreement makes reference to keeping temperature rises to "well below 2°C" and pursuing efforts to limit the temperature increase to 1.5°C. However it offers no clear guidance on what "well below 2°C" means in practice, or what probabilities should be attached to the temperature goals.For the purpose of this report, it was chosen to focus on a scenario with a 66% probability of keeping the average global surface temperature rise throughout the 21st century to below 2°C, without any temporary overshoot. Understanding the associated CO_2 budget consistent with this definition is a critical consideration for modelling the pace and extent of the energy sector transition (Table ES.1). To generate an estimate of CO_2 budget for a 66% chance of staying below 2°C, it is necessary to estimate levels and rates of non-CO_2 emissions. For the purpose of this study, non-CO_2 emissions originating from non-energy sectors rely on the scenarios from the database of the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). With these assumptions, for the purpose of this study, we estimate that the CO_2 budget between 2015 and 2100 is 880 gigatonnes (Gt). This lies towards the middle of the 590 – 1 240 Gt CO_2 range from a study discussing CO_2 budgets commensurate with a 66% chance of staying below 2°C.

Table ES.1 • Energy sector CO_2 budget in the decarbonisation scenarios developed by the IEA and IRENA in this study

(Gt CO_2)	2015 - 2100
Total CO_2	880
Industry processes	-90
Land use, land-use change and forestry	0
Energy sector CO_2 budget	790

It is important to recognise that the 66% 2°C scenarios explored in this report keep the temperature rise below 2°C not just in 2100 but also over the course of the 21st century. It does not permit any temporary overshooting of this temperature in any year. The main reason for this working assumption is that permitting a temporary overshoot of a specific temperature rise before falling back to this level in 2100 would imply relying on negative-CO_2 technologies (such as direct air capture, enhanced rock weathering, afforestation, biochar and bioenergy with carbon capture and storage) at scale sometime in the future. The assessment of the implications of widespread adoption of bioenergy with carbon capture and storage (BECCS) for land-use requirements or the potential uptake of non-energy technologies for CO_2 removal is outside the scope of this report.

Nevertheless, many of the scenarios assessed by the IPCC in its Fifth Assessment Report that aim to limit the specific temperature rise in 2100 to 2°C rely heavily upon BECCS such that the global energy sector as a whole absorbs CO_2 emissions from the atmosphere by the end of the century. The scenarios developed in this study are therefore ambitious in terms of the timing and scope of required energy emissions reductions for meeting the 2°C goal as they offer no possibility to delay CO_2 emissions reduction until negative-emissions technologies are available at scale. Nevertheless, the scenarios offer the possibility for achieving more stringent climate targets in the future, should negative-emissions technologies become available.

To arrive at an *energy sector only* CO_2 budget for the 66% 2°C scenario it is necessary to subtract from the total CO_2 budget those CO_2 emissions not related to fossil fuel combustion in the energy sector. These emissions predominantly arise from two sources: industrial processes and from land use, land-use change and forestry (LULUCF). For the latter, the outlook for CO_2 emissions from LULUCF used in this study are based on the median of 36 unique decarbonisation scenarios analysed by the IPCC. For this study, the assumption is that CO_2 emissions from LULUCF fall from 3.3 Gt in 2015 to zero by mid-century. LULUCF subsequently becomes a net absorber of CO_2 over the remainder of the 21st century, and, as a result, cumulative CO_2 emissions from LULUCF between 2015 and 2100 are close to zero.

The net effect of these two factors is to reduce the total CO_2 budget from 880 Gt to an energy sector only budget of 790 Gt. The challenge is stark: by means of comparison, current Nationally Determined Contributions (NDCs) imply that, until 2050, the energy sector would emit almost 1 260 Gt, i.e. nearly 60% more than the allowed budget.

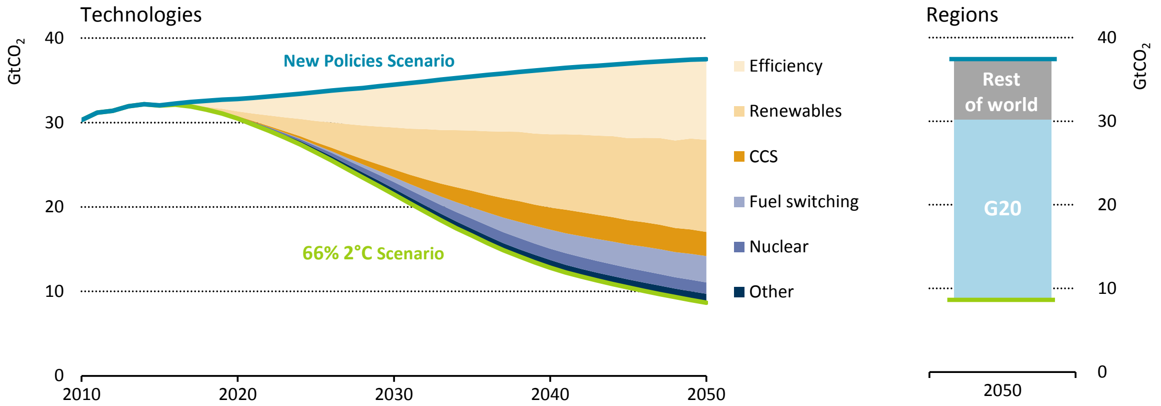
IEA findings

Limiting the global mean temperature rise to below 2°C with a probability of 66% would require an energy transition of exceptional scope, depth and speed. Energy-related CO_2 emissions would need to peak before 2020 and fall by more than 70% from today's levels by 2050. The share of fossil fuels in primary energy demand would halve between 2014 and 2050 while the share of low-carbon sources, including renewables, nuclear and fossil fuel with carbon capture and stoage (CCS), would more than triple worldwide to comprise 70% of energy demand in 2050.

The 66% 2°C Scenario would require an unparalleled ramp up of all low-carbon technologies in all countries. An ambitious set of policy measures, including the rapid phase out of fossil fuel subsidies, CO_2 prices rising to unprecedented levels, extensive energy market reforms, and stringent low-carbon and energy efficiency mandates would be needed to achieve this transition. Such policies would need to be introduced immediately and comprehensively across all countries in order to achieve the 66% 2°C Scenario, with CO_2 prices reaching up to US dollars (USD) 190 per tonne of CO_2. The scenario also requires broader and deeper global efforts on technology collaboration to facilitate low-carbon technology development and deployment.

Improvements to energy and material efficiency, and higher deployment of renewable energy are essential components of any global low-carbon transition. In the 66% 2°C Scenario, aggressive efficiency measures would be needed to lower the energy intensity of the global economy by 2.5% per year on average between 2014 and 2050 (three-and-a-half times greater than the rate of improvement seen over the past 15 years); wind and solar combined would become the largest source of electricity by 2030. This would need to be accompanied by a major effort to redesign electricity markets to integrate large shares of variable renewables, alongside rules and technologies to ensure flexibility.

Figure ES.1 • Global emissions abatement by technology and region in the 66% 2°C Scenario relative to the New Policies Scenario



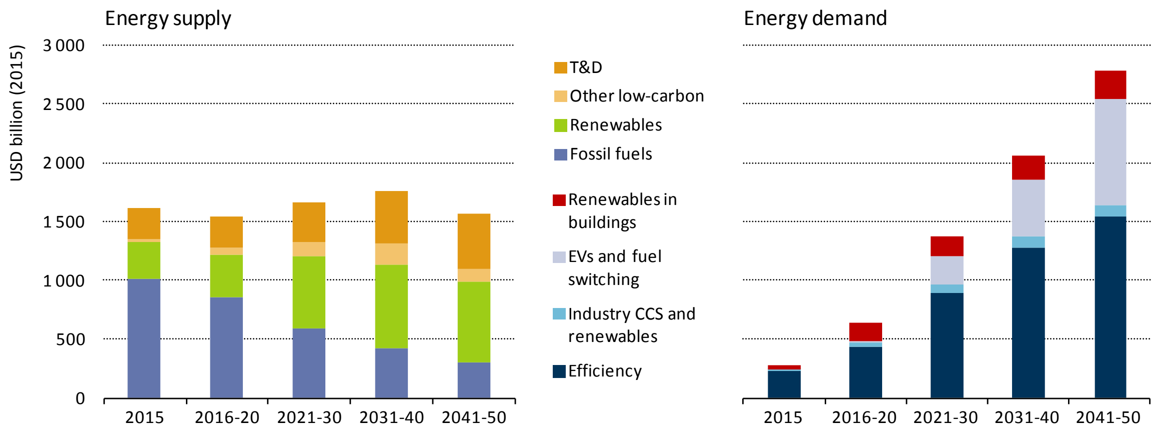
Note: The New Policies Scenario reflects the implications for the energy sector of the NDCs of the Paris Agreement.

Key message • G20 countries provide almost three-quarters of the emissions reductions in 2050 between the 66% 2°C and New Policies Scenarios.

A deep transformation of the way we produce and use energy would need to occur to achieve the 66% 2°C Scenario. By 2050, nearly 95% of electricity would be low-carbon, 70% of new cars would be electric, the entire existing building stock would have been retrofitted, and the CO2 intensity of the industrial sector would be 80% lower than today.

A fundamental reorientation of energy supply investments and a rapid escalation in low-carbon demand-side investments would be necessary to achieve the 66% 2°C Scenario. Around USD 3.5 trillion in energy sector investments would be required on average each year between 2016 and 2050, compared to USD 1.8 trillion in 2015. Fossil fuel investment would decline, but would be largely offset by a 150% increase in renewable energy supply investment between 2015 and 2050. Total demand-side investment into low-carbon technologies would need to surge by a factor of ten over the same period. The additional net total investment, relative to the trends that emerge from current climate pledges, would be equivalent to 0.3% of global gross domestic product (GDP) in 2050.

Figure ES.2 • Average annual global energy supply- and demand-side investment in the 66% 2°C Scenario



Note: T&D = transmission and distribution; EVs = electric vehicles; CCS = carbon capture and storage.

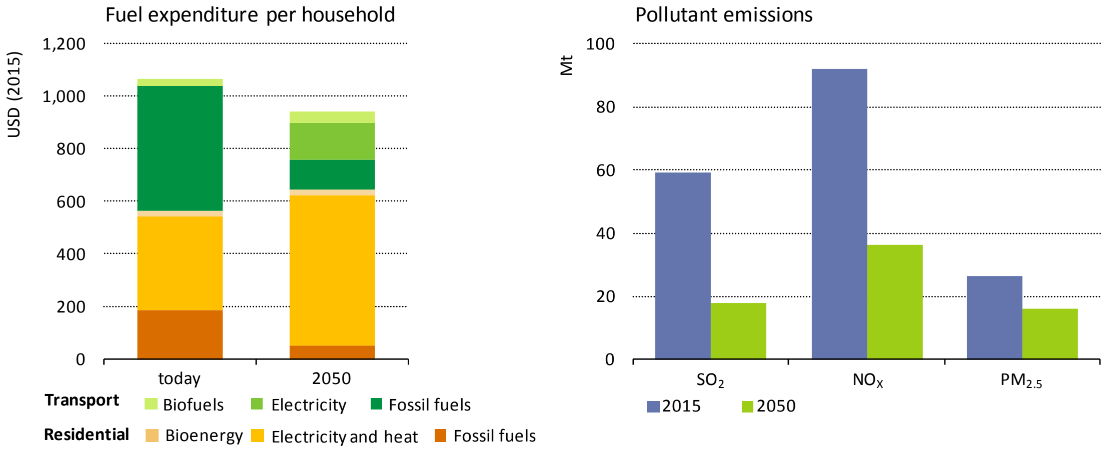
Key message • The level of supply-side investment remains broadly constant, but shifts away from fossil fuels. Demand-side investment in efficiency and low-carbon technologies ramps up to almost USD 3 trillion in the 2040s.

Fossil fuels remain an important part of the energy system in the 66% 2°C Scenario, but the various fuels fare differently. Coal use would decline most rapidly. Oil consumption would also fall but its substitution is challenging in several sectors. Investment in new oil supply will be needed as the decline in currently producing fields is greater than the decline in demand. Natural gas plays an important role in the transition across several sectors.

Early, concerted and consistent policy action would be imperative to facilitate the energy transition. Energy markets bear the risk for all types of technologies that some capital cannot be recovered ("stranded assets"); climate policy adds an additional consideration. In the 66% 2°C Scenario, in the power sector, the majority of the additional risk from climate policy would lie with coal-fired power plants. Gas-fired power plants would be far less affected, partly as they are critical providers of flexibility for many years to come, and partly because they are less capital-intensive than coal-fired power plants. The fossil fuel upstream sector may, besides the power sector, also carry risk not to recover investments. Delaying the transition by a decade while keeping the same carbon budget would more than triple the amount of investment that risks not to be fully recovered. Deployment of CCS offers an important way to help fossil fuel assets recover their investments and minimise stranded assets in a low-carbon transition.

With well-designed policies, drastic improvements in air pollution, as well as cuts in fossil fuel import bills and household energy expenditures, would complement the decarbonisation achieved in the 66% 2°C Scenario. Achieving universal access to energy for all is a key policy goal; its achievement would not jeopardise reaching climate goals. The pursuit of climate goals can have co-benefits for increasing energy access, but climate policy alone will not help achieve universal access.

Figure ES.3 • Trends for selected key indicators in the 66% 2°C Scenario



Key message • The transition to a low-carbon energy sector could help achieve other key energy policy goals, such as reducing air pollution and household fuel expenditures.

IRENA findings

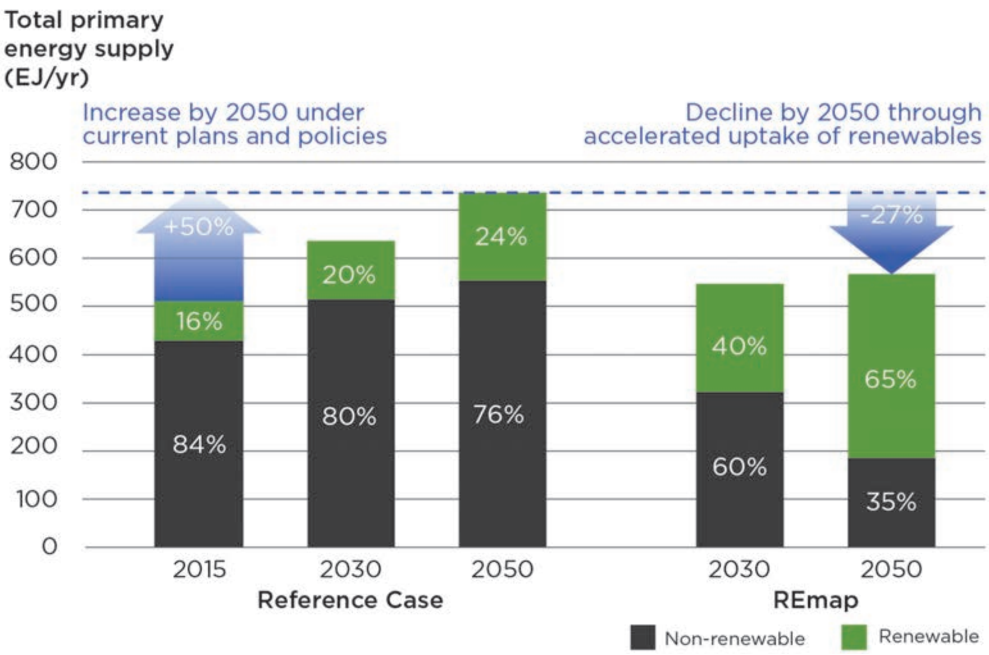
Accelerated deployment of renewable energy and energy efficiency measures are the key elements of the energy transition. By 2050, renewables and energy efficiency would meet the vast majority of emission reduction needs (90%), with some 10% achieved by fossil fuel switching and CCS. In the REmap decarbonisation case nuclear power stays at the 2016 level and CCS is deployed exclusively in the industry sector.

The share of renewable energy needs to increase from around 15% of the primary energy supply in 2015 to 65% in 2050. Energy intensity improvements must double to around 2.5% per year by 2030, and continue at this level until 2050. Energy demand in 2050 would remain around today's level due to extensive energy intensity improvements. Around half of the improvements could be attributed to renewable energy from heating, cooling, transport and electrification based on cost-effective renewable power.

The energy supply mix in 2050 would be significantly different. Total fossil fuel use in 2050 would stand at a third of today's level. The use of coal would decline the most, while oil demand would be at 45% of today's level. Resources that have high production costs would no longer be exploited. While natural gas can be a "bridge" to greater use of renewable energy, its role should be limited unless it is coupled with high levels of CCS. There is a risk of path dependency and future stranded assets if natural gas deployment expands significantly without long-term emissions reduction goals in mind.

The energy transition is affordable, but it will require additional investments in low-carbon technologies. Further significant cost reductions across the range of renewables and enabling technologies will be major drivers for increased investment, but **cumulative additional investment would still need to amount to USD 29 trillion over the period to 2050.** This is in addition to the investment of USD 116 trillion already envisaged in the Reference Case. Reducing the impact on human health and mitigating climate change would save between two- and six-times more than the costs of decarbonisation.

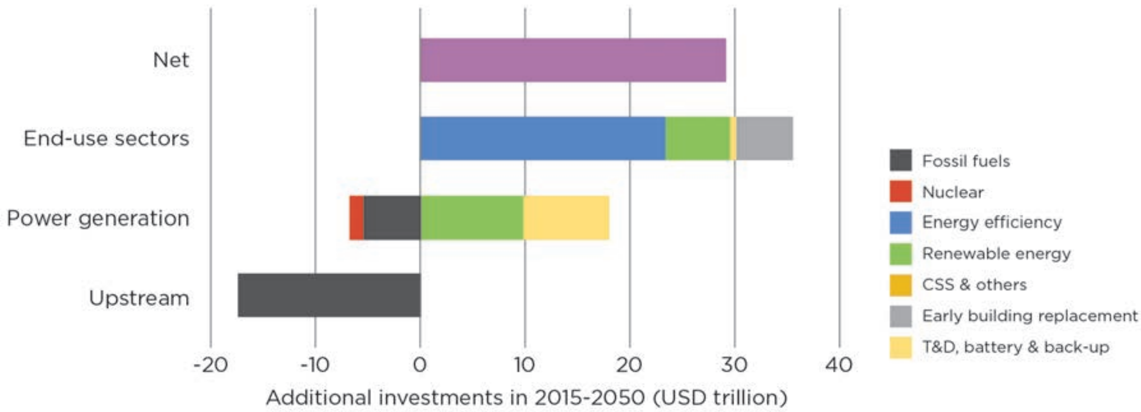
Figure ES.4 • Global total primary energy supply, 2015-2050



Key message • Renewable energy would be the largest source of energy supply under REmap in 2050, representing two-thirds of the energy mix. This requires an increase of renewables' share of about 1.2% per year, a seven-fold acceleration compared to recent years.

Early action is critical in order to limit the planet's temperature rise to 2°C and to maximise the benefits of this energy transition, while reducing the risk of stranded assets. Taking action early is also critical for feasibly maintaining the option of limiting the global temperature rise to 1.5°C. Delaying decarbonisation of the energy sector would cause the investments to rise and would double stranded assets. In addition, delaying action would require the use of costly technologies to remove carbon from the atmosphere.

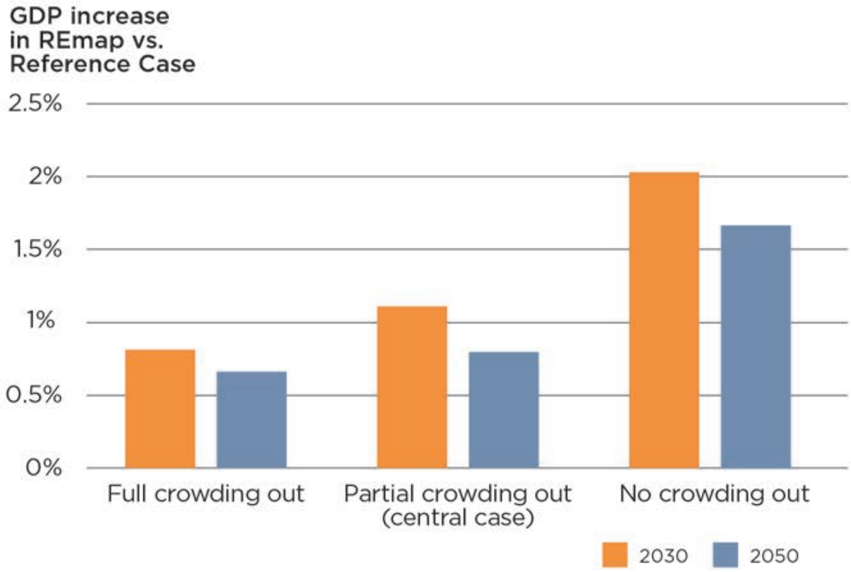
Figure ES.5 • Additional investment needs in REmap compared to the Reference Case, 2015-2050



Key message • Meeting the 2°C target requires investing an additional USD 29 trillion between 2015 and 2050 compared to the Reference Case.

The energy transition can fuel economic growth and create new employment opportunities. Global GDP will be boosted around 0.8% in 2050 (USD 1.6 trillion). The cumulative gain through increased GDP from now to 2050 will amount to USD 19 trillion. Increased economic growth is driven by the investment stimulus and by enhanced pro-growth policies, in particular the use of carbon pricing and recycling of proceeds to lower income taxes. In a worst-case scenario (full crowding out of capital), GDP impacts are smalller but still positive (0.6%) since the effect of pro-growth policies remains favourable. Important structural economic changes will take place. While fossil fuel industries will incur the largest reductions in sectoral output, those related to capital goods, services and bioenergy will experience the highest increases. The energy sector (including energy efficiency) will create around six million additional jobs in 2050. Job losses in fossil fuel industry would be fully offset by new jobs in renewables, with more jobs being created by energy efficiency activities. The overall GDP improvement will induce further job creation in other economic sectors.

Figure ES.6 • Global GDP impacts in different cases of crowding out of capital



Notes: Partial crowding out is modelled by forcing savings to be at least 50% of investment. Full crowding out imposes savings to be equal to investment. Null crowding out does not impose any relation between savings and investment.

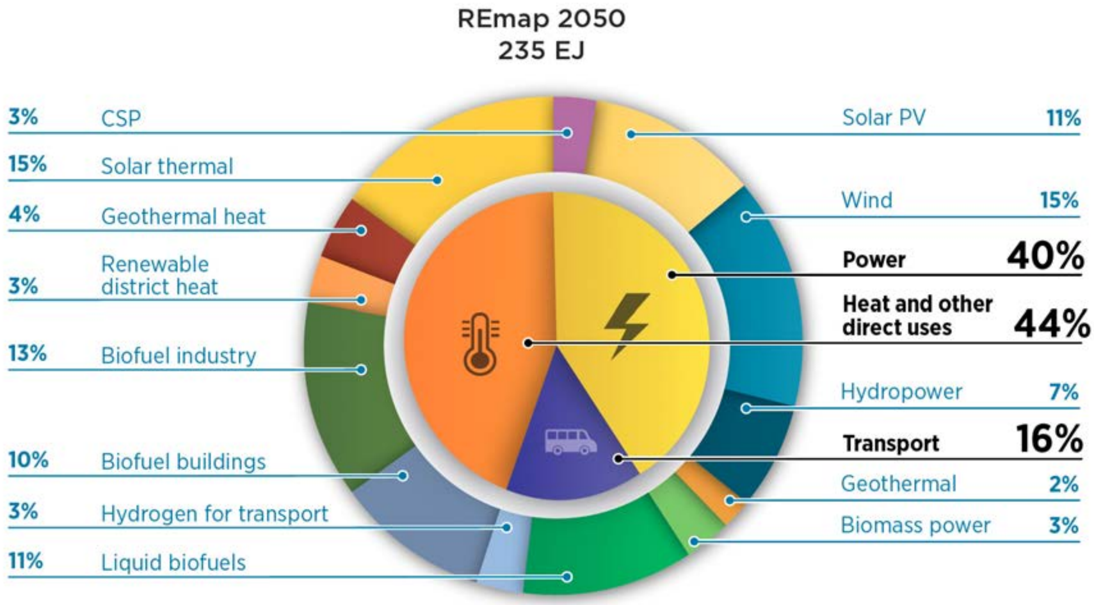
Key message • **Global GDP will be boosted by around 0.8% in 2050 (USD 1.6 trillion). In a worst-case scenario (full crowding out of capital), GDP impacts are smalller but still positive (0.6%) since the effect of pro-growth policies is still favourable.**

Improvements in human welfare, including economic, social and environmental aspects, will generate benefits far beyond those captured by GDP. Around 20% of the decarbonisation options identified are economically viable without consideration of welfare benefits. The remaining 80% are economically viable if benefits such as reduced climate impacts, improved public health, and improved comfort and performance are considered. However, today's markets are distorted – fossil fuels are still subsidised in many countries and the true cost of burning fossil fuel, in the absence of a carbon price, is not accounted for. To unlock these benefits, the private sector needs clear and credible long-term policy frameworks that provide the right incentives.

Deep emission cuts in the power sector are a key opportunity and should be implemented as a priority. Sectoral approaches must be broadened to system-wide perspectives, to address the main challenge of reducing fossil fuel use in end-use sectors. The power sector is currently on track to achieving the necessary emissions reductions, and its ongoing efforts must be sustained, including a greater focus on power systems integration and coupling with the end-use sectors. In transport, the number of electric vehicles needs to grow and new solutions will need to be developed for freight and aviation. It is critical that new buildings are of the highest efficiency standards and that existing buildings are rapidly renovated. Buildings and city designs should facilitate renewable energy integration.

Increased investment in innovation needs to start now to allow sufficient time for developing the new solutions needed for multiple sectors and processes, many of which have long investment cycles. Technology innovation efforts will need to be complemented by new market designs, new policies and by new financing and business models, as well as technology transfer.

Figure ES.7 • Final renewable energy use by sector and technology in REmap, 2050



Key message • **Under REmap, final renewable energy use is four-times higher in 2050 than it is today. Power and heat consume about 40% and 44% of the total renewable energy, respectively.**

Key messages

1. Transformation of the energy system in line with the "well below 2°C" objective of the Paris Agreement is technically possible but will require significant policy reforms, aggressive carbon pricing and additional technological innovation. Around 70% of the global energy supply mix in 2050 would need to be low-carbon. The largest share of the emissions reduction potential up to 2050 comes from renewables and energy efficiency, but all low-carbon technologies (including nuclear and carbon capture and storage [CCS]) play a role.
2. The energy transition will require significant additional policy interventions.
   - Renewables will assume a dominant role in power generation. Skillful integration of variable renewables at very high levels becomes a key pillar of a cost-effective energy sector transition.
   - Power market reform will be essential to ensure that the flexibility needs of rising shares of variable renewables can be accommodated.
   - Ensuring access to modern energy services for those currently deprived remains a high priority, alongside improved air quality through deployment of clean energy technologies.

3. Total investment in energy supply would not need to rise over today's level to achieve climate targets, while there is significant additional investment needed in end-use sectors.
   - Investment needs in energy supply would not exceed the level of investment undertaken by the energy sector today. It requires appropriate and significant policy signals to ensure that investment in low-carbon technologies compatible with the "well below 2°C" objective becomes the market norm.
   - The additional investment needs in industry and households for more efficient appliances, building renovations, renewables and electrification (including electric vehicles and heat pumps) are significant. In order for energy consumers to reap the potential benefits of lower energy expenditure offered by the use of more efficient technologies, policy would need to ensure that the higher upfront investment needs could be mobilised.
4. Fossil fuels are still needed through 2050.
   - Among fossil fuel types, the use of coal would decline the most to meet climate targets.
   - Natural gas would continue to play an important role in the energy transition to ensure system flexibility in the power sector and to substitute for fuels with higher carbon emissions for heating purposes and in transport.
   - The use of oil would fall as it is replaced by less carbon-intensive sources, but its substitution is challenging in several sectors, such as petrochemicals.
   - CCS plays an important role in the power and industry sectors in the IEA analysis while only in the industry sector in the IRENA analysis.
5. A dramatic energy sector transition would require steady, long-term price signals to be economically efficient, to allow timely adoption of low-carbon technologies and to minimise the amount of stranded energy assets. Delayed action would increase stranded assets and investment needs significantly.
6. Renewable energy and energy efficiency are essential for all countries for a successful global low-carbon transition, but they will need to be complemented by other low-carbon technologies according to each country's circumstances, including energy sector potentials, and policy and technology priorities.
7. The energy sector transition would need to span both the power and end-use sectors.
   - Electric vehicles would account for a dominant share of passenger and freight road transport.
   - Renewables deployment would need to move beyond the power sector into heat supply and transport.
   - Affordable, reliable and sustainable bioenergy supply would be a priority especially in light of limited substitution options in particular end-use sectors
8. Technology innovation lies at the core of the long-term transition to a sustainable energy sector.
   - Near-term, scaled-up research, development, demonstration and deployment (RDD&D)spending for technological innovation would help to ensure the availability of crucial technologies and to further bring down their costs.
   - Not all of the needed emission reductions can be achieved with existing technology alone. Additional low-carbon technologies that are not yet available to the market at significant scale, such as electric trucks or battery storage, will be required to complement existing options.

- Technology innovation must be complemented with supportive policy and regulatory designs, new business models and affordable financing.

9. Stronger price signals from phasing out inefficient fossil fuel subsidies and carbon pricing would help to provide a level playing field, but would need to be complemented by other measures to meet the well below 2°C objective.

- Price signals are critical for the energy sector to ensure climate considerations are taken into account in investment decisions.
- It is important to ensure that the energy needs of the poorest members of society are considered and adequately taken into account.

10. The IEA and IRENA analyses presented here find that the energy sector transition could bring about important co-benefits, such as less air pollution, lower fossil fuel bills for importing countries and lower household energy expenditures. Both analyses also show that while overall energy investment requirements are substantial, the incremental needs associated with the transition to a low-carbon energy sector amount to a small share of world gross domestic product (GDP). According to IEA, additional investment needs associated with the transition would not exceed 0.3% of global GDP in 2050.[1] According to IRENA, the additional investment required would be 0.4% of global GDP in 2050 with net positive impacts on employment and economic growth.

1 The Organisation for Economic Co-operation and Development (OECD) analysis of how the IEA scenarios play out in the broader macroeconomic policy context will be presented in a forthcoming publication titled *Investing in Climate, Investing in Growth*.

Introduction

Around two-thirds of global greenhouse gas (GHG) emissions stem from energy production and use, which puts the energy sector at the core of efforts to combat climate change. The transition to a cleaner, more efficient energy system is a key policy goal, and the Paris Agreement, which entered into force in November 2016, provides a unique international framework for collective action towards holding the increase in the global average temperature to well below 2 degrees Celsius (°C) above pre-industrial levels. In addition, the importance of the energy sector for policy makers extends well beyond climate change mitigation: reliable, sustainable and affordable energy supply is critical to economic activity, social development and poverty reduction in order to provide all people with access to modern energy services.

Each country therefore faces the challenge of meeting climate goals while also ensuring that other vital social and economic functions of the energy sector are met in parallel. Circumstances can vary widely across countries, depending on levels of development, resource endowments and policy priorities. This is well illustrated by the countries of the Group of 20 (G20)[2]: home to more than 60% of the world's population and responsible for around 80% of global gross domestic product (GDP), G20 countries are collectively responsible for more than 80% of global energy-related CO_2 emissions. This means that efforts made by this group of countries to reduce energy-related GHG emissions are crucial for the prospects of meeting the climate targets set out in the Paris Agreement. Yet, at the same time, the G20 region is very diverse: energy demand per capita varies by a factor of 12 between countries, as energy access is still a major concern for example in Indonesia, India and South Africa. And while some of the countries are net exporters of fossil fuels, others rely heavily on imports.

The energy sector is diverse and spans a wide range of different assets in power generation, heating and cooling, industry, transport and buildings. All have in common that investment cycles tend to be long, which means that investment decisions taken today have long-term implications for the achievement of climate and other energy policy goals. G20 economies have played, and will continue to play, a leading role in the transformation of the energy sector. The challenges vary according to each country's own circumstances. In emerging economies and developing countries, substantial energy investment will have to be committed to support economic growth and alleviate energy poverty. Mature economies, meanwhile, are faced with the need to replace an ageing capital stock. A smooth and cost-effective transition towards a low-carbon energy sector, while meeting the other multiple energy policy goals, will require long-term oriented policy guidance.

In light of these needs, the German government has requested the International Energy Agency (IEA) and the International Renewable Energy Agency (IRENA) to shed light on the essential elements of an energy sector transition that would be consistent with limiting the rise in global temperature rise to well below 2°C, as set out in the Paris Agreement. The overarching objective of the study is to analyse the scale and scope of investments in low-carbon technologies in power generation, transport, buildings and industry (including heating and cooling) that are needed to facilitate such a transition in a cost-effective manner, while working towards other policy goals. The analysis in this report is framed by several key questions which include:

- How can the energy sector achieve a transition to a decarbonised, reliable and secure energy sector at reasonable costs?

2 The G20 is an international forum that includes 19 countries (Argentina, Australia, Brazil, Canada, China, France, Germany, India, Indonesia, Italy, Japan, South Korea, Mexico, Russian Federation, Saudi Arabia, South Africa, Turkey, United Kingdom, United States) and the European Union.

- What are the investment needs associated with the energy sector transition and how do investment patterns need to change to reach a low-carbon energy system?
- What are the co-benefits for other energy policy objectives that could result from an energy sector transformation?
- Assuming a timely and effective low-carbon energy sector transition, what is the outlook for stranded assets? What is the impact for stranded assets if action is delayed and the transition is sharper?
- How does the trend of declining costs for renewables and other low-carbon energy technologies, as well as acceleration of efficiency gains, support the decarbonisation? How can policy accelerate this development?
- What are the roles of carbon pricing and the phase-out of fossil-fuel subsidies in ensuring a cost-effective decarbonisation of energy systems?
- What are the roles of more stringent regulations, better market design and/or higher carbon prices for the energy sector transition?
- What is the role of research, development and demonstration, and how can early deployment of a broad array of low-carbon technologies support an efficient and effective energy sector transition?

The findings of this report will inform G20 work on energy and climate in the context of the 2017 German G20 Presidency.

The focus of this study is on the energy sector and its long-term evolution towards meeting climate goals. Its analysis is embedded in the wider context of a report entitled "*Investing in Climate, Investing in Growth*", being conducted by the Organisation for Economic Co-operation and Development (OECD). The OECD study aims to bring together the growth, development and climate agendas to better understand the economic and investment implications of the transition to a low-carbon, climate-resilient economy. Building on the analysis of energy sector decarbonisation of this study, the OECD project takes a broader perspective on the development pathways and investment flows needed to achieve the goals of the Paris Agreement. It provides a new macroeconomic assessment of the growth and structural implications of these pathways, underlining how ambitious climate policies can be positive for growth provided they are co-ordinated with pro-growth reforms and a well-aligned policy environment. Supported by the German Ministry for the Environment, Nature Conservation, Building and Nuclear Safety in the context of the German G20 Presidency, the study will be released in conjunction with the Petersberg Climate Dialogue in May 2017 and the results of the analysis will be provided to the G20 process during the German G20 Presidency.

Report Structure

In order to address the questions presented above, the IEA and IRENA have examined separately the investment needs for energy sector pathways that would foster putting the world on track towards a significant reduction in energy-related GHG emissions until the middle of this century. Each institution has developed one core scenario that would be compatible with limiting the rise in global mean temperature to 2°C by 2100 with a probability of 66%, as a way of contributing to the "well below 2°C" target of the Paris Agreement. Both the IEA and IRENA analyses start with the same carbon budget for the energy sector. But the pathways to reaching the goal differ between the two analyses: the modelling analysis conducted by the IEA aims at laying out a pathway towards energy sector decarbonisation that is technology-neutral and includes all low-carbon technologies, taking into account each country's own circumstances. The analysis conducted by IRENA maps out an energy transition that stresses the potential of energy efficiency and renewable energy sources to achieving the climate goal, while also taking into consideration all other technologies.

This report has four chapters, of which two have jointly been formulated by the IEA and IRENA (Chapters 1 and 4), while the other two have been developed by each institution separately (Chapters 2 and 3), using their respective analytical tools.

- **Chapter 1 *Energy and climate change* (authors IEA and IRENA):** This chapter provides an overview of the international climate change framework, highlights the important role of investment for the energy sector and describes the present investment landscape. It spotlights the significant role of energy for climate change, with particular attention to the situation in G20 countries. It also defines the carbon budget used for the analysis in the subsequent chapters.
- **Chapter 2 *Energy sector investments to meet climate goals* (author IEA):** This chapter provides a full IEA analysis of the investment challenge associated with a 66% chance of staying below a long-term global mean temperature rise of 2°C, focusing on G20 countries and putting their investment needs into a global context. It analyses – sector-by-sector – the investments, technologies and policies needed to meet the well below 2°C goal compared with already announced policy targets and quantifies co-benefits on air pollution, energy access and energy expenditures.
- **Chapter 3 *Global energy transition prospects and the role of renewables* (author IRENA):** This chapter assesses the technology options for emission reductions associated with a 66% chance of staying below 2°C with a focus on renewable energy and energy efficiency. It discusses what this would entail in terms of costs, investment requirements, benefits and other implications, both for the world as well as for G20 countries. Additional attention is given to the economic growth and employment impacts of the energy transition.
- **Chapter 4 *Key insights for policy makers* (authors IEA and IRENA):** This chapter summarises high-level policy insights that can be drawn from the findings in Chapters 2 and 3.

Methodology

For the purpose of this study, IEA and IRENA used their respective analytical tools to provide insights into the energy sector transition.

For the IEA, the scenarios in this study were developed from the IEA World Energy Model (WEM), benchmarked against the IEA *Energy Technology Perspectives* model to allow for a high-level extension of projections out to 2050. The IEA WEM has been providing medium- to long-term energy projections since 1993. It is a large-scale technology- and data-rich simulation model, designed to replicate how energy markets function. It is the principal tool used to generate detailed sector-by-sector and region-by-region projections for the annual IEA flagship publication, the *World Energy Outlook*. It is updated, expanded and further improved every year. The model consists of three main modules: final energy consumption (covering residential, services, agriculture, industry, transport sectors and non-energy use); energy transformation (including power generation and heat, refinery and other transformation); and energy supply (covering oil, natural gas, coal and bioenergy). Among the main outputs from the model are the energy flows by fuel, investment needs and costs, carbon dioxide (CO_2) and other energy-related GHG emissions, and end-user prices. The WEM embodies a variety of modelling techniques. Technology choices, for example, are generally conducted on a least-cost basis, while taking into account policy targets (for example, energy efficiency and renewables policies, and climate goals). Technology cost evolutions are a function of cumulative technology additions, using learning rates from literature. Technology cost reductions vary by scenario as different levels of policy ambition trigger different levels of technology deployment and, hence, different levels of cost reductions. In the power sector, WEM is complemented by an additional hourly model for selected regions that quantifies the challenge arising from the integration of high shares of variable renewables and assesses the measures to minimise curtailment, providing additional insights into the operation of power systems.[3]

In order to derive insights into other aspects of possible future energy sector developments, the WEM benefits from coupling with other well-known models. For example, WEM has been coupled with several macroeconomic models from the OECD (ENV-Linkages and YODA), which allows the assessment of the macroeconomic impacts of different energy sector developments.[4] Similarly, an active link exists with the the Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) model of the International Institute for Applied Systems Analysis (IIASA),[5] which allows for the assessment of future prospects for energy-related air pollutants and the impact on human health.

For IRENA, the scenarios are developed based on IRENA's REmap (Renewable Energy Roadmap[6]) tool. The REmap approach is a techno-economic assessment of energy system developments on a country level, for all G20 countries, assessing energy supply and demand by sector and energy carrier. The REmap tool allows for assessment of the accelerated potential of decarbonisation technologies, and subsequent effects on costs, externalities, investments, CO_2 emissions and air pollution. REmap has been previously deployed as part of the G20 toolkit of voluntary options for renewable energy deployment.[7] The country level perspective is combined with global sector and sub-sector analysis in order to strengthen the consistency of assumptions such as cost and potential of decarbonisation technologies across the power generation, district heating, buildings, industry and transport sectors.

Additional modelling is undertaken to assess the macroeconomic effects on GDP growth and employment, feeding the REmap energy mixes into a global macro-econometric model, the E3ME[8] model that covers the global economy. This allows consideration of the linkages between the energy system and the world's economies within a single and consistent quantitative framework.

The IRENA analysis of the potentials for the energy sector transition draws on input provided by a pool of technology experts, including the Institute of Sustainable Futures, University of Technology Sydney. REmap is supplemented with the PLEXOS dispatch model to assess the technical feasibility of the power sector transformation. Air pollution and human health effects are calculated using a method developed by IRENA and the Basque Centre for Climate Change.[9]

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3 For further details, see Annex A or the WEM manual at: www.worldenergyoutlook.org/media/weowebsite/2016/WEM_Documentation_WEO2016.pdf.

4 The assessment of the possible macroeconomic implications of the energy sector pathways as projected by the IEA is not subject to this study, but will be subject to a report entitled "Investing in Climate, Investing in Growth", currently undertaken by the OECD under the German G20 Presidency. Therefore, the results of such analysis are not presented here. For details on ENV-Linkages, see Chateau, J., Dellink, R. and E. Lanzi (2014), "An Overview of the OECD ENV-Linkages Model: Version 3", OECD Environment Working Papers, No. 65, OECD Publishing, Paris, http://dx.doi.org/10.1787/5jz2qck2b2vd-en.

5 For further information, see www.iiasa.ac.at/web/home/research/modelsData/GAINS/GAINS.en.html.

6 For more information about the REmap tool and approach, key assumptions, data sources and related information, see Annex B and www.irena.org/remap.

7 See www.irena.org/remap/IRENA_REmap_G20_background_paper_2016.pdf.

8 Developed by Cambridge Econometrics. More information can be found below in Annex B, and the full description is in www.e3me.com. An application of this model to measure the macroeconomic impacts of renewable energy deployment can be found here: http://www.irena.org/DocumentDownloads/Publications/IRENA_Measuring-the-Economics_2016.pdf.

9 See http://www.irena.org/DocumentDownloads/Publications/IRENA_REmap_externality_brief_2016.pdf

The analysis of stranded assets uses an approach developed by IRENA together with the Environmental Change Institute at the University of Oxford. Documentation regarding these in-depth studies is available from the REmap website.[10]

10 www.irena.org/remap.

Chapter 1: Energy and Climate Change

Authors: International Energy Agency and International Renewable Energy Agency

Climate change and a changing energy investment landscape

Investment is the lifeblood of the global energy system. Individual decisions about how to direct capital to various energy projects – related to the collection, conversion, transport and consumption of energy resources – combine to shape global patterns of energy use and emissions for decades to come. Government energy and climate policies seek to influence the scale or nature of investments across the economy, and long-term climate goals depend on their success. Understanding the energy investment landscape today and how it can evolve to meet decarbonisation goals are central elements of the energy transition.

This transition has been given additional impetus and direction by the signature and entry into force of the Paris Agreement. Under the Agreement, countries aim to achieve a peak in global emissions as soon as possible and reach net-zero emissions in the second-half of this century. The Agreement also sets the objective of keeping the global average temperature rise "well below 2 degrees Celsius (°C) and pursuing efforts to limit this to 1.5°C". Although the precise temperature threshold implied in the Paris Agreement to limit temperature rise to "well below 2°C" is currently uncertain, it is clear that achieving the goal in a cost-effective manner will be a complex and unprecedented effort.

A key mechanism to achieve these objectives is via Nationally Determined Contributions (NDCs), which were submitted by countries under the Agreement and in most cases include coverage of energy sector greenhouse gas emissions (GHG). Their aim to reduce GHG emissions and to accelerate the transition to a lower carbon energy system, coupled with rapidly declining costs and increased deployment of clean and energy-efficient technologies, will have significant implications for future energy investment flows, creating both new opportunities and risks.

The impact of the current pledges on future investments in the energy sector was examined in detail in the IEA's *World Energy Outlook 2016*.[11] It found that countries are generally on track to achieve, and even exceed in some cases, many of their stated targets. It also found that reaching the targets of the NDCs is sufficient to slow the projected rise in global energy-related CO_2 emissions, compared with historical trends since 2000. In line with the review-and-revise every five-year approach incorporated into the Paris Agreement, these pledges should become more ambitious with time. For the moment, however, their cumulative impact, while significant, is not nearly enough to reach a peak in global energy-related emissions and to limit the temperature rise to less than 2°C (IEA, 2016a; IRENA, 2016a). The pledges represent an important step in the right direction, but more effort is needed. So despite some encouraging signs, an accelerated reallocation of capital flows in the energy sector in favour of efficient and low-carbon technologies is essential.[12]

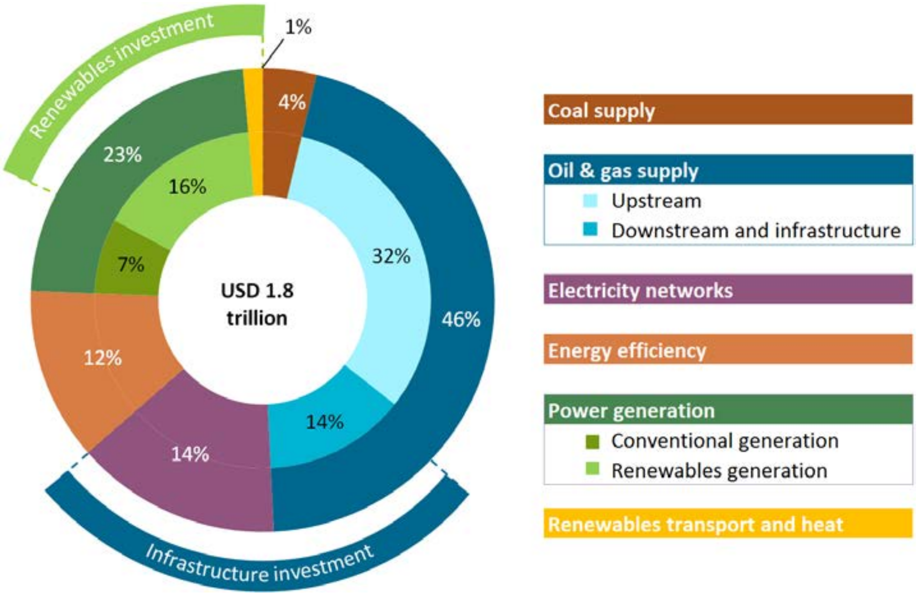
11 International Energy Agency (2016a), *World Energy Outlook 2016*.

12 IEA and IRENA both investigate possible pathways towards reducing energy sector emissions in line with the 2°C target. For the IEA, the analysis includes its 450 Scenario and the 66% 2°C Scenario, which aim to illustrate pathways towards energy sector decarbonisation that are technology-neutral and include all low-carbon technologies, taking into account each country's own circumstances. For IRENA, the REmap analysis maps out an energy transition that stresses the potential of energy efficiency and renewable energy to achieve the climate goal, while also taking into consideration all other technologies.

Energy investment today

Global energy investment in 2015 amounted to US dollars (USD) 1.8 trillion[13] (IEA, 2016), across the entire energy sector from oil and gas exploration to energy efficiency (Figure 1.7).[14] Half of all investment was directed to oil, gas and coal supply. Fossil fuel spending was dominated by upstream oil and gas exploration, despite capital spending in this sector falling 25% compared to the previous year on the back of an oil price collapse. However, total investment in low-carbon energy, energy efficiency and electricity networks has been growing, up 6% in 2015, and increasing from 39% of total energy investment in 2014 to 45% in 2015. Its share has been boosted in particular by the decline in fossil fuel investment and current indications are that this share grew again in 2016 (Table 1.1).

Figure 1.6 • Global energy investment in 2015 (USD)



Note: Coal supply here includes mining and transport infrastructure; electricity networks include transmission and distribution lines, and grid-scale storage.
Source: IEA (2016b).

Key message • Half of energy investments today are in fossil fuel supply, having declined from 60% in 2014.

In the power sector, wind and solar power, representing nearly USD 110 billion and USD 100 billion of investment, respectively, are now the major components of investment. Overall renewable energy capacity additions in the power sector have been growing rapidly and are now larger than that of any other source (Figure 1.8). G20 countries accounted for around 85% of the USD 288 billion of global renewables investment in 2015, a share that has risen from 75% a decade ago. Hydro, at around USD 60 billion, was the third-largest component of renewables investment in 2015.

13 A detailed analysis of energy sector investments is available in *World Energy Investment Outlook 2016* (IEA, 2016g).

14 Measured in terms of overnight capital expenditures on new assets that became operational in 2015. (2015 is the most recent t year for which there is reliable such data for all sectors.)

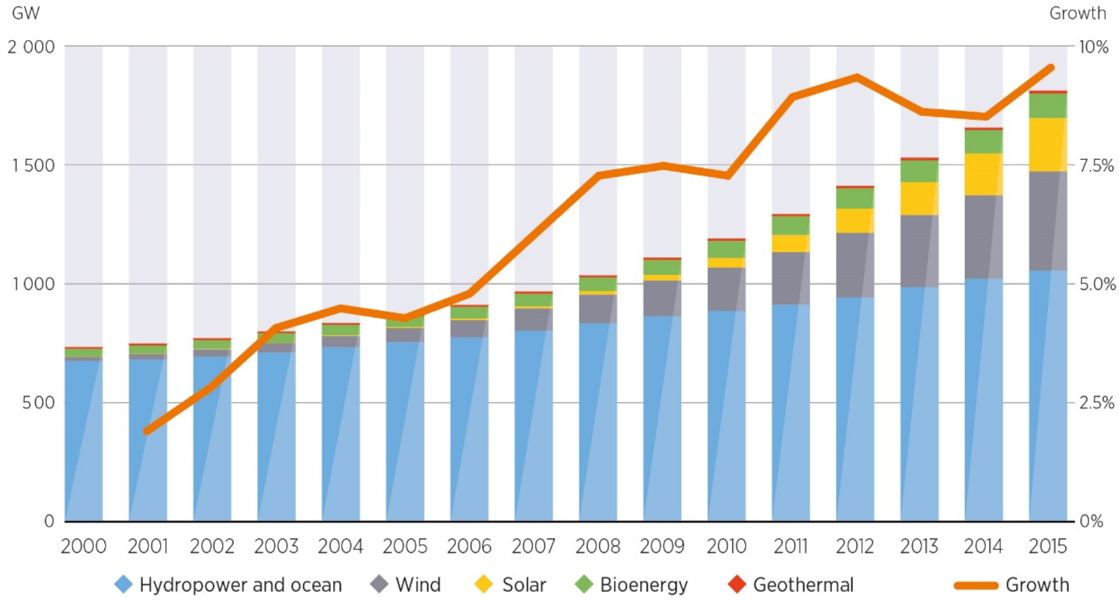
Table 1.1 • Selected 2015 energy investments and trends in 2016 and beyond

Energy resource or technology	Investment in 2015(USD)	Recent investment and financing trends
Oil and gas upstream	583 billion	Investment fell by 26% in 2016 and is likely to rebound only modestly in 2017 despite oil majors and the US unconventional sector being in healthier cash flow positions. Many of these companies have shed personnel and substantially increased debt, but are far from abandoning oil and gas investment.
Wind	107 billion	Asset financing for onshore wind was lower in 2016 than the previous year, largely due to the impacts of policy changes. Offshore wind financing edged up to an all-time high in 2016, but due to long-lead times, the impacts on investment may be spread out over several years.
Solar photovoltaic (PV)	98 billion	Solar PV capacity additions may have increased by as much as 50% in 2016 compared with 2015, but asset financing for solar PV was significantly lower, largely because of cost declines, policy changes and integration concerns in specific markets, such as China and Japan.
Hydro	59 billion	The project pipeline for new hydro plants has been in decline since 2013. Investment in 2016 is expected to have fallen compared to 2015, as costs remained relatively stable and the market looks towards technology improvements for existing plants.
Nuclear	21 billion	The amount of new nuclear capacity connected to the grid in 2016 was almost the same as the 10 gigawatts (GW) registered in 2015, but investments likely rose slightly, according to IEA methodology. New construction starts in 2016 were noticeably lower than 2015, however.
Grid-scale electricity storage	10 billion	Whereas pumped hydro storage represented 90% of storage investment in 2015, lithium ion batteries (1% in 2015) are growing most rapidly in terms of market share, with indications that around one-fifth more grid-connected batteries were added in 2016 than in 2015.
Biofuels	3 billion	Investment is estimated to have rebounded slightly in 2016 but remains considerably lower than levels achieved pre-2010. Investment in Asia led the way, while the projection for Europe is limited given that the medium-term outlook for policy support has weakened.
Carbon capture and storage	0.7 million	2016 was a quiet year for CCS, but with five large-scale assets coming online soon, more CO_2 capture capacity will be added worldwide in 2017 than during the fifteen preceding years. New investment decisions, especially in industrial applications, remain well below decarbonisation needs.

Source: IEA analysis.

Coal and gas power plant investments totalled just USD 78 billion and USD 31 billion in 2015, respectively. In fact, the estimated new low-carbon generation – renewables and nuclear – that will be produced from capacity that was scheduled to come online in 2015 exceeds the entire growth of global power demand in that year. Regionally, China's share of total energy supply investment grew from 18% in 2014 to 20% in 2015, largely the result of spending on coal-fired power and electricity networks, which together accounted for 77% of the increase in power sector spending in China. The United States' share of total energy supply investment dropped from 20% in 2014 to 18% in 2015 as oil and gas companies spent less and fewer coal-fired power plants were commissioned. Outside China, the only region that did not see a drop in energy supply investment in 2015 was Europe, while the overall shares of the Middle East and Southeast Asia were unchanged.

Figure 1.7 • Renewable power generation capacity and annual growth rate



Source: IRENA (2016b).

Key message • Renewable energy capacity in the power sector has been growing rapidly over the last decade with record growth in 2015.

Energy efficiency and electricity networks are two other significant areas of investment. Electricity networks represent nearly 40% of all power sector investment, and grew by over USD 30 billion to USD 260 billion in 2015 as China improved its distribution grids and ageing infrastructure was upgraded in North America. Energy efficiency investments were around USD 220 billion in 2015, mostly in buildings and transport, and have been largely resilient to falls in fuel prices due to the increase in the coverage of energy efficiency standards around the world.

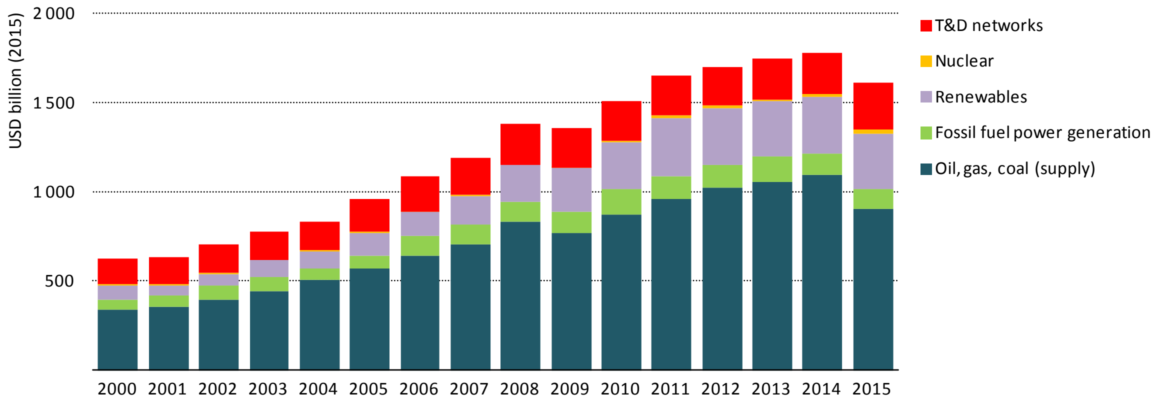
Factors affecting energy investments

While trends may indicate that a reorientation of energy investment is underway, more consideration of three contextual elements is needed (Figure 1.9). These are:

- macroeconomic conditions,
- cost trends in all sectors, from upstream oil and gas to wind turbines to downstream such as energy-using consumer goods,
- government policies.

Investment trends are heavily influenced by the macroeconomic environment. One reason for the increased share of clean energy investment in 2015 was not only higher spending in this area (which reached a new record in 2015 also in absolute terms); but the 25% drop in investment in upstream oil and gas as oil prices collapsed by over 60% between mid-2014 and the end of 2015. IEA estimates that, in 2016, spending in the upstream oil and gas sector declined by a further quarter. In many major markets, prices for oil, natural gas, coal and wholesale electricity reached multi-year lows despite continued global economic expansion – in the power sector in particular, low prices reflect the deployment of low-carbon technologies in support of the energy transition. In addition, consistent downgrading of gross domestic product (GDP) growth outlooks over recent years has generated macroeconomic uncertainty that discourages investment in capital-intensive projects with long payback periods. On the other hand, macroeconomic policies have, for now at least, enabled access to low cost capital in many parts of the energy system.

Figure 1.8 • Global investment in energy supply



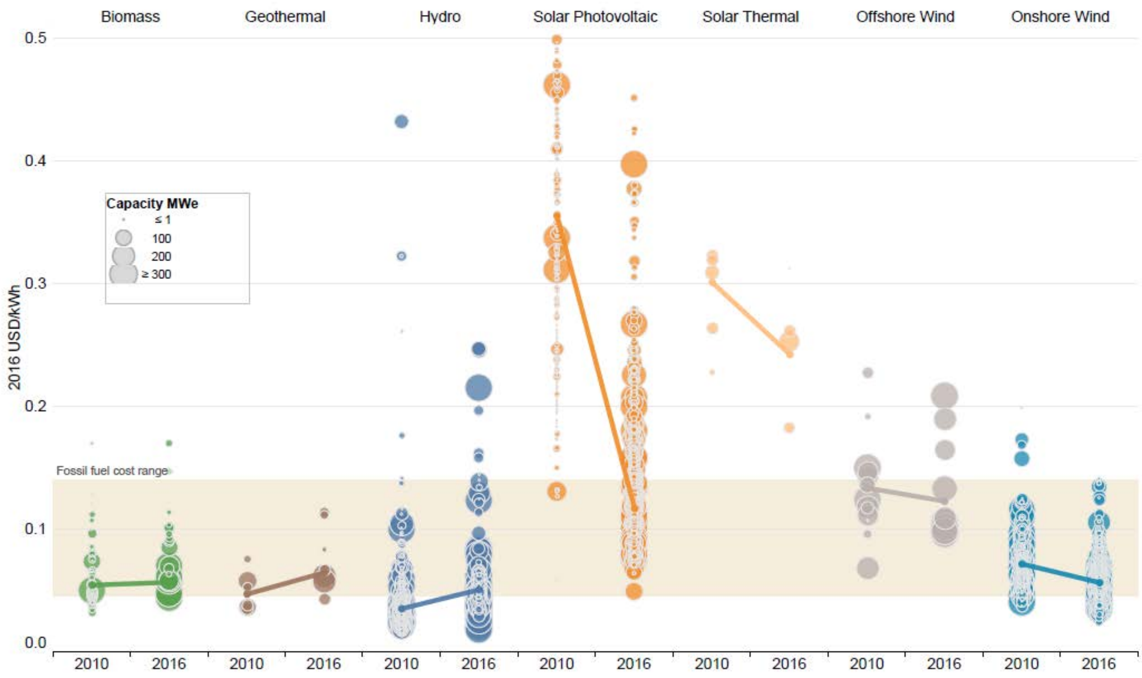
Source: IEA data and analysis.

Key message • Investment in renewable energy supply increased to around USD 290 billion in 2015: its share in overall energy supply investment rising faster than fossil fuel investment.

Renewable energy investments are affected in different ways by macroeconomic conditions. Investments in renewables have traditionally been dependent on government policies and weaker macroeconomic prospects and fiscal pressures have resulted in countries paring back certain support schemes such as feed-in tariffs. On the other hand, weak economic growth and monetary policy have combined to benefit renewables in many regions by keeping interest rates low. In some countries, government guaranteed revenues for renewables served to boost the attractiveness of wind and solar projects by lowering the cost of capital.

Costs play an important role in determining investment levels across the energy system. The fall in costs of solar photovoltaics (PV), wind, batteries and light-emitting diodes (LEDs) as a result of their rapidly increasing deployment is well-documented, and helps to explain why the headline dollar figure for investment in renewable electricity was essentially flat between 2011 and 2015 despite annual capacity additions rising by 40% according to IEA data. IRENA analysis shows that since the end of 2009, solar PV module prices have fallen by around 80% and those of wind turbines by 30-40%. Biomass for power, hydropower, geothermal and onshore wind can all now provide electricity competitively compared to fossil fuel-fired electricity generation (Figure 1.10). The levelised cost of electricity of solar PV has fallen by more than 60% between 2010 and 2016 based on preliminary data, so that solar PV is also increasingly competitive at utility scale.

Figure 1.9 • Levelised cost of electricity from utility-scale renewable technologies (ranges and average)**, 2016**



Sources: IRENA (2017a).

Key message • Weighted average costs of many renewable power technologies are at or below the range of estimated fossil fuel-fired power generation costs. Solar PV costs also increasingly fall within that range.

Such cost declines change the relative attractiveness of investment in different energy sources. For example, in Europe, the investment case for new gas-fired plants has been undercut by the falling costs of onshore wind generation, alongside continued government support for renewables and depressed wholesale power prices (pushed lower in large part also by the growth of renewable-based generation with low operational costs). Some reprieve from competition has been provided by natural gas prices remaining at relatively low levels, without which onshore wind generation costs in more locations would likely have fallen below those from a combined-cycle gas plant in the past two years. In North America, the inter-fuel dynamic is different and coal is the fuel being squeezed by the ample availability of inexpensive shale gas and the rise of renewables. In many parts of Asia, however, where natural gas prices are higher and existing gas networks at an earlier stage of development, the relative costs of gas and coal infrastructure also make investments in gas-fired power plants harder to justify than their levelised costs would suggest (Box 1.1).

Costs play a hugely influential role in the upstream oil and gas sector and the outlook for these fuels. After oil prices collapsed in mid-2014, spending by oil and gas companies was curtailed as revenues fell and higher cost new projects became uneconomic. Since then, spending has also declined as a result of cost-cutting and average upstream costs in the oil and gas sector have fallen by about 30% since 2014.[15] In terms of costs, oil is therefore in a more competitive position in 2017 than it has been for many years. If prolonged, an expansion of lower cost oil supply could impede the growth of more efficient technologies and of alternatives to oil in the transport sector. However, the longevity of these cost reductions is an area of some uncertainty; while

15 In the case of the US shale industry, the IEA estimates that upstream costs declined up to 50% between 2014 and 2016.

there is a structural component – notably with the efficiency and technology gains in North American shale production – there are also cyclical elements that are likely to be reversed as markets for upstream services and supplies tighten.

Improvements in vehicle efficiency and in the costs and availability of electric mobility options are major factors in the outlook for global oil demand. As of today, three-out-of-four passenger cars being sold on global markets are already subject to fuel-economy standards, constraining total market growth. The electric vehicle (EV) market is growing rapidly. In 2015, USD 4 billion was invested in EV sales and charging stations, and global registrations of EVs further rose by more than 50% in 2016. Battery and manufacturing cost reductions are now firmly on the horizon, as vehicles that can travel further per battery charge enter mass market price ranges in 2017. Yet, despite recent growth, EVs account for a very small share of the car market (0.1% of the total fleet) (IEA, 2016b). Wider market uptake will require additional battery cost reductions beyond those already achieved, and policy efforts to ensure existing deployment hurdles such as limited charging infrastructure are overcome (IEA, 2016a).

However, a focus on the outlook for passenger vehicles (where alternatives to oil are gaining momentum) should not ignore the importance of other transport mode that rely on oil where alternative fuels or technologies are less readily available and efficiency standards or related measures are much less widespread. In the absence of further policy changes, IEA analysis points to the large potential for continued growth in oil use for heavy-duty vehicles, aviation, shipping and as feedstock for petrochemicals; these provide powerful impetus for continued rises in overall oil consumption, albeit at a lower rate than in the past (IEA, 2016a).

Policy is the third key element of context for the discussion about energy investment. In the electricity sector, the IEA estimates that in 2015 most power generation investment, worldwide and across all technologies, was based on regulated prices, long-term contracts or support policies, which implies that they were not exposed to the same revenue risks associated with wholesale pricing. This share of investment is increasing despite moves in some countries to liberalise electricity markets. Policy ambition and commitment by an increasing number of governments has consistently raised investment levels and expectations for renewables, creating a virtuous cycle of improvement; deployment of wind and solar technologies that benefit from mass manufacturing techniques as a result of policy support has accelerated cost reductions, leading to rising policy support in an increasing number of countries and further investment. This dynamic has not previously been typical in the electricity sector, which has traditionally been dominated by large engineering projects commissioned to particular specifications. The adoption of such enabling policies, the emergence of new markets and growing competitiveness all contributed to increased global investment in renewable-based power, which saw a three-fold rise over the past decade and reached a record high in 2014. Investment in new renewable-based power capacity has exceeded investment in additional fossil fuel capacity for at least three consecutive years. The difference was largest in 2015, despite the sharp decline in fossil fuel prices.

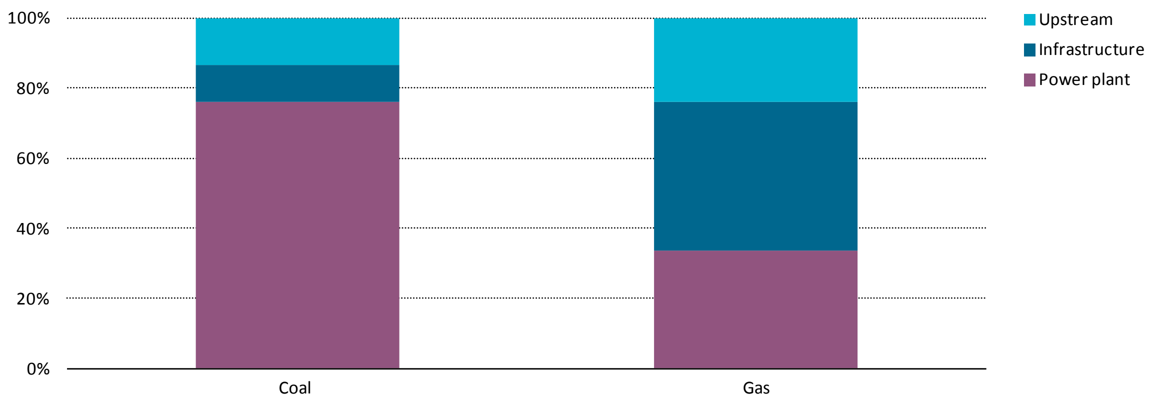
Government policies to support renewable energy are expected to continue to underpin investments in wind and solar capacity. To date, 173 countries have established renewable energy targets at the national, state or provincial level (REN21, 2016). Over 150 countries have adopted specific policies for renewables-based power, 75 have policies for renewables-based heat and 72 for renewables in transport (IEA, 2016a). High capital intensities make wind and solar especially sensitive to costs of capital, and policy measures can provide confidence to investors of stable remuneration thereby significantly lowering the cost of capital. Low contract clearing prices for solar and wind auctions in countries such as the United Arab Emirates (solar), Morocco (onshore wind) and Denmark (offshore wind) therefore reflect a combination of good resources and technology improvements, but also policy measures that help to reduce the cost of capital. In

Jordan (solar PV), the government established a direct proposal (auction) process for renewable energy that standardised terms of reference and contracts, which enabled aggregation of small-size projects and in turn lowered transaction costs. Government guarantees targeted at mitigating off-taker risk was crucial for geothermal projects in Indonesia to access finance and move the project forward (IRENA, 2016c). In the United States, tax credits coupled with high predictability of electricity off-take prices from wind and solar projects make renewables contracting highly attractive to corporate buyers. In 2015, 3 GW of solar and wind were installed in North America compared with 1 GW in 2014.

Box 1.1 • Challenges of shifting towards natural gas investments in Asia

Investment in gas-fired power generation in many developing Asian countries has remained modest compared with investment in coal-fired capacity despite recent falls in liquefied natural gas (LNG) prices and the environmental and flexibility benefits of gas-fired generation. In many cases, preference is still given to coal-fired plants, which emit double the CO_2 per megawatt-hour (MWh) of gas-fired plants. This is mainly because economic and energy security considerations are the dominant decision criterion: coal is still much cheaper than gas and generally abundant in the region. Another reason is the much larger investment needs associated with gas-fired power when the outlays required for the full supply chain are taken into account. Midstream infrastructure, in the form of pipelines, liquefaction and regasification terminals, typically represents 40% of the capital costs of developing gas-fired power generation capacity in Asia, compared with only 10% for coal-based power (Figure 1.11). The upstream component for gas, at 25% of total investment needs, is almost double that for coal power. As such, gas, more so than coal, requires greater co-ordination in terms of matching upstream development with contracted gas off-takers in the power sector as well as an appropriate market framework and financing for infrastructure development. These factors have been generally most supportive in the United States and the Middle East, the two largest destinations for gas power investment in 2015.

Figure 1.10 • Investment needs related to new gas- and coal-fired power generation by component in importing Asian countries



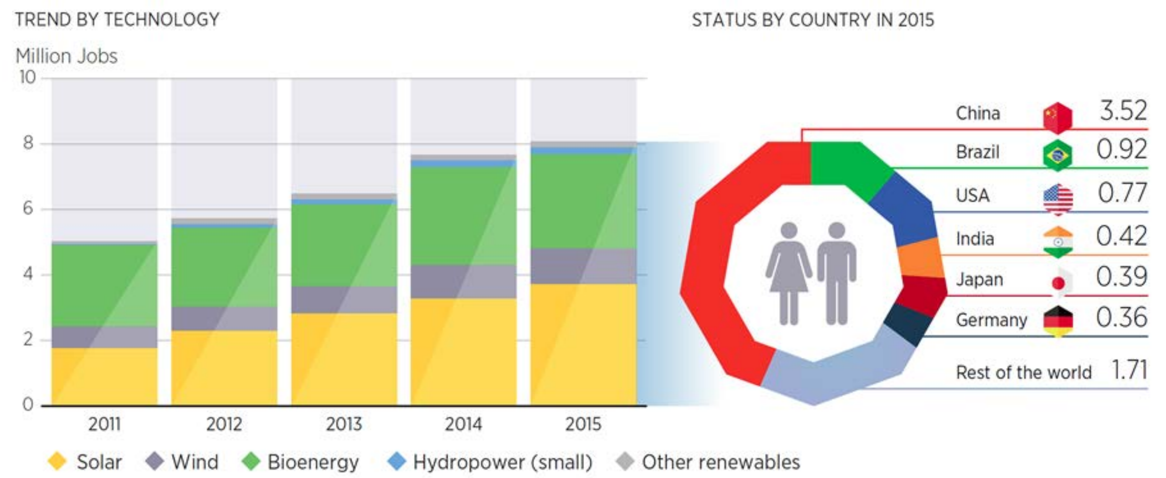
Note: Calculation assumes a 1 GW power plant in Asia running on imported coal and LNG.
Source: IEA analysis.

Key message • Transportation infrastructure is key to understanding the relative economics of coal- and gas-fired power generation investment.

The benefits of renewables are increasingly featuring prominently in the policy debate. The sector has become a significant source of new employment in many markets around the world (Figure 1.12). IRENA estimates that the number of jobs in renewable energy rose by 5% in 2015 to an estimated 8.1 million, plus an additional 1.3 million in large-scale hydropower (IRENA, 2016d). Solar PV was the largest single renewable energy employer, supporting 2.8 million jobs, up 11% from 2014. There were similar employment figures in bioenergy (including liquid biofuels, biomass and biogas), but these contracted slightly in 2015. Meanwhile, wind power experienced significant growth, rising 5% in 2015 to 1.1 million. Asia provides 60% of renewable energy employment, largely due to the solar industry in China, where a major share of the world's PV and solar thermal heating technologies are manufactured and installed (IRENA, 2016d).

While renewable energy job numbers continue to rise, trends vary by country and region (IRENA, 2016d). Countervailing effects of increased labour productivity, as well as automation and mechanisation of production, contributed to slower growth in 2015 compared to previous years. However, according to IRENA, the continuing growth in renewables employment contrasts starkly with the depressed labour market in the broader energy sector (excluding energy efficiency) (IRENA, 2016d).

Figure 1.11 • Global employment in renewable energy



Note: excludes large hydropower
Source: IRENA (2016d).

Key message • The total number of jobs in renewables worldwide continues to rise and is becoming a major source of employment particularly in solar PV and bioenergy technologies.

For energy efficiency too, policy has been vitally important to securing investment, via standards, loans and market-based instruments such as efficiency obligations. Spending on energy efficiency has risen as standards for buildings, appliances and vehicles have been implemented and their further tightening has been signalled by governments. However, much of this is indirect consumer spending on efficiency as manufacturers pass on the costs of complying with standards. This cost pass-through is often hard to distinguish among the price differentiation of other characteristics of appliances and vehicles, but is usually expected to be outweighed by fuel cost savings. Investment in road freight efficiency lags behind that for passenger vehicles, partly due to much more limited coverage of fuel-economy standards.

Through policies such as obligations for utilities to reduce demand for electricity, direct policy-induced efficiency investments have risen. IEA analysis shows that utilities worldwide spend more than USD 11 billion per year on such programmes, more than half of it in the United States. These types of measures in the buildings and industrial sectors, as well as policy tools such as government loans, tax credits and auctions have increased efficiency investments by drawing on the large balance sheets of electricity suppliers and governments who spread costs among ratepayers and taxpayers. Policy has so far been less successful in increasing the role of third-party finance, for which revenue based on future cost savings is generally required. Government policies can help address key challenges – which include the relatively small size of projects, uncertainties regarding the value of future savings and a limited project pipeline – but only through concerted effort and tailored approaches.

Policy lessons and future challenges for low-carbon energy investment

Policies have played a fundamental role in attracting low-carbon energy investments, increasing deployment and driving cost reductions as described. Learning the lessons from past policy efforts to accelerate the uptake of low-carbon technologies (such as renewables for power generation) and applying them to other emerging, yet crucial, low-carbon technologies (such as EVs vehicles or carbon capture and storage) would facilitate the transition to a low-carbon energy sector in a cost-effective manner. A wide range of different policy tools have been – and are currently being – deployed around the world with the intention of stimulating and supporting investment in low-carbon energy technologies (Table 1.2). The types of measures have typically varied between countries in line with their institutional characteristics and capacities. IRENA suggests that they must support stable, transparent and predictable market conditions while being flexible enough to adjust to changing circumstances (IRENA, 2014a).

As technologies have matured and costs have been reduced and become more transparent, policy instruments have evolved and in some cases consolidated around standard models. An example is the evolution of renewable electricity support schemes in a number of countries from portfolio standards and feed-in-tariffs to auctions. The growing interest in auctions is due largely to their ability to achieve deployment of renewable technologies in a planned, cost-efficient and transparent manner (IRENA and CEM, 2015). In other sectors, initiatives that provide grants to new technology projects have given way to minimum performance standards when confidence in the new technology has been assured.

Financial support for low-carbon technologies can raise cost concerns. While it is often essential to stimulate early deployment of novel technologies, the level of support that is appropriate for projects in a nascent sector will be too expensive once higher levels of adoption are reached. Unless policy measures adapt to the increasing volumes and decreasing costs of maturing markets, costs can be a serious burden on government budgets or consumers. To address this, several governments are adopting new policy design features (such as degression mechanisms for feed-in tariffs) and a new generation of support policies that acknowledge the growing competitiveness of renewable energy technologies, such as auctions (IRENA, 2014a). In many countries with high (and growing) shares of variable renewable energy technologies, the policy focus is increasingly shifting away from financial incentives alone. Instead, new challenges have emerged for renewable energy and the entire power sector, and new policy frameworks are needed to facilitate the transition to smarter, more decentralised, more resilient and more flexible power systems (IEA, 2016a; IEA, 2016b; IRENA, 2017b). Measures to enhance flexibility – including policies to advance demand-side management and storage, and changes in market design – are at the centre of attention. They look to ensure adequate, reliable and safe electricity services at reasonable prices, while sharing system costs and benefits among stakeholders. Cross-technology and cross-sector market-based measures will be needed to deliver more efficient outcomes. While likely not sufficient by itself, carbon pricing is expected to play a growing role in this regard as it reaches more jurisdictions, sectors and as markets become linked.

From an investment perspective, shifting the share of new assets further towards energy efficiency, low-carbon technologies and electricity networks, demands that particular policy challenges be effectively addressed.[16] These challenges are emerging more clearly as the

16 See, for example, *20 Years of Carbon Capture and Storage - Accelerating Future Deployment* (IEA, 2016c)

business models for widespread deployment of low-carbon technologies are becoming better understood. Scaling up the investment volume requires expanding the investor base to large-scale investors (such as institutional investors), who can be attracted to sizable investment portfolios (IRENA, 2016c). Examples in some countries suggest that standardised documentation and due diligence processes (e.g. United Kingdom and Jordan) can enable aggregation of assets and projects to capture scale and efficiency. Furthermore, by securitising a portfolio of solar leases (as in the United States) or off-grid solar receivables in the pay-as-you-go model (Kenya and Rwanda), projects can gain access to capital markets for larger sums of debt capital.

Table 1.2 • Selected policy tools for a reorientation of energy investment

Type of project	Typical policy tools that facilitate investment	Other measures that can affect future investment decisions
Utility-scale renewables	Auctions for long-term power purchase agreements; portfolio standards; tradable certificates.	Carbon pricing; long-term arrangements with modulated market premiums.
Distributed generation (e.g. rooftop solar)	Feed-in-tariffs and net metering.	Carbon pricing; retail electricity tariff design; minimum performance building standards.
Coal-to-gas switch and biomass power	Carbon pricing; minimum performance standards.	Rules for export credits and multilateral financing; financial disclosure rules.
CCS in industry and power	Grants to cover additional costs of CO_2 capture and storage; CO_2 storage tax credits.	Carbon pricing; CO_2 infrastructure deployment; minimum performance standards.
Industrial energy efficiency	Utility obligations; energy efficiency auctions; mandatory efficiency opportunity audits.	Carbon pricing; minimum performance standards; elimination of energy subsidies.
Buildings and appliances efficiency	Minimum performance standards; utility obligations; property tax repayment schemes; public procurement; tradable certificates; revolving funds.	Energy performance certificates; performance data transparency; energy services companies.
Vehicle efficiency	Fuel-economy standards; fuel and vehicle taxation.	Differential road pricing and congestion policies; elimination of consumer fuel subsidies.
Electric vehicles	Purchase subsidies; charging infrastructure deployment; tradable credits; fleet average fuel-economy standards; exemptions from traffic fees.	Differential road pricing; parking restrictions; minimum performance standards.
Electricity storage	Regulated rates of return; purchase subsidies; utility obligations.	Market design to support flexible resources; deferred network investment strategies; electric vehicle policies that reduce battery costs.

Source: IEA analysis.

One issue to be tackled in power generation is how to mobilise capital for flexible assets that can complement variable renewable technologies. Assets including gas turbines, biomass power plants, electricity storage (including pumped storage hydropower), interconnectors and smart controls for flexible demand are expected to be vital at times of scarcity of renewable-based power generation. However, given the low marginal prices in electricity markets with wholesale pricing and high shares of solar and wind, the business case for investing in assets that provide the flexibility to capture infrequent high scarcity prices is likely to remain risky. Long-term price signals are needed to provide confidence that these investments will provide adequate financial returns without weakening the efficiencies of competitive markets. Combinations of carbon pricing, more dynamic and locational pricing, integration with other system services will play a role, but will rely fundamentally on careful forward-looking policy and market design. Without these investments, the system value of renewable generation will be more difficult to secure at growing shares and the expansion of renewable assets will be harder to finance.

Table 1.3 • Typical sources of financing for various types of energy projects by region

Types of projects	Mature market economies	Emerging markets with a strong role for state-directed investment	Lower-income developing markets
Oil and gas upstream	Corporate balance sheet; corporate bonds.	Government and state-owned enterprise balance sheet.	Corporate balance sheet; corporate bonds.
Electricity networks; oil and gas pipelines	Corporate balance sheet.	Government and state-owned enterprise balance sheet.	Government and state-owned enterprise balance sheet; development banks.
Conventional power generation	Corporate balance sheet; corporate bonds; project finance.	Government and state-owned enterprise balance sheet; public bank loans.	Government, state-owned enterprise and private conglomerate balance sheet; development banks; export credit agencies.
Utility-scale PV and wind	Project finance; Corporate balance sheet.	Government and state-owned enterprise balance sheet; corporate balance sheet.	Development banks; project finance; export credit agencies; government and state-owned enterprise balance sheet.
Residential solar PV; efficient cars and appliances	Third-party financing; household balance sheet; private bank loans.	Household balance sheet; public and private bank loans.	Household balance sheet; third-party finance.
Electric vehicles; energy efficiency programmes for buildings	Government balance sheet, via tax credits or conditional grants; private bank loans; corporate bonds.	Government balance sheet; public and private bank loans.	Development banks; public and private bank loans.
Early stage and pre-commercial low-carbon technologies	Angel investors; venture capital; corporate balance sheet; government balance sheet via R&D grants.	Government and state-owned enterprise balance sheet.	

Source: IEA analysis.

Another consideration lies in ensuring that market designs attract capital from different sources efficiently. There is a variety of capital sources currently at play in the energy sector (Table 1.3). Consequently, the various projects that made up the USD 1.8 trillion of energy investments in 2015 were not made with the same expectation of risks, returns and payback periods. Some sources of debt or equity are not well-suited to certain energy projects. For example, project finance is not well matched to the size and nature of energy efficiency measures. This has implications for ensuring a smooth transition to a low-carbon economy if some capital sources need to grow in importance and others need to be reallocated outside the energy sector. Policies such as regulations, standards, taxes and deregulation influence risks and returns and can explain why some efficiency opportunities are not currently financed despite being lower cost than new energy supply from a system perspective. Unlocking large-scale private capital further requires mitigation of risks, both perceived and real, and mobilisation of capital markets through the standardisation, aggregation and, potentially, securitisation of assets. Based on an analysis of best practice and recent case studies, IRENA has elaborated five action areas for government and financers that, if addressed, would help scale up renewable energy investment (IRENA, 2016c):

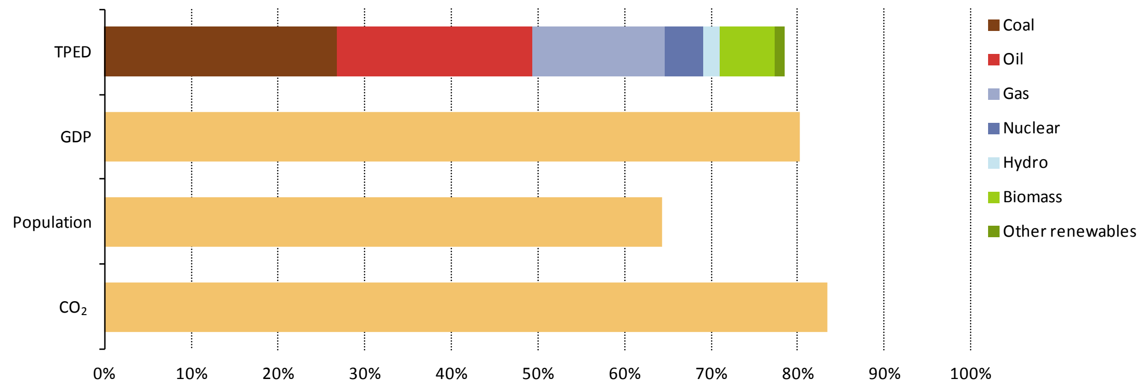
- Advance projects from initiation to full investment maturity through capacity building, dedicated grants and networking platforms.
- Engage local financial institutions in renewable energy finance through capacity building with local financial institutions and on-lending facilities.
- Mitigate risks to attract private investors through instruments that reduce off-taker risk and emerging market currency risk.
- Mobilise more capital market investment through standardisation of project processes and green bond guidelines, as well as project aggregation.
- Create facilities dedicated to scaling up renewable energy investment by covering transaction fees, supporting design of structured finance mechanisms and providing funds.

Energy-efficient building refurbishments present a particular challenge in terms of mobilising new sources of finance that have lower costs of capital but seek more certain returns. One example of how progress in aggregating small projects, managing risks and monitoring performance is already helping to broaden this space into the secondary market is the Warehouse for Energy Efficiency Loans (WHEEL) in the United States. In 2015, WHEEL became the first asset-backed security transaction for efficiency, totalling USD 13 million, comprising unsecured home energy efficiency loans each up to USD 20 000. Another growing area that is bringing transparency and interest to secondary markets is green bonds, of which 20% of the USD 42 billion of issuances in 2015 was for energy efficiency, with the rest going mostly to renewable energies.

Role of G20 countries in energy and climate change

Energy production and use account for more than two-thirds of all anthropogenic greenhouse gas emissions, mostly in the form of CO_2. This reflects the energy sector's heavy reliance on the combustion of fossil fuels, meaning that increasing demand for energy over the past decades has consistently been accompanied by rising CO_2 emissions. Reducing greenhouse gas emissions therefore depends, to a large extent, on changes and developments in the energy sector. The members of the G20 are central to this challenge. As a group, the G20 accounts for around 80% of the world's total primary energy demand (including almost 95% of its coal demand and nearly three-quarters of its gas and oil demand) and is responsible for more than 80% of total CO_2 emissions (Figure 1.13).

Figure 1.12 • Share of G20 members in key global indicators, 2014



Note: TPED = total primary energy demand.
Source: IEA data and analysis.

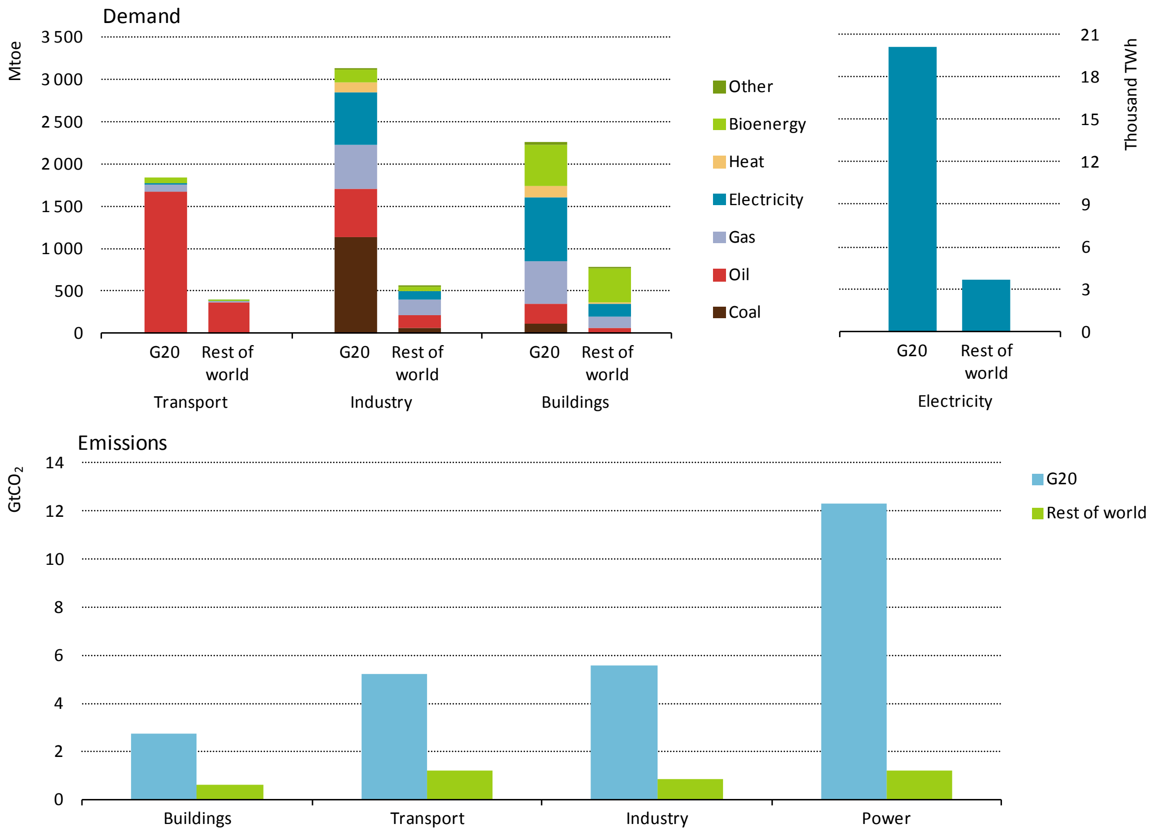
Key message • G20 countries as a group account for the majority of global energy demand and energy-related CO_2 emissions.

The energy mix of the G20 group as a whole today depends largely on the use of coal (34%), oil (29%) and gas (19%); nuclear represents a share of 6% and renewables the rest, with bioenergy being the largest at 8% (of which, almost half is the traditional use of solid biomass) (Figure 1.14). But the G20 group is a very diverse set of countries and individual energy consumption patterns reflect factors that are unique to each. Resource endowments, for example, help to explain why coal is the backbone of the energy mix in China and South Africa (at around two-thirds of the total), while 70% of Saudi Arabia's energy demand is met by oil (the remainder being gas). Another important criterion is the level of access to modern sources of energy: for India and Indonesia, bioenergy is an integral part of the energy mix (at around one-quarter of total energy demand), mostly in the form of solid biomass. Achieving their quest to ensure access to modern energy services should reduce the share of solid biomass in the mix. Brazil has the highest share of low-carbon fuels in the total primary energy mix among G20 countries, at around 40%.

The power sector is the largest single sector consuming energy in G20 countries. With more than 60% of total coal and nearly 40% of total gas demand, the power sector is also the largest source of CO_2 emissions in G20 countries as a whole. Among end-use energy sectors, the industry sector is the largest energy consumer in the G20. More than one-third of industrial energy demand is met by coal and its use has increased rapidly since 2000, mostly linked to the rapid expansion of infrastructure and manufacturing output in China. Electricity has overtaken oil as the second-largest fuel consumed in the industry sector after coal, but oil remains prominent. The industrial sector is the second-largest consumer of oil after transport. The energy mix in the buildings sector is diversified, reflecting the varied circumstances across the G20.[17] Electricity and gas, the mainstay of consumption in the more affluent countries, together account for around 55% of energy consumption in buildings, but are closely followed by solid biomass, which is widely used for cooking and heat in India and Indonesia. The transport sector is dominated by oil, although gas plays a significant supporting role in a number of large markets, including Russia and Argentina, and biofuels provide a meaningful contribution in Brazil, Argentina and the United States.

17 The buildings sector includes energy used in residential, commercial and institutional buildings, and non-specified other.

Figure 1.13 • Electricity generation, energy demand by fuel and CO_2 emissions in selected sectors in the G20 and rest of the world, 2014



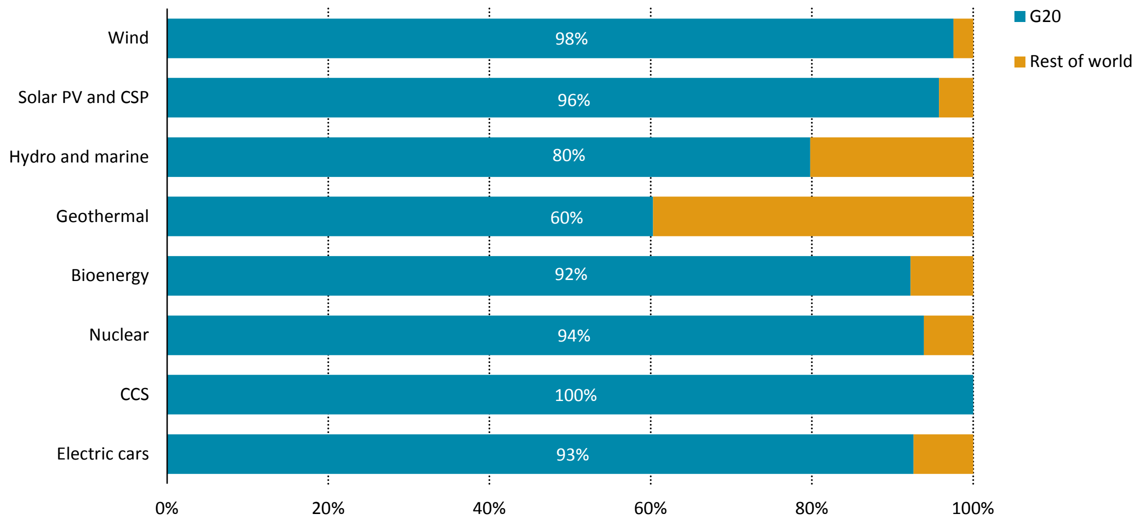
Source: IEA data and analysis.

Key message • The G20 accounts for the bulk of global energy demand and CO_2 emissions.

While the G20 group is a major source of energy demand and energy-related GHG emissions, it also plays an integral role in combatting climate change. Collectively, G20 countries are the key driver of low-carbon technology deployment: the G20 holds 98% of global installed wind power generation, 96% of solar PV and 94% of nuclear power capacity, while its passenger vehicle fleet represents almost 95% of all electric vehicles worldwide (Figure 1.15).

Energy intensity (measured as total energy use per unit of GDP) is a key indicator of movement towards a low-carbon energy sector, reflecting structural economic shifts but also efforts to improve energy efficiency. Recent trends give cause for optimism: since 2000, the energy intensity of global economic output has fallen by 10% (in market exchange rate terms). This overall trend belies some significant regional differences (Figure 1.16). In parts of the G20, growth in GDP was at times associated with a slight decline in primary energy demand, reflecting shifts in economic structure, saturation effects and efficiency gains. This has led to peaks in primary energy demand in Japan (2004) and in Europe (2006), where demand has since fallen by around 15%, while demand in the United States today is 5% below its 2007 peak. For countries outside the G20, the link between economic growth and energy consumption remains strong; in the period from 2000 to 2014 every one percentage point increase in economic growth was accompanied by a 0.6% point increase in energy demand.

Figure 1.14 • Share of G20 in global low-carbon technology deployment in the power and transport sectors, 2015

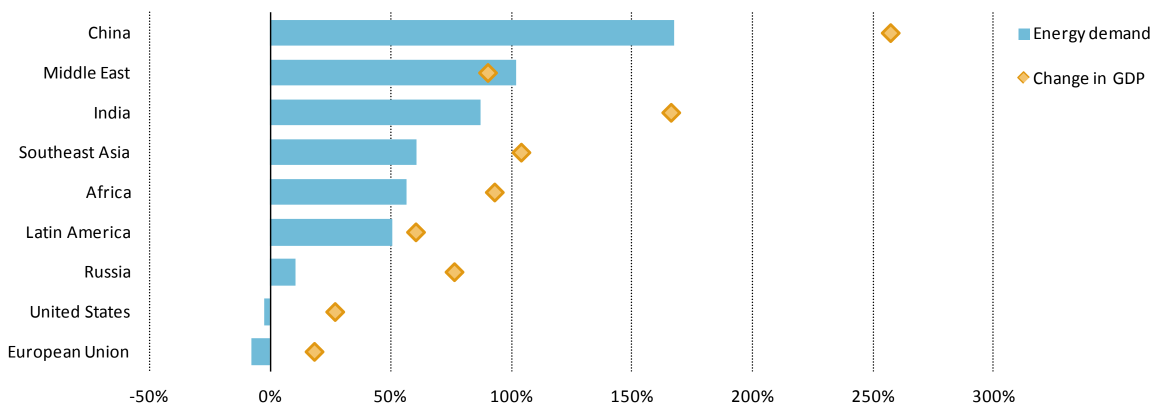


Note: For power generation, shares are by capacity; for electric cars, shares are of stock.
Source: IEA data and analysis.

Key message • The G20 accounts for all but a small proportion of low-carbon technology uptake to date.

Improvements in the energy intensity of the global economy, together with the expanded use of cleaner energy worldwide, have supported a slowdown in energy-related CO_2 emissions: on a global basis, the growth in emissions stalled over 2014 and 2015, amid economic expansion. In previous instances in which emissions stood still or fell compared to the previous year, they were typically associated with global economic weakness.

Figure 1.15 • Changes in GDP and energy demand in selected countries and regions, 2000-14



Note: GDP = gross domestic product expressed in year-2015 dollars in purchasing power parity (PPP) terms.
Source: IEA data and analysis.

Key message • Comparing the pace of economic growth from 2000 to 2014 with energy demand growth over the same period shows wide country and regional variations.

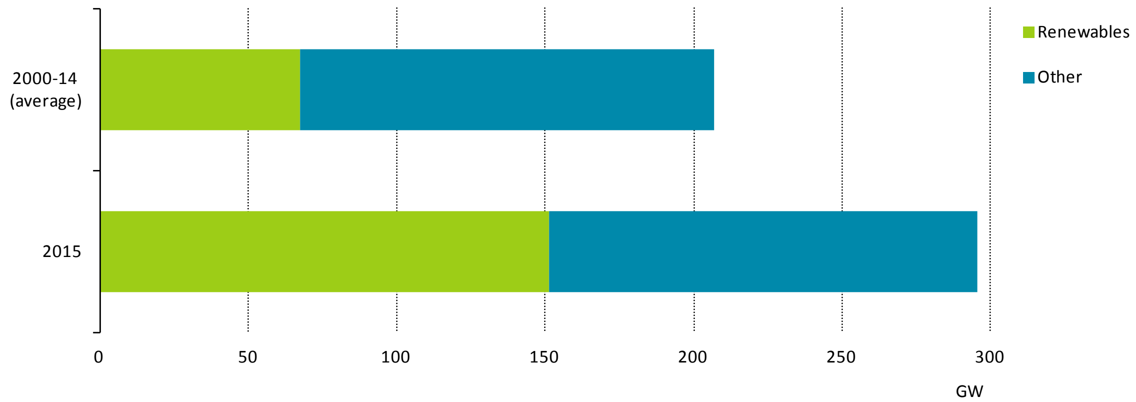
Power sector

CO_2 emissions from the power sector worldwide have grown by more than 45% since 2000 (and at a similar rate in the G20), while electricity demand increased by more than 50%, signifying a marginal 3% decrease in the emissions intensity of generation. The modesty of this overall decrease reflects two counterbalancing factors: on the one hand, the effect of the increasing momentum of renewable energy technologies and the deployment of more efficient combustion technologies; and on the other, the growth of coal-fired electricity generation was equivalent to 44% of the global increase in the total electricity supply. In total, emissions from the power sector accounted for around 45% of all energy-related CO_2 emissions in 2014.

As described previously in this chapter, the pace of investment in renewable sources of power has accelerated in recent years, pushed by increasing policy support and lower costs. The majority of countries in the world now have policies promoting the deployment of renewables in place, in particular for power generation. This support and falling costs have shifted the balance of capacity additions in their favour. In 2015, renewables-based generation technologies accounted for more than half of total power plant capacity additions, outpacing the combined total of fossil-fuelled and nuclear power plants (Figure 1.17).

In the power sector more than any other, the variations in emission intensities between members of the G20 group are especially large. These variations reflect a variety of regional conditions, including the availability of domestic resources, access to international energy markets, as well as the degree of industrial and economic development. Energy policy priorities are also an important factor that is reflected in emission intensities in the power sector. China and India, facing the imperative to provide access to hundreds of millions of people while securing affordable energy for fast growing economies, are the two countries that have accounted for almost three-quarters of the increase in electricity demand in the G20 since 2000 (and 60% of the world's increase). But, over the same period, they managed successfully to bring access to 720 million people (with 600 million people gaining access in India alone and China achieving universal access by end-2015). Both countries are facing significant local air pollution issues, but are pursuing ambitious efforts to increase the penetration of renewables-based generation in their power systems.[18] China alone accounted for one-third of the total global investment in renewables-based capacity in 2015, and has seen the growth in its emissions from power generation slow in recent years. India, meanwhile, where 245 million people still lack access to electricity, is increasingly looking towards solar and wind as part of its efforts to increase its renewables-based generation capacity (excluding large hydropower) to 175 GW by 2022.

Figure 1.16 • Recent power generation capacity additions



Source: IEA data and analysis.

Key message • Renewables accounted for more than half of total power capacity additions in 2015.

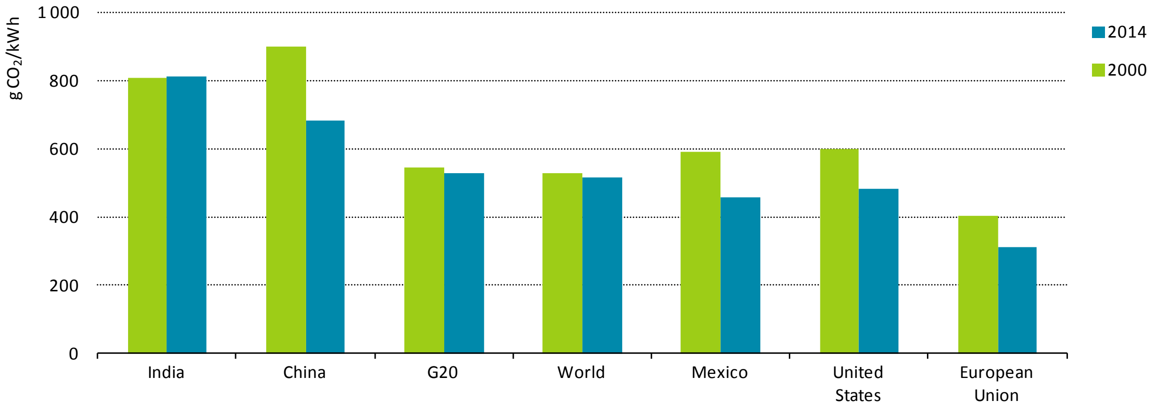
18 See Energy and *Air Pollution: World Energy Outlook Special Report* (IEA, 2016d).

In the United States, the rapid increase in shale gas production has served to reduce natural gas prices and increase the competitiveness of gas-fired generation versus coal, which had been a mainstay of the system. In addition, there has been a strong push for power generation from renewables, with yearly net renewables-based capacity additions over 10 GW in several years since 2009, mainly in wind power and more recently solar PV. The impact on the power mix (and therefore the overall carbon intensity of power generation) has been significant. From 2000 to 2014, the share of coal in the US power generation mix has fallen from over half to 40%, while that of gas-fired generation has increased from 16% to 27% and the share of renewables has risen by nearly five percentage points. Over the period, the overall carbon intensity of power fell by almost 20% (Figure 1.18). Preliminary data for 2015 suggests that the US power mix has continued to move in this direction, with less coal, more gas and a greater contribution from renewables. The United States is one of only two countries in the world where plans for carbon capture in power generation have materialised, with the facility at the Petra Nova coal-fired power plant now in operation and capturing 1.6 million tonnes of CO_2 per year. (The Boundary Dam facility in Saskatchewan, Canada, is the world's only other operational power plant equipped with CCS). A second facility, at the Kemper power plant in the United States, is due to become operational in early 2017, with a power generation capacity greater than the two existing CCS-equipped plants combined.

The switch from oil-fired to gas-fired and renewables generation features prominently in a number of countries among the G20. In Mexico, the availability of relatively cheap natural gas imports from the southern United States has accelerated a significant shift away from oil (the share of oil in generation has fallen from almost half in 2000 to just over 10% in 2014), delivering a 23% decrease in the CO_2 emissions intensity of power generation. Recently, power market reform has created new incentives to tap Mexico's considerable potential for wind and solar power, including through the establishment of a clean energy certificate system designed to provide an additional source of income for investors in low-carbon power. In 2016, two auctions awarded contracts for almost 5 GW of clean power generation capacity to private investors.

In Saudi Arabia, oil and gas had been the sole providers of electricity until solar started to make in-roads in 2012. The country has recently taken steps to reform fossil fuel subsidies and announced a substantial investment programme in renewables, both of which will serve to reduce domestic fossil fuel use. Japan has also taken steps to minimise the use of oil in the power sector for many years; the share of oil in total power generation steadily declined from over 30% in 1990 to 16% in 2000 and less than 10% in 2010. The Fukushima Daiichi nuclear accident in 2011 led to an increase in the use of oil and other fossil fuels in the power sector, temporarily raising the overall carbon intensity of power generation. Since then, aggressive energy efficiency measures and the increased use of renewables (mostly solar PV) helped to return the share of oil in the power mix to near 10% in 2014. As of mid-September 2016, three nuclear reactors had restarted, with others approved in principle but delayed by local opposition or judicial proceedings.

Figure 1.17 • CO_2 intensity of power generation in selected countries and regions



Source: IEA data and analysis.

Key message • The carbon intensity of power generation has been in decline in most regions, but large variations remain.

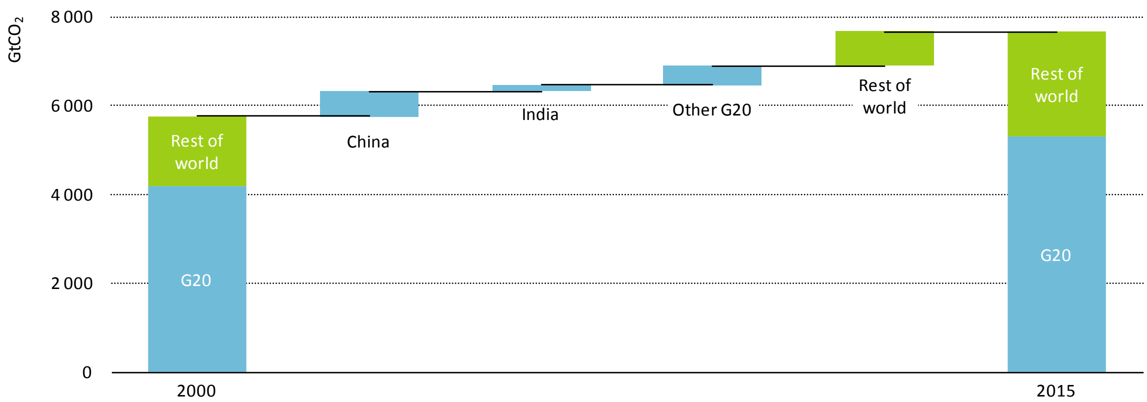
Transport sector

The global transport sector accounts for 20% of energy-related greenhouse gas emissions, composed almost entirely of CO_2 from the combustion of oil. Emissions have increased by over 30% since 2000, largely as a result of an increase in the vehicle stock by 300 million over this period (Figure 1.19). Over half of the increase in CO_2 emissions came from the G20, with China and India, where growing demand for mobility for the burgeoning middle classes has resulted in 130 million vehicles being added to the automotive stock, leading the way.

The increase in transport-related CO_2 emissions is almost entirely in line with the increase in energy demand in transport, given the sector's heavy reliance on oil-based fuels, with every percentage point increase in transport energy demand bringing about a commensurate rise in emissions. In the G20, the CO_2 emissions intensity of the vehicle stock has increased since 2000, reflecting growth in the average size of the vehicle fleet. This though does not tell the full story. The CO_2 emissions intensity of new cars sold in Europe, for example, has fallen by nearly 30% since 2000, with the rate of improvement accelerating after 2009, when the first emissions standard was introduced. Increasingly stringent standards have since been announced, the latest of which limits emissions to 130 grammes of CO_2 per kilometre (g/km) (with a further target of reducing this to 95 g/km by 2021). Similarly, in the United States, the gradual tightening of the Corporate Average Fuel Economy (CAFE) standards has helped reduce the average CO_2 emissions per kilometre of new passenger vehicles by around 22% since 2000. In Canada, the passage in 2010 of mandatory regulations (setting a target of 98 g/km by 2025) has helped reduce the average CO_2 emissions for new cars sold by over 15%. In Japan, amendments of the Energy Conservation Law since 1999 to introduce ever-increasing fuel-economy standards have helped reduce the CO_2 emissions intensity of new vehicles by more than 35%. Globally, mandatory fuel-economy standards now cover around 80% of passenger vehicles sold. Without these measures, global oil demand would have been 2.3 million barrels per day (mb/d) higher in 2015 (IEA, 2016e). One area in which progress has been slower is the fast growing freight fleet. Only four countries (Canada, China, Japan and the United States) have introduced efficiency standards for heavy-duty freight vehicles. Facilitating the introduction of such standards in other G20 countries, through international collaboration, would yield important climate, local air pollution and health benefits. As an example, worldwide adoption of new emission and fuel standards could, by some estimates, help avoid 210 000 premature deaths in urban areas annually by 2030 (ICCT, 2013).

In some cities, modal shifts in transport have also played a prominent and increasing role in reducing private car use. In Paris, for example, the introduction of Velib' and Autolib' programmes, which make available shared bicycles and electric-powered cars, and the development of bus and bicycle lanes, has contributed to a 25% reduction in car use (IEA, 2016d).

Figure 1.18 • CO_2 emissions in the transport sector and contributions by region



Source: IEA data and analysis.

Key message • Countries outside the G20 account for a growing share of CO_2 emissions from the transport sector.

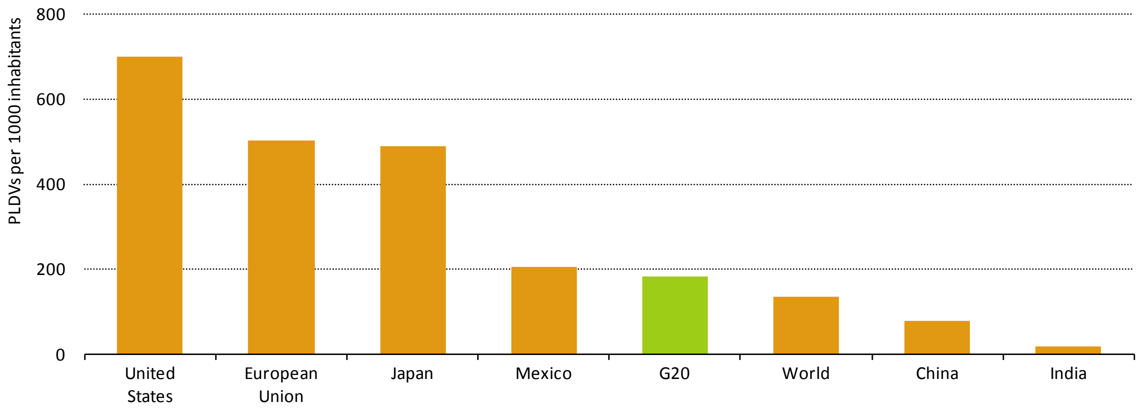
China, the world's largest market for automotive sales, has seen its stock of passenger vehicles, trucks and buses, more than double in the last five years. The potential for further growth, particularly for personal mobility, is tremendous. At around 100 cars per 1 000 people, ownership rates in China are currently low when compared to the United States (700) and Europe (510) (Figure 1.20). While the emissions profile is currently lower than that of the United States, this mostly reflects the abundance of small cars in China's stock. This makes concerted efforts to increase fuel economy a vital measure to avoid deterioration in environmental indicators as well as a rapid increase in reliance on imported fuels. China introduced fuel-economy standards in 2005, helping to reduce average emissions per kilometre for new cars by around 15%, and has been gradually tightening these since, with the latest Phase IV standards, which came into effect in 2016, setting a standard for light-duty vehicles of 5 litres per 100 kilometres by 2020.

Energy demand for aviation and shipping has grown robustly since 2000 (by 1.4% per year and 1.8% per year respectively), and accounts for around one-fifth of both energy demand and CO_2 emissions in transport. Energy efficiency has mitigated further rises in aviation emissions as engines and air traffic management have improved. Regulations for both aviation and shipping still lag behind those for passenger vehicles, but efforts are now being made. For example, the Energy Efficiency Design Index introduced by the International Maritime Organisation, which entered into force in 2013, is the first globally binding energy efficiency standard for shipping; it mandates a minimum 10% improvement in the energy efficiency per tonne-km of new ship designs from 2015, 20% from 2020 and 30% from 2025.[19] In aviation, many airlines, aircraft manufacturers and industry associations have committed to voluntary, aspirational targets that

19 One policy under discussion in the European Union is the establishment of a Maritime Climate Fund under the current Emissions Trading System, which among other aims, would facilitate investment in technologies to reduce the sector's CO_2 emissions.

would collectively achieve carbon neutral growth by 2020 and a 50% reduction in GHG emissions by 2050 (relative to 2005 levels) (IRENA 2017c).

Figure 1.19 • Passenger vehicle ownership per 1 000 people in selected countries and regions, 2014



Source: IEA data and analysis.

Key message • Notable discrepancies between G20 countries suggest that there is large scope for increasing vehicle ownership.

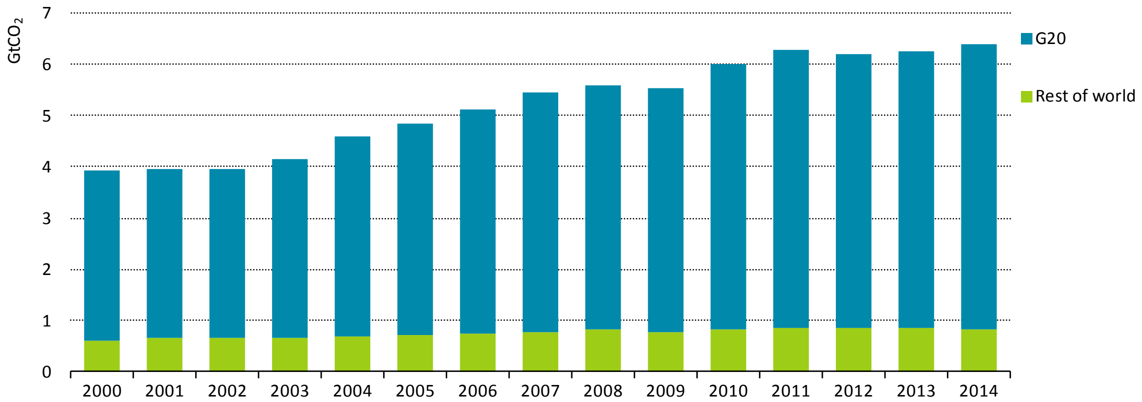
Industry sector

The global industry sector accounts for almost 40% of final energy demand and is responsible for one-fifth of global energy-related CO_2 emissions.[20] The G20 accounts for 85% of industrial energy demand and is responsible for three-quarters of industrial natural gas demand, and more than 90% of industrial coal use (China consumes around 65% of all coal used in industry). Three industries (iron and steel, chemicals and cement) account for almost 60% of total industrial demand in the G20 and are responsible for more than 60% of industrial CO_2 energy emissions. Process emissions, which are not energy-related but are generated through chemical processes in the formation of intermediary inputs, are also significant in a number of industries: CO_2 emissions related to the production of clinker, an intermediary input for cement production, are almost twice the energy-related CO_2 emissions in the cement industry globally. In absolute terms, energy-related CO_2 emissions have grown by more than 60% since 2000, with more than four-fifths of this increase from China alone (Figure 1.21), whose consumption of energy in industry is now larger than that of the combined industrial consumption of the OECD countries as a whole.

So far, efforts to mitigate the increase in energy use and emissions in industry have focused on improving energy efficiency, including through the introduction of regulation: in the last 15 years, the share of global final energy consumption in industry that is covered by mandatory energy efficiency regulation has increased to 37% (from virtually nothing), led by efficiency policy in China, which alone accounts for around three-quarters of the global industry consumption that is covered by such regulations. While mandatory energy efficiency regulation is not the only instrument available to policy makers, it becomes particularly important in times when energy prices are low: low prices lengthen the payback period of energy efficiency investments that might otherwise be made on commercial grounds. To date, renewable energy use in manufacturing has received little attention. Yet, renewable energy technologies can be suitable alternatives for process heat generation and as a carbon source for the production of chemical and plastics (IRENA, 2014b).

20 The industry sector includes blast furnaces, coke ovens and petrochemical feedstocks.

Figure 1.20 • Growth in energy-related CO_2 emissions in the industry sector in the G20 and the rest of the world



Source: IEA data and analysis.

Key message • The G20 accounts for virtually all of the net increase in CO_2 emissions from industry since 2000.

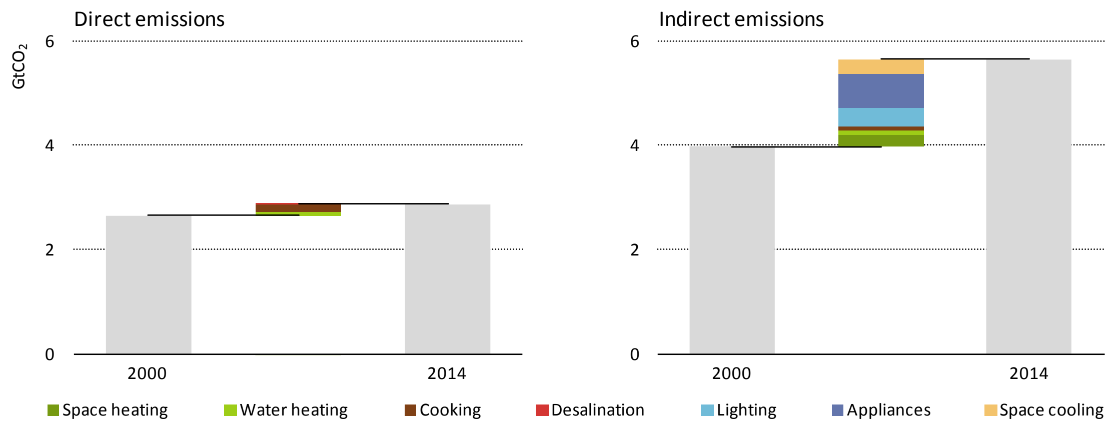
Buildings sector

Energy consumption in buildings accounts for around a third of final energy consumption, and less than 10% of energy-related CO_2 emissions, meaning that the emissions intensity per unit of energy used in the buildings sector is two-to-three times lower than that of other sectors. However, this does not tell the whole story. It is important to take into account that buildings are also responsible for around half the global demand for electricity and for district heating and cooling; indirect emissions from these sources, at 5.6 Gt, are equivalent to almost twice the direct emissions from buildings (Figure 1.22).

Direct emissions in buildings come from the on-site generation of heat for space and water heating and cooking. The need for space heating has grown at only a moderate pace in the last 15 years, with the greatest increase in energy demand instead coming from the increasing use of appliances and cooling systems, and higher demand for hot water. This is partly a result of the geography of demand: developing countries were responsible for 90% of population growth and 75% of global economic growth (leading to increased access to modern energy services – such as water heating – but also greater numbers of appliances and cooling systems). Direct emissions have stalled over the last three decades, as growth in heat demand was partly mitigated by increasing efficiency in buildings, due in large part to more stringent buildings code. The composition and efficiency of energy provision in this sector has also been affected by other shifts: the switch away from coal towards gas and electricity for heating (globally, the share of coal in the energy mix of buildings has fallen by seven percentage points since 1990, to just 4%); and, particularly in more affluent countries, a shift from oil to gas as a source of heat has occurred. Consumption of district heat has also doubled in the same period, providing heat in dense urban areas and shifting even more direct emissions towards indirect emissions, with most district heating currently produced through fossil fuels in combined heat and power processes or heat plants. Currently, district heating and cooling mainly relies on fossil fuels, and only a few countries have taken advantage of their renewable resource potential or put in place policies that can promote further uptake of renewables. As electrification and electricity use have increased, so too have indirect emissions in the buildings sector, which have increased by 40% since 2000. The emissions profile here mirrors changes in the broader electricity sector (see above). The current use of district cooling in dense urban areas is very low: only a few cities in Europe rely on district systems to satisfy cooling needs of non-residential buildings (offices, malls, government buildings, etc.).[21]

The emissions intensity of energy use in the buildings sector has been on an upward trend despite more efficient production of energy and efforts to promote energy efficiency (mandatory regulations now cover more than 30% of final energy consumption in the buildings sector). This is attributable to several factors. First, around 2.7 billion people still rely on solid biomass for cooking. Among the many associated health downsides, the traditional use of biomass is inefficient and polluting. A further driver for increased global emissions from buildings is the rising wealth and energy consumption in developing countries, particularly through the acquisition and use of household appliances. In India, the number of people without access to electricity has decreased by 360 million and air conditioning ownership has more than doubled, while in China, refrigerator ownership has also almost doubled.

Figure 1.21 • Direct vs indirect CO_2 emissions in the buildings sector



Source: IEA data and analysis.

Key message • Over the last 15 years, indirect CO_2 emissions in the buildings sector increased by 40%, while direct emissions stalled.

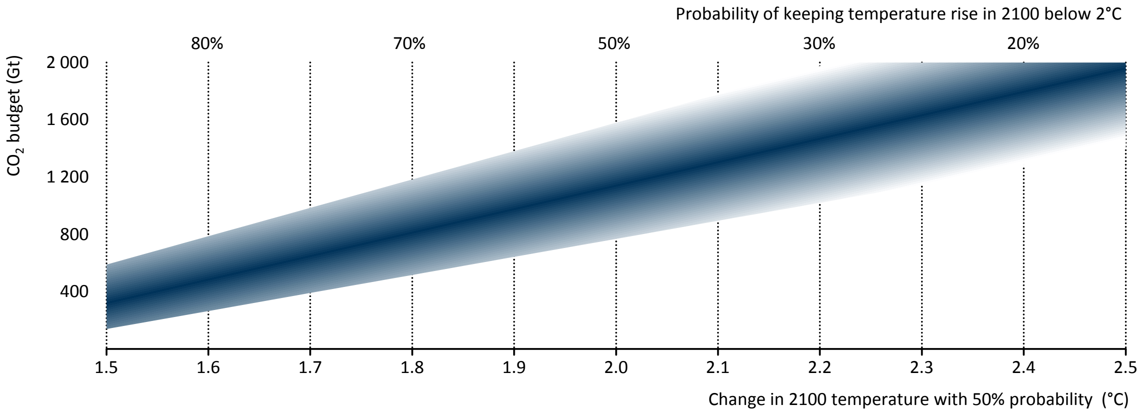
Carbon budget

The important role of the energy sector for global GHG emissions, and particularly CO_2 emissions, puts energy into the limelight of climate change. But how much do energy-related GHG emissions have to be reduced to be compatible with climate targets? Recent climate studies have indicated that the average global surface temperature rise has an almost linear relationship with the cumulative emissions of CO_2. This useful relationship has resulted in the concept of a remaining global "CO_2 budget" (the cumulative amount of CO_2 emitted over a given timeframe) that can be associated with a probability of remaining below a chosen temperature target (IPCC, 2014). Despite its importance for climate change, CO_2 is not the only agent to affect global mean temperature. Emissions of non-CO_2 forcers, such as methane (CH_4), nitrous oxide (N_2O) and aerosols, mean that the CO_2 budget must be reduced in order to achieve the same probability of a given temperature rise. While most non-CO_2 emissions originate from non-energy sectors (in particular from agriculture and waste), variations in the projections from these sectors affect the necessary rates of transformation of the energy sector. To allow for this, publications such as the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report associate a range of

21 See IEA, *Energy Technology Perspectives 2016 - Towards Sustainable Urban Energy Systems* (IEA, 2016f)

CO_2 budgets with a given probability of staying below a defined temperature rise: higher non-CO_2 emissions mean a lower CO_2 budget and vice versa (Figure 1.23).

Figure 1.22 • Relationship between temperature rise and CO_2 budgets



Source: IEA (2016a).

Key message • Remaining CO_2 budgets are very sensitive to small changes in target temperature thresholds and probabilities.

Long-term temperature targets and probabilities often refer only to the temperature rise in 2100. But it is also important to consider the temperature rise over the course of the 21st century. The average global surface temperature rise could temporarily exceed, or overshoot, a given threshold (such as 2°C), before returning to this level in 2100. One key consideration for this is whether or not it might be possible for CO_2 emissions to turn negative in the future. This is possible only if technologies are available that can remove CO_2 from the atmosphere, examples of which include direct air capture, enhanced rock weathering, afforestation and biochar (see Chapter 3). Another example, which is relied upon heavily in deep decarbonisation scenarios assessed by the IPCC, is bioenergy with carbon capture and storage (BECCS). This technology uses bioenergy, produced by photosynthesis that removed CO_2 from the atmosphere when it was growing, to produce electricity, biofuels, hydrogen or heat. With BECCS, the CO_2 emissions that occur during the transformation process are captured and stored, and are therefore prevented from being remitted to the atmosphere. If BECCS were to be deployed on a wide enough scale, and accompanied by decarbonisation of all energy sub-sectors, it is theoretically possible for the entire energy sector to absorb CO_2 emissions from the atmosphere.

Deriving an energy sector CO_2 budget for limiting global warming to 2°C

The Paris Agreement makes reference to keeping temperature rises to "well below 2°C" and pursuing efforts to limit the temperature increase to 1.5°C. However it offers no clear guidance on what "well below 2°C" means in practice, or what probabilities should be attached to the temperature goals.

For the purpose of this report, it was chosen to focus on a scenario with a 66% probability of keeping the average global surface temperature rise throughout the 21st century to below 2°C. Understanding the CO_2 budget consistent with this definition is a critical consideration for modelling the pace and extent of the energy sector transition (Table 1.4).

To generate an estimate of CO_2 budget for a 66% chance of staying below 2°C, it is necessary to estimate levels and rates of non-CO_2 emissions. The IPCC Fifth Assessment Report scenario database, which contains projections of non-CO_2 emissions over the 21st century under a wide range of scenarios provides a measure of the level of non-CO_2 emissions mitigation that is possible under deep decarbonisation pathways.

Table 1.4 • **Energy sector CO_2 budget in the decarbonisation scenarios developed by IEA and IRENA**

($GtCO_2$)	2015 - 2100
Total CO_2	880
Industry processes	-90
Land use, land-use change and forestry	0
Energy sector CO_2 budget	790

The analytical tools used in this study directly project all energy-related GHG emissions, both CO_2 and non-CO_2. But for the decarbonisation scenarios developed by IEA and IRENA in the subsequent chapters, non-CO_2 emissions originating from non-energy sectors rely on the scenarios from the IPCC database. Using the climate model MAGICC[22], widely employed in studies assessed in the IPCC reports, the distribution over the non-CO_2 contribution to the temperature rise in 2100 from scenarios in this database that have a reasonable chance of keeping the temperature rise in 2100 below 2°C suggest that non-CO_2 forcers are likely to contribute between around 0.4°C and 0.7°C of warming. In the scenarios developed in this study that have a 66% chance of keeping the temperature rise in 2100 to below 2°C, it was assumed that the contribution of non-CO_2 emissions to the temperature rise in 2100 will be around 0.5°C.

It is important to recognise that the 66% 2°C Scenarios explored in this report keep the temperature rise below 2°C not just in 2100 but also over the course of the 21st century. It does not permit any temporary overshooting of this temperature in any year. The main reason for this working assumption is that permitting a temporary overshoot of a specific temperature rise before falling back to this level in 2100 would imply relying on negative-CO_2 technologies at scale sometime in the future. This is technically feasible, but the assessment of the implications of widespread adoption of BECCS for land-use requirements or the potential uptake of non-energy technologies for CO_2 removal is outside the scope of this report. This means that one unique assumption as to how much CO_2 can be removed in the future cannot be taken. In addition, there are also questions surrounding whether bioenergy can truly be considered to be a low- or zero-carbon fuel (see Chapter 2).

With these assumptions, for the purpose of this study, we estimate that the CO_2 budget between 2015 and 2100 is 880 gigatonnes (Gt). This lies towards the middle of the 590 – 1 240 $GtCO_2$ range from a study discussing CO_2 budgets commensurate with a 66% chance of staying below 2 °C (Rogelj et al., 2016). Nevertheless, as discussed above, many of the scenarios assessed by the IPCC in its Fifth Assessment Report that aim to limit the specific temperature rise in 2100 to 2°C rely heavily upon BECCS such that the global energy sector as a whole absorbs CO_2 emissions from the atmosphere by the end of the century.

The scenarios developed in this study are therefore ambitious in terms of the timing and scope of required energy emissions reductions for meeting the 2°C goal as they offer no possibility to delay CO_2 emissions reduction until negative-emissions technologies are available at scale. Nevertheless, the scenarios offer the possibility for achieving more stringent climate targets in the future, should negative-emissions technologies become available.

To arrive at an *energy sector only* CO_2 budget for the 66% 2°C scenario it is necessary to subtract from the total CO_2 budget those CO_2 emissions not related to fossil fuel combustion in the energy

22 MAGICC = Model for the Assessment of Greenhouse-Gas Induced Climate Change.

sector. These emissions predominantly arise from two sources: industrial processes and from land use, land-use change and forestry (LULUCF).

Annual industrial process emissions are currently around 2 Gt, about 70% of which arises from cement production. With material efficiency and the use of CCS becoming more widespread in a stringent decarbonisation scenario, projections suggest that these emissions would rise marginally to the mid-2020s before declining over the remainder of the century: in 2050, process emissions therefore fall to around 1 Gt. This assumption is used by both institutions in this study in developing decarbonisation scenarios for the energy sector.

Estimates of LULUCF emissions are uncertain. One estimate for 2013 indicated emissions were around 3.3 Gt, but could range from 1.5 $GtCO_2$ to 5.1 $GtCO_2$ (Le Quéré et al., 2015). The high degree of uncertainty arises from the differing methods that can be used to generate LULUCF estimates, the poor quality of land-use change data in some key regions and the difficulty in attributing emissions to human activities or to natural processes. As per agreement by the participating institutions, the outlook for CO_2 emissions from LULUCF used in this study are based on the median of 36 unique decarbonisation scenarios analysed by the IPCC. For this study, the assumption is that CO_2 emissions from LULUCF fall from 3.3 Gt in 2015 to zero by mid-century. LULUCF subsequently becomes a net absorber of CO_2 over the remainder of the 21st century, and, as a result, cumulative CO_2 emissions from LULUCF between 2015 and 2100 are close to zero.

The net effect of these two factors is to reduce the total CO_2 budget from 880 Gt to an energy sector only budget of 790 Gt. This study analyses in detail the transformation of the energy sector between 2015 and 2050, but also takes into account the emissions that might occur thereafter. The challenge is stark: by means of comparison, current NDCs imply that, until 2050, the energy sector would emit almost 1 260 Gt, i.e. nearly 60% more than the allowed budget.

Pursuing efforts to stay below a temperature rise of 1.5°C present unchartered territories. The IPCC indicated that to have a 50% chance of keeping global warming to 1.5°C, the remaining CO_2 budget from 2015 ranges between 400 and 450 $GtCO_2$ (IPCC, 2014). But more recent reports have suggested it could be as low as 50 $GtCO_2$ (Rogelj et al., 2015). Even if the CO_2 budget is at the upper end of this range, at around 400 $GtCO_2$, energy sector emissions would need to fall to net-zero by around 2040, if global energy-related CO_2 emissions cannot turn net-negative at any point (IEA, 2016a).

References

ICCT (International Council on Clean Transportation) (2013), *The Impact of stringent fuel and vehicle standards on premature mortality and emissions*, ICCT, Washington, DC.

IEA (International Energy Agency) (2016a), *World Energy Outlook 2016*, OECD/IEA, Paris.

- (2016b), *World Energy Investment 2016*, OECD/IEA, Paris.

- (2016c), *20 Years of Carbon Capture and Storage - Accelerating Future Deployment,* OECD/IEA, Paris.

- (2016d), *Energy and Air Pollution: World Energy Outlook Special Report*, OECD/IEA, Paris.

- (2016e), *Medium Term Energy Efficiency Market Report*, OECD/IEA, Paris.

- (2016f), *Energy Technology Perspectives 2016 2016 - Towards Sustainable Urban Energy Systems*, OECD/IEA, Paris.

- (2015), *World Energy Outlook 2015*, OECD/IEA, Paris.

- (2014), *The Power of Transformation: Wind, Sun and the Economics of Flexible Power Systems*, OECD/IEA, Paris.

IPCC (UN Intergovernmental Panel on Climate Change) (2014), *Climate Change 2014: Mitigation of Climate Change, Contribution of Working Group III to the Fifth Assessment Report*, Edenhofer, O. et al. (eds.), IPCC, Cambridge University Press, Cambridge, United Kingdom and New York.

IRENA (International Renewable Energy Agency) (2017a), *Renewable Cost Database*, IRENA, Abu Dhabi.

- (2017b), *Adapting Electricity Market Design for High Shares of Variable Renewable Energy,* IRENA, Abu Dhabi.

- (2017c), *Biofuels for Aviation: Technology Brief*, IRENA, Abu Dhabi, www.irena.org/DocumentDownloads/Publications/IRENA_Biofuels_for_Aviation_2017.pdf.

- (2016a), *Roadmap for a Renewable Energy Future- 2016 edition*, IRENA, Abu Dhabi.

- (2016b), *Renewable Capacity Statistics 2016*, IRENA, Abu Dhabi.

- (2016c), *Unlocking Renewable Energy Investment: The Role of Risk Mitigation and Structured Finance*, IRENA, Abu Dhabi.

- (2016d), R*enewable Energy and Jobs Annual Review- 2016*, IRENA, Abu Dhabi.

- (2014a), *Adapting Renewable Energy Policies to Dynamic Market Conditions*, IRENA, Abu Dhabi.

- (2014b), *Renewable Energy in Manufacturing: A technology roadmap for REmap 2030*, IRENA, Abu Dhabi, www.irena.org/remap/REmap%202030%20Renewable-Energy-in-Manufacturing.pdf.

IRENA and CEM (International Renewable Energy Agency and Clean Energy Ministerial) (2015), *Renewable Energy Auctions: A Guide to Design*, IRENA, Abu Dhabi.

Le Quéré, C. et al. (2015), “Global Carbon Budget 2015”, *Earth System Science Data*, Vol.7, pp.349-396.

REN21 (Renewable Energy Network for the 21st Century) (2016), *Renewables 2016 Global Status Report*, Paris.

Rogelj, J. et al. (2015), “Energy system transformations for limiting end-of-century warming to below 1.5 °C”, *Nature Climate Change,* Vol.5, pp. 519–527.

Rogelj, J. et al. (2016), “Differences between carbon budget estimates unravelled”, *Nature Climate Change,* Vol.6, pp. 245–252.

Chapter 2: Energy Sector Investment to Meet Climate Goals

Author: International Energy Agency

Key messages

Limiting the global mean temperature rise to below 2°C with a probability of 66% would require an energy transition of exceptional scope, depth and speed. Energy-related CO_2 emissions would need to peak before 2020 and fall by more than 70% from today's levels by 2050. The share of fossil fuels in primary energy demand would halve between 2014 and 2050 while the share of low-carbon sources, including renewables, nuclear and fossil fuel with CCS, would more than triple globally to comprise 70% of energy demand in 2050.

The 66% 2°C Scenario would require an unparalleled ramp up of all low-carbon technologies in all countries. An ambitious set of policy measures, including the rapid phase out of fossil-fuel subsidies, CO_2 prices rising to unprecedented levels, extensive energy market reforms, and stringent low-carbon and energy efficiency mandates would be needed to achieve this transition. Such policies would need to be introduced immediately and comprehensively across all countries for achieving the 66% 2°C Scenario, with CO_2 prices reaching up to USD 190 per tonne of CO_2. The scenario also requires broader and deeper global efforts on technology collaboration to facilitate low-carbon technology development and deployment.

Improvements to energy and material efficiency, and higher deployment of renewable energy are essential components of any global low-carbon transition. In the 66% 2°C Scenario, aggressive efficiency measures would be needed to lower the energy intensity of the global economy by 2.5% per year on average between 2014 and 2050 (three-and-a-half times greater than the rate of improvement seen over the past 15 years); wind and solar combined would become the largest source of electricity by 2030. This would need to be accompanied by a major effort to redesign electricity markets to integrate the large shares of variable renewables, alongside rules and technologies to ensure flexibility.

A deep transformation of the way we produce and use energy would need to occur to achieve the 66% 2°C Scenario. By 2050, nearly 95% of electricity would be low-carbon, 70% of new cars would be electric, the entire existing building stock would have been retrofitted, and the CO_2 intensity of the industrial sector would be 80% lower than today.

A fundamental reorientation of energy-supply investments and a rapid escalation in low-carbon demand side investments would be necessary to achieve the 66% 2°C Scenario. Around USD 3.5 trillion in energy-sector investments would be required on average each year between 2016 and 2050, compared to USD 1.8 trillion in 2015. Fossil fuel investment would decline, but would be largely offset by a 150% increase in renewable energy supply investment between 2015 and 2050. Total demand-side investment into low-carbon technologies would need to surge by a factor of ten over the same period. The additional net total investment, relative to the trends that emerge from current climate pledges, would be equivalent to 0.3% of global GDP in 2050.

Fossil fuels remain an important part of the energy system in the 66% 2°C Scenario, but the various fuels fare differently. Coal use would decline most rapidly. Oil consumption would also fall but its substitution is challenging in several sectors. Investment in new oil supply will be needed as the decline in currently-producing fields is greater than the decline in demand. Natural gas plays an important role in the transition across several sectors.

Early, concerted and consistent policy action would be imperative to facilitate the energy transition. Energy markets bear the risk for all types of technologies that some capital cannot be recovered ("stranded assets"); climate policy adds an additional consideration. In the 66% 2°C Scenario, in the power sector, the majority of the additional risk from climate policy would lie with coal-fired power plants. Gas-fired power plants would be far less affected, partly as they are critical providers of flexibility for many years to come, and partly because they are less capital-intensive than coal-fired power plants. The fossil fuel upstream sector may, besides the power sector, also carry risk not to recover investments. Delaying the transition by a decade while keeping the same carbon budget would more than triple the amount of investment that risks not to be fully recovered. Deployment of CCS offers an important way to help fossil fuel assets recover their investments and minimise stranded assets in a low-carbon transition.

With well-designed policies, drastic improvements in air pollution, as well as cuts in fossil-fuel import bills and household energy expenditures, could complement the decarbonisation achieved in the 66% 2°C Scenario. Achieving universal access to energy for all is a key policy goal; its achievement would not jeopardise reaching climate goals. The pursuit of climate goals can have co-benefits for increasing energy access, but climate policy alone will not help achieve universal access to all.

Introduction

This chapter presents detailed new International Energy Agency (IEA) analysis of the energy sector transformation through 2050 that would be needed if the world is to limit the global mean temperature rise to below 2°C with a probability of 66%, as well as the major reallocation of investment capital that would be required to do so. This assessment uses scenarios to illustrate the degree of difference in policies required and their consequences on energy markets, investment requirements and energy-related emission trajectories. It is one possible interpretation of the "well below 2°C" objective of the Paris Agreement.

Two main scenarios, varying in their assumptions about the evolution of government policies are presented: the New Policies Scenario and the 66% 2°C Scenario. The New Policies Scenario reflects the implications for the energy sector of the climate pledges, known as Nationally Determined Contributions (NDCs), which were made as part of the Paris Agreement. This scenario reflects the result of a detailed quantitative evaluation of the implications of the energy-related components of these pledges, as well as extensive consultation with country representatives and other stakeholders. This assessment was first published in the *World Energy Outlook 2016* (IEA, 2016a), but for the purpose of this report the analysis has been extended to the 2050 time horizon.[23] The other main scenario takes a different approach, describing a trajectory for energy-related emissions consistent with a 66% probability of limiting the long-term rise in global temperatures to less than 2 degrees Celsius (°C), illustrating the scale and speed of the transition that this would necessitate in the energy sector. In addition, we include a comparison with the *World Energy Outlook's* 450 Scenario, the widely used reference for the low-carbon energy sector transition, which maps out an energy future consistent with a 50% chance of staying within a 2°C limit.[24] This scenario was introduced in 2007 and has since been updated on a yearly basis to take account of policy progress, market dynamics, technology cost declines and countries' priorities.

The modelling and analysis incorporates the most recent information available on an array of factors including energy markets, prices and technology costs. On this basis, the analysis

23 The modelling time horizon of the *World Energy Outlook 2016* is 2040.

24 The probability of the temperature increase refers to the end of this century.

determines energy supply and demand outlooks, emissions abatement and investment needs in the energy supply, power generation and end-use sectors (industry, transport and buildings) in the two main scenarios. It also examines the co-benefits for local pollution, energy access and energy security in a transition to a low-carbon energy system and its implications for the energy industry.

Defining the scenarios

The scenarios discussed in this chapter are generated using the IEA's large-scale World Energy Model (WEM). Developed over a period of around 30 years, the WEM generates comprehensive sector-by-sector and region-by-region projections covering the whole energy system from primary energy production to transformation through to final energy consumption (Annex A). The starting year for the projections is 2014, as reliable official market data for all countries were, in most instances, available only up to the end of 2014. For technology costs (such as renewables) and fuels (such as oil) for which more recent data were available, those were fully taken into account in the analysis.

Global gross domestic product (GDP) is assumed to grow at an average annual rate of 3.1% between 2014 and 2050 (measured in terms of purchasing power parity [PPP]), based on economic forecasts by the International Monetary Fund (IMF, 2016), the World Bank and the OECD.[25] The world's population is projected to grow at a slower rate of 0.8%,[26] although there is a high degree of variation between regions. These assumptions remain the same across the various scenarios examined in this chapter.[27] Our analysis here focuses on trends at the global or regional (G20 versus "rest of world") level, although modelling within the WEM is carried out with much greater granularity.

The direction that policy ambitions, as stated in the NDCs, will take the energy sector is illustrated in the **New Policies Scenario**. It assesses the impact on the evolution of the energy system of all the policies and measures that had been adopted as of mid-2016. It also takes account of the targets and policy measures that countries have announced, even if these have yet to be enacted into legislation or the means for their implementation are still taking shape. The energy-related components of the NDCs form a key component of this scenario. The pledges are assessed on an individual country-by-country basis, and, where policies exist to support them and the implementing measures are clearly defined, incorporated into the New Policies Scenario. However, where political, regulatory, market, infrastructure or financing constraints exist, the announced targets may be met later than officially anticipated or not at all. Conversely, there may also be cases in which energy demand, macroeconomic conditions and/or cost trends lead countries to go further and faster than their declared objectives. But the New Policies Scenario incorporates policies beyond NDCs, ranging from policies to increase energy security, fight local pollution and to provide energy access. Nearly 1.2 billion people still lacked access to electricity (25% of which are in G20 countries) in 2014 and over 2.7 billion did not have access to clean cooking facilities and so rely on the traditional use of biomass (50% of which are in G20 countries). Providing modern forms of energy to the world's poorest people occupies a priority place in national policy making in countries without universal energy access and forms a crucial backdrop to the growth in energy demand looking forwards.

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25 Based on the scenarios examined in this chapter, the Organisation for Economic Co-operation and Development (OECD) is conducting a study examining the implications of the energy sector transition for global economic growth (OECD, forthcoming).

26 Based on United Nations Population Division forecast with medium fertility (UNPD, 2015).

27 For further details, see www.worldenergyoutlook.org.

While the New Policies Scenario gives policy makers, investors, consumers and other stakeholders an indication of how policy ambitions as of mid-2016 are likely to shape the energy sector, it should not be considered a forecast. The New Policies Scenario is not an attempt to predict shifts in policy, beyond those already announced, that affect energy supply and use in response to uncertainties such as the pace of economic growth and technology advances. Our analysis shows that the New Policies Scenario does not meet the Paris Agreement temperature limiting objectives, but it provides a sound basis for expectations about developments in the energy sector and their implications for the future, and serves as a guidepost for policies and other factors that need to change in order to meet goals related to economic development, energy security and sustainability (IEA, 2016a).

The **66% 2°C Scenario** – the main focus of this chapter – describes an energy transition of exceptional scope, depth and speed. This is based on the assumption that policies are implemented to follow a trajectory of greenhouse gas (GHG) emissions from the energy sector consistent with the international target "to limit the rise in global average temperature to well below 2°C from pre-industrial levels". The interpretation of this target in this scenario is that energy-related carbon dioxide (CO_2) emissions (from all sources and sectors) are bound by a tight CO_2 budget: as described in Chapter 1, the cumulative amount of energy-related CO_2 emissions between 2015 and 2100 consistent with this carbon budget is 790 gigatonnes (Gt). If energy-related CO_2 emissions were to follow the New Policies Scenario, the entire energy sector CO_2 budget for the 66% 2°C Scenario would be depleted in just over 20 years.

An array of ambitious policies and approaches, and unprecedented deployment of an array of low-carbon technologies would be required to stay within this CO_2 budget and to channel the types of investment that dramatically accelerate the transition to a low-carbon energy sector. CO_2 prices in the industry and power sectors are an essential component and would be introduced across all countries by 2020 in the 66% 2°C Scenario. Staying within the CO_2 budget of the 66% 2°C Scenario would require a price of US dollars (USD) 190 per tonne of CO_2 (t/CO_2) by 2050 in all developed countries, more than three-times the level in the New Policies Scenario, in which the CO_2 price is less than USD 60/tonne in 2050 (where it exists at all).[28] In addition, to facilitate the rapid and transformative worldwide changes across the energy sector in the 66% 2°C Scenario, CO_2 prices would also be necessary in *all* other countries, albeit at lower levels and with a more progressive implementation (Table 2.1).

Table 2.1 • Summary of CO_2 prices in the 66% 2°C Scenario (USD/tCO_2)

	2020	2030	2040	2050
OECD countries	20	120	170	190
Major emerging economies*	10	90	150	170
Other regions	5	30	60	80

* includes People's Republic of China (hereafter "China"), the Russian Federation (hereafter "Russia"), Brazil and South Africa.

Yet even at these unprecedented levels, CO_2 prices alone would be insufficient to stimulate the required pace and extent of energy sector transformation and would need to be accompanied by the phase out of fossil fuel subsidies and additional fuel taxation In addition, the co-ordinated enforcement of mandates, standards, energy market reforms, research, development and deployment (RD&D) and other emissions reduction policies would also be required. These additional measures would be essential across all sectors, and, as with CO_2 prices, go well beyond those enacted to date.

28 For further details on assumptions in the New Policies Scenario, see IEA, (2016a).

Table 2.2 • Selected key policy assumptions in the New Policies Scenario and additional measures in the 66% 2°C Scenario

Sector	New Policies Scenario	66% 2°C Scenario
Cross-cutting measures	• CO_2 prices in specific countries in the power and industry sectors implemented with a variety of delays ranging from USD 25 to USD 60 per tonne in 2050. • Cautious implementation of announced NDCs as part of the Paris Agreement. • All net-importing countries and regions phase out fossil fuel subsidies completely within ten years.	• CO_2 prices in all countries ranging from USD 80 to USD 190 per tonne in 2050 in the power and industry sectors. • Fossil fuel subsidies removed by 2025 in all countries.
Power	• Implementation of GHG emission performance standards, renewable energy mandates and nuclear power development in accordance with NDC targets and national/regional policies.	• Widespread market reforms, including toreflect the value of flexibility. • Introduction of measures to integrate high shares of variable renewables, including RD&D for storage and support for demand-side responses. • Comprehensive GHG emission performance standards. • Widespread renewable energy mandates. • Expansion of nuclear power deployment (where acceptable). • Widespread deployment of CCS for both fossil fuels and bioenergy.
Industry	• Existing energy efficiency mandates and policies extended to 2050. • Standards and financial support for efficient and low-carbon technologies.	• Stringent mandates to realise energy efficiency potentials. • Widespread industrial use of material efficiency. • Widespread deployment of CCS for both fossil fuels and bioenergy. • Extensive support for electrification to meet low-temperature heat demand, especially through the deployment of heat pumps. • Measures to stimulate widespread deployment of direct low-carbon heat (including bioenergy, solar thermal and geothermal)
Transport	• Fuel economy targets for passenger vehicles and light-duty trucks (and heavy-duty trucks in some countries). • Biofuel blending mandates. • Targets for the share of sales for next-generation vehicles. • Realisation of goals for improvements in aviation efficiency. • Sulfur dioxide emission standards for shipping.	• Stringent fuel economy and emissions standards. • Extensive support for electrification of road vehicles and necessary infrastructure including catenary lines for trucks. • Increased taxation of oil-based fuels. • Strong efforts to improve urban planning and increase low-carbon public transport. • International fuel efficiency standards for aviation and shipping, and incentives for biofuels.
Buildings	• Partial implementation of energy efficiency mandates. • Strengthening efficiency standards for appliances and lighting (including full phase out of incandescent light bulbs).	• Mandates to maximise insulation and retrofits for new and existing buildings. • Prioritising the construction of zero-energy buildings. • Phase out of coal and kerosene for cooking. • Enforced phase out of fossil fuel boiler sales by 2025 in all regions, with exceptions. • Extensive support and mandates for electrification including the use of heat pumps, solar thermal and biomass. • Ban of all light bulb sales other than LEDs by 2025.

Notes: The precise policy instruments introduced in each of the scenarios varies across different countries/regions. NDCs = Nationally Determined Contributions; RD&D = research, development and demonstration; CCS = carbon capture and storage; LEDs = light-emitting diodes.

Selected key policy assumptions, for the New Policies and 66% 2°C Scenarios are highlighted in Table 2.2. Additional approaches in the 66% 2°C Scenario include widespread deployment of carbon capture and storage (CCS) in both the power and industry sectors, including initial uses of CCS with bioenergy as a feedstock (which removes CO_2 from the atmosphere) (Box 2.1), a much larger push to electrify end-use sectors, particularly for transport, along with the needed infrastructure, and the direct use of renewables for heat generation and as transport fuels. Given the need for dynamic development to move beyond existing technologies across all sectors, an intensified effort to innovate is also a necessary component of the energy sector transition in the 66% 2°C Scenario to continue meeting rising demand for energy services. This would require both increased private and public investment into RD&D to lower the cost of technologies that would otherwise entail a huge cost to deploy on a widespread basis (IEA, 2016b).

The analysis included in the next section focuses on the main aggregate and sector trends in the period to 2050, with projections for the 66% 2°C Scenario compared with and benchmarked against the New Policies Scenario. The intention is to highlight the differences between the policies and implementing measures that would be required to meet the well below 2°C target on the one hand, and the policies and measures that were actually pledged in the NDCs on the other. The differences in policies encompassed in the two scenarios have a major impact on the projection for carbon-intensive fuels and consequently the outlook for fossil fuel prices diverges markedly (Table 2.3). Oil and gas prices would initially rise from 2015 levels in the 66% 2°C Scenario, given the need to ensure ongoing investments in oil and gas supply to offset the observed declines in current sources of production (see Implications of the 66% 2°C Scenario section). The lower international fossil fuel price levels in the 66% 2°C Scenario relative to the New Policies Scenario would not translate into lower prices for end-use consumers since the decarbonisation policies (fossil fuel subsidies removal, taxation for road fuels, market reforms in the power sector, CO_2 prices, etc.) implemented in the 66% 2°C Scenario would offset these reductions to varying degrees across difference sectors and countries.

Table 2.3 • Fossil fuel import prices by scenario

		New Policies Scenario				66% 2°C Scenario			
	2015	2020	2030	2040	2050	2020	2030	2040	2050
IEA crude oil (USD/barrel)	51	79	111	124	137	73	66	64	61
Natural gas (USD/MBtu)									
United States	2.6	4.1	5.4	6.9	8.9	3.8	4.3	4.2	4.2
European Union	6.9	7.1	10.3	11.5	12.2	6.7	8.3	7.9	7.5
Japan	10.5	9.6	11.9	12.4	12.8	8.9	10.0	9.3	8.9
OECD steam coal (USD/tonne)	64	72	83	87	90	66	63	55	53

Notes: All prices are in real USD (2015) terms. MBtu = million British thermal units. Natural gas prices are weighted averages expressed on a gross calorific-value basis. All prices are for bulk supplies exclusive of tax. The US price reflects the wholesale price prevailing on the domestic market. The European Union gas import prices reflect a balance of liquefied natural gas (LNG) and pipeline imports, while the Japan import price is solely LNG.

Overview of trends in the 66% 2°C Scenario

Energy demand

In the 66% 2°C Scenario, global primary energy demand would be 4% higher in 2050 than in 2014, while fuelling a global economy that is three-times larger (Table 2.4).[29] Indeed, between 2020

29 Primary energy is measured using the physical energy content method (see www.iea.org/statistics).

and 2030, primary energy demand would fall marginally, even though there is robust economic growth of around 3.7% per year. This would represent a profound break with previous historical trends, when economic growth has typically been accompanied by steady growth in energy consumption: for example, annual global economic growth averaged 3.8% per year between 2000 and 2010, while primary energy demand grew by 2.6% on average over the same period.

The key reason for this trend break in the 66% 2°C Scenario would be the comprehensive, systematic, immediate and ubiquitous implementation of strict energy and material efficiency measures. These measures mean that energy would be used much more productively, reducing the overall energy intensity of the economy.[30] A large portion of these measures are assumed to be implemented over the next 15 years and would result in huge changes in the levels and manner of energy consumption across the end-use sectors: for example, about one in three existing buildings would be retrofitted by 2030 and conventional trucks would use 40% less fuel than today, bending an historically flat trend for the first time.

Table 2.4 • Global primary energy mix by fuel in the 66% 2°C Scenario (Mtoe)

	2014	2020	2030	2040	2050	CAAGR* 2014-50	Difference in 2050 to NPS**
Coal	3 926	3 421	2 032	1 475	1 318	-3.0%	-68%
Oil	4 266	4 260	3 474	2 534	1 760	-2.4%	-63%
Gas	2 892	3 255	3 325	2 789	2 426	-0.5%	-50%
Nuclear	662	816	1 272	1 807	2 021	3.1%	56%
Hydro	335	381	516	639	733	2.2%	25%
Bioenergy***	1 421	1 574	2 038	2 543	2 928	2.0%	48%
Other renewables	181	395	1 228	2 277	3 018	8.1%	120%
Total	**13 683**	**14 102**	**13 885**	**14 064**	**14 204**	**0.1%**	**-26%**
Fossil fuel share	*81%*	*78%*	*64%*	*48%*	*39%*	*n.a.*	*-47%*
Renewables share	*14%*	*17%*	*27%*	*39%*	*47%*	*n.a.*	*128%*
*Low-carbon share*** **	*19%*	*23%*	*39%*	*59%*	*70%*	*n.a.*	*153%*

*Compound average annual growth rate. **New Policies Scenario. *** Includes traditional and modern biomass use and bioenergy from waste. **** Includes nuclear, hydro, bioenergy, other renewables and fossil fuel use with CCS.

After 2030, there would be a slight increase in primary energy demand in the 66% 2°C Scenario. In parallel with this massive deployment of energy and material efficiency measures in the earlier part of the projection period, there would need to be a concurrent scaling up of electrification in a number of end uses, particularly in the transportation sector, and a massive infrastructure build-up to accommodate the new electric car and electric truck fleets. However, because much of this increase is building from a low base (e.g. less than 0.1% of the global vehicle fleet in 2015 was electric), this growth takes time to have a significant impact on overall energy demand. After 2030, underpinned by this growth in electrification, primary energy demand therefore would rise marginally.

Outlook by fuel

The share of fossil fuels in the overall primary energy fuel mix would plunge from 81% today to 39% in 2050 in the 66% 2°C Scenario (compared with around 73% by 2050 in the New Policies Scenario). Coal would fall throughout the 66% 2°C Scenario at a particularly rapid rate to less

30 Energy intensity is measured as total primary energy demand per unit of gross domestic product expressed in market exchange rates.

than half of today's level just after 2030 and to two-thirds lower by 2050, levels not seen since the 1960s. Most significant is the decline of coal in the power sector, which by 2050 would be nearly 80% below today's level. Over 65% of the remaining coal consumption in 2050, most of which is in the power and industry sectors, would be in conjunction with CCS.

Oil use would peak around 2020 in the 66% 2°C Scenario, with the decline in demand accelerating over the course of the subsequent decade. Throughout the 2030s, oil demand falls by around 2 million barrels per day (mb/d) every year, such that in 2050 demand would be 60% below today's level at less than 40 mb/d – also a level not seen since the 1960s. The sole sector in which oil demand would increase is the chemical industry, due to the difficulty of finding alternatives to oil as a petrochemical feedstock. By 2050 the use of oil as a feedstock would account for around 30% of total oil consumption, up from just over 10% today. Such a drastic shift for oil demand represents a huge challenge both to the oil industry and to those countries heavily reliant upon oil exports for fiscal revenue (see Implications of the 66% 2°C Scenario section).

Natural gas would fare best among the fossil fuels in the 66% 2°C Scenario: demand increases through to the mid-2020s. Over 70% of this initial increase is related to fuel switching in the power sector as natural gas displaces coal-fired generation over the next decade in countries that have or can mobilise the necessary resources and infrastructure. After 2025, however, natural gas-fired generation would be displaced by lower carbon sources of electricity and therefore gas demand in the power sector falls, on average, by 2.5% each year between 2025 and 2050.

Natural gas demand in the buildings sector would fall by 400 billion cubic metres (bcm) in the period to 2050, a drop of more than 50% as efficiency measures and low-carbon alternatives are widely adopted. This would be offset to some extent by an increase in natural gas demand in a number of other areas, most notably road transportation, as a bunker fuel and petrochemical feedstock. But this growth would be insufficient to offset the lower demand in the power and buildings sectors (alongside smaller changes elsewhere). As a result, natural gas demand would decline after 2025.

All low-carbon sources of energy exhibit rapid growth in the 66% 2°C Scenario. There is a particularly quick uptake of CCS after 2025. In 2025 there would be nearly 15 gigawatts (GW) of power generation capacity equipped with CCS (compared with less than 0.2 GW today), which would expand to almost 130 GW by 2030 and then further swell by a factor of four over the next ten years. By 2050, CCS-equipped generation capacity is over 600 GW and accounts for just under 10% of total electricity generation. The use of bioenergy would more than double in the period to 2050, and, by 2030, exceed coal demand. Biofuels would play an increasingly important role in decarbonising the transportation sector, in particular road freight, aviation and shipping: shortly before 2050, more biofuels are consumed in the transportation sector than gasoline and by 2050, consumption of biofuels would reach almost 12 mboe/d. The use of bioenergy with CCS (BECCS), offers an important opportunity to generate net-negative CO_2 emissions in the energy sector. By 2050, power generation capacity equipped with BECCS would be nearly 50 GW and some industrial sub-sectors (e.g. paper and cement) would also be employing BECCS technologies.

The most rapid growth would be in renewable sources of energy other than hydropower and bioenergy, particularly wind, solar photovoltaic (PV) and concentrated solar power. Collectively, they increase by a factor of 15 between 2014 and 2050 and just before 2050 become the largest component of primary energy demand, overtaking bioenergy. Annual increases in electricity generation from wind would be more than 12% and from solar by 18% over the next 15 years: together, they would account for the largest source of electricity by 2030.

Box 2.1 • Bioenergy – a precious commodity in a low-carbon world

Today, bioenergy is mainly used in two distinct manners. The "traditional" method is solid biomass for cooking, typically using inefficient stoves in poorly ventilated spaces. In 2014, over 2.7 billion people – nearly 40% of the world's population – did not have access to clean cooking facilities and so around 770 million tonnes of oil equivalent (Mtoe) of bioenergy was consumed in traditional uses. The noxious particles emitted by burning biomass are linked to more than three million premature deaths a year, mostly women and children (IEA, 2016c). More "modern" methods use bioenergy as a feedstock for the production of synthetic fuels or electricity, as a substitute for petrochemicals or to be combusted directly for heat. In 2014, modern bioenergy consumption was around 650 Mtoe.

The cultivation of bioenergy is based on processes of photosynthesis which remove CO_2 from the atmosphere. The CO_2 is returned to the atmosphere when the bioenergy is consumed. In our analysis, bioenergy is considered to be a zero-carbon fuel (although it is important to recognise that for this to be the case there must have been only a negligible amount of CO_2 emitted during cultivation and conversion of the land to be suitable for growing bioenergy). However, with modern bioenergy uses, it is also possible to capture and store the CO_2 that is emitted when the bioenergy is consumed. The life-cycle emissions of this process, called bioenergy with carbon capture and storage (BECCS), can therefore be negative. In other words, the use of BECCS technologies in the supply of electricity, heat or liquid fuels represents a net sink of CO_2, which is removed from the atmosphere and sequestered permanently.

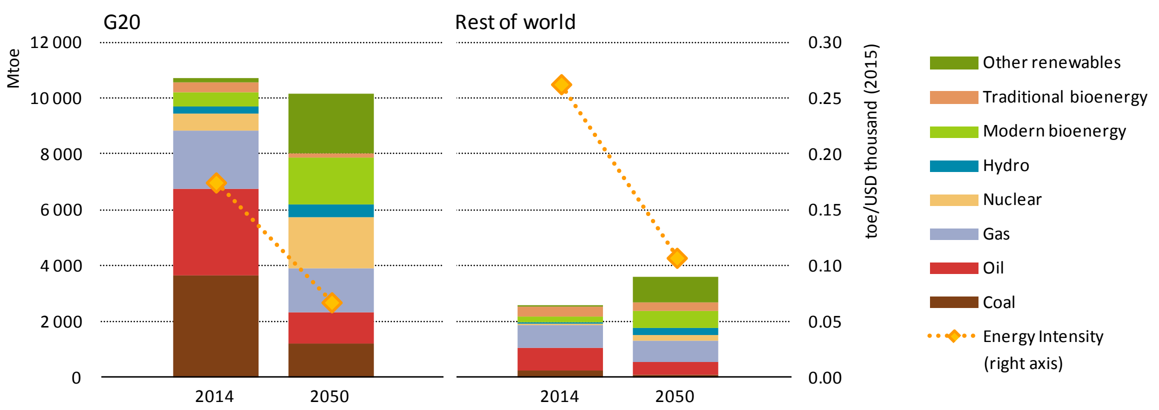
In decarbonisation pathways, bioenergy, both with and without CCS, typically becomes an important mechanism to lessen reliance on fossil fuels and so to reduce CO_2 emissions in a number of end-use sectors. However, the amount of bioenergy available in a given year is not unlimited. The land required to produce bioenergy is multi-functional and can be used for a variety of purposes including food, feed, timber and fibre production, as well nature conservation. The level of bioenergy that can be produced in a sustainable manner, which takes into account competing uses and minimises local factors such as water stress, is therefore a key consideration in assessing its potential to help in the low-carbon energy transition. While there is a high degree of uncertainty in the amount of sustainable bioenergy that can be supplied for energy purposes, a commonly quoted figure for the global potential is around 100 exajoules (EJ) or 2 400 Mtoe (for use in modern technologies only) (Rose et al., 2013).

As a result of such availability constraints, bioenergy becomes an increasingly valuable commodity in the 66% 2°C scenario. In addition, when working to a strict trajectory for decarbonisation, it becomes increasingly important to ensure that bioenergy is used, wherever possible, by technologies with higher shares of CO_2 that can be captured. When using BECCS, only CO_2 produced when the bioenergy is converted can be captured: the various conversion processes for bioenergy therefore result in different potential levels of CO_2 removal. For example, when bioenergy is transformed into electricity or heat, it is possible to capture nearly all of the CO_2 during the transformation process at a point source. Conversely, biofuels for use in transport, even if produced using BECCS, will produce CO_2 that cannot be captured when the fuel is combusted. While biofuels may offer an attractive option to decarbonise some end-use sectors, there may be greater benefit in producing electricity or heat with BECCS since this will remove a greater level of CO_2 from the atmosphere. Allocating bioenergy most effectively across the different end-use sectors becomes an increasingly important consideration when pursuing an ambitious decarbonisation agenda. In the 66% 2°C Scenario, biofuels play a key role in decarbonising transport, particularly in aviation and shipping. But, in 2050, the transport sector would account for less than 25% of total modern bioenergy consumption while the power sector would consume around 40%, given the higher share of CO_2 that it can remove from the atmosphere.

Regional trends

All regions would need to undertake a prolonged and dramatic drop in energy intensity in the 66% 2°C Scenario, as energy and material efficiency measures take effect. The energy intensity of the G20 group would need to fall by more than 60% in the period to 2050 (Figure 2.1) and total primary energy demand to peak around 2020. From 2020 to 2050, energy demand in G20 countries would fall by around 0.2% per year even with economic growth of nearly 3% per year. There are similarly significant improvements elsewhere. Energy intensity in the 66% 2°C Scenario falls by a similar percentage in the non-G20 countries even though their total energy demand continues to grow, led by Africa and the Middle East. Nevertheless, energy demand in the G20 group would still remain more than twice the level of the rest of the world even by 2050. The increase in energy demand of less than 40% between 2014 and 2050 in countries outside the G20 is even more striking when considered alongside the other demographic changes that occur during this period. For example, three-quarters of the increase in the global population occurs in countries outside the G20 (an expansion of 1.8 billion people), while the percentage of people without access to electricity drops from one-third in 2014 to 10% in 2050. Many of these countries also have an expanding wealthy middle class increasingly seeking access to mobility and other energy services.

Figure 2.1 • Primary energy demand by fuel and energy intensity by region in the 66% 2°C Scenario



Notes: Mtoe = million tonnes of oil equivalent; toe = tonne of oil equivalent; MER = market exchange rate.

Key message • Energy intensity decreases 60% and there is a substantial shift away from fossil fuels in the G20 countries.

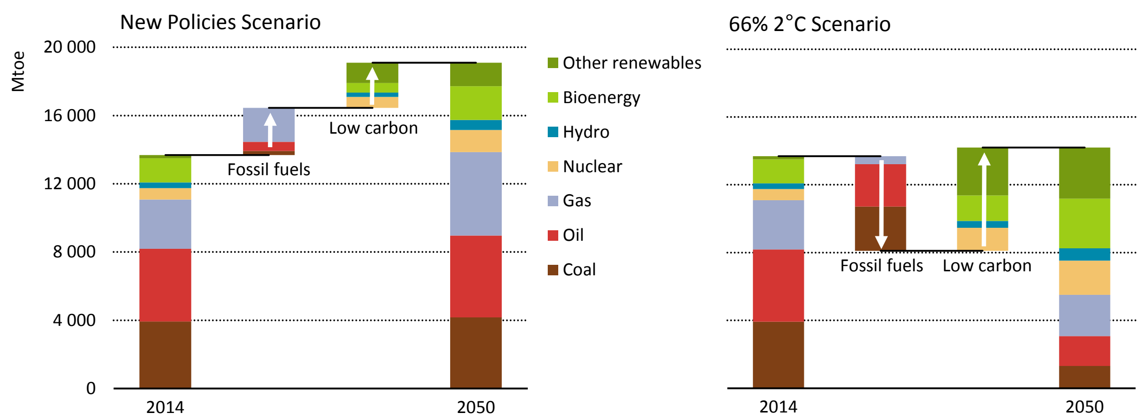
The use of bioenergy would need to expand substantially over the period in the G20 and elsewhere. By 2050 in the G20, the largest portion (over 700 Mtoe) is for use in the power sector (increasingly with CCS to mitigate GHG emissions) while demand in the industry, transport and buildings sectors each accounts for about 350 Mtoe. The use of solid biomass for cooking falls in the G20 countries in the 66% 2°C Scenario. Decarbonisation policies help improve access to clean cooking facilities as renewable sources of electricity in urban areas displace the use of liquefied petroleum gas (LPG). This means that additional levels of LPG would be available to be used in modern cookstoves in rural locations. However in the absence of specific policies to address access to clean cooking facilities, the energy transition may make switching to cleaner fuels and technologies more difficult for the poorest people. In the absence of dedicated policies in the 66% 2°C Scenario, more than 1.3 billion people, mostly outside G20 countries, would still lack access to clean cooking facilities in 2050. While this is a significant improvement over today's level of 2.7 billion people, lack of energy access nonetheless remains a significant contributor to premature deaths and poverty.

Energy trends in the 66% 2°C Scenario relative to the New Policies Scenario

Effective implementation of the measures assumed in the 66% 2°C Scenario would have profound implications for global energy demand and GHG emissions. The striking differences from the trends in the New Policies Scenario are highlighted in Figure 2.2, starting with the overall projection for primary energy demand. While overall global demand would flatten in the 66% 2°C scenario, a less dramatic policy push for energy and material efficiency in the New Policies Scenario means that world primary energy demand expands by nearly 40% between 2014 and 2050.

The contrasts are particularly sharp in relation to the trajectories for fossil fuels. In the 66% 2°C Scenario, demand for all types of fossil fuels would decline in the period to 2050; in the New Policies Scenario, demand for all fossil fuels increases. Coal and oil exhibit the largest difference between the two scenarios: in the case of oil, demand in 2050 in the 66% 2°C Scenario is some 65 mb/d lower than in the New Policies Scenario. Oil demand in 2050 would be at least 50% lower across all regions, with the largest absolute differences occurring in major G20 countries. Natural gas would initially grow to 2025 but by 2050 consumption would be 16% below current levels in the 66% 2°C Scenario, compared with a nearly 70% increase between 2014 and 2050 in the New Policies Scenario. Natural gas demand increases by nearly 50% in the G20 countries in the New Policies Scenario between 2014 and 2050 (but falls by almost 25% in the 66% 2°C Scenario) and by 110% in the rest of the world (but would largely stay flat in the 66% 2°C Scenario). Wind and solar are the energy sources that grow most rapidly in both scenarios, but the rate of growth over the period to 2050 in the New Policies Scenario is less than half that in the 66% 2°C Scenario.

Figure 2.2 • Global primary energy demand by fuel in the New Policies and 66% 2°C Scenarios



Key message • All energy sources increase to meet demand growth in the New Policies Scenario, while the growth in low-carbon sources offsets the declines in fossil fuels in the 66% 2°C Scenario.

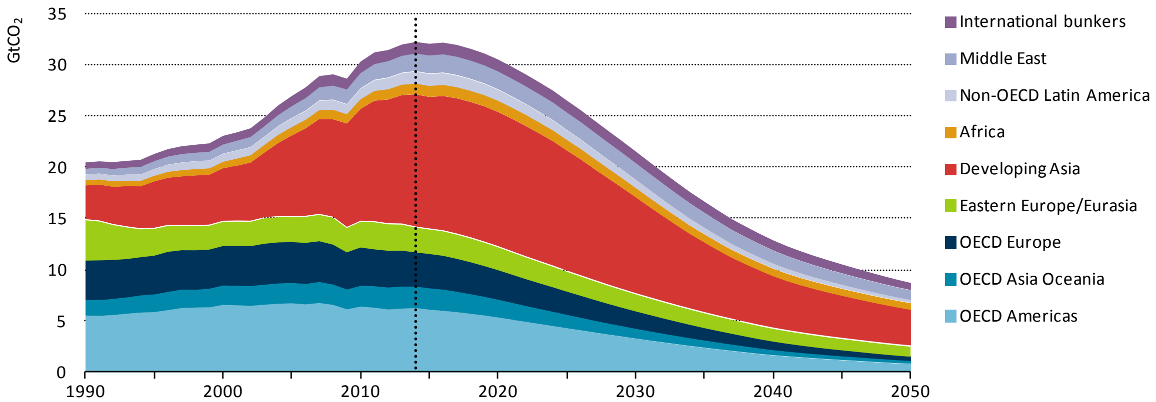
On a sectoral level the largest difference is in the transport sector, where nearly 1 500 Mtoe less fuel would be consumed in the 66% 2°C Scenario than in the New Policies Scenario, partly as a result of increased energy efficiency and partly because of a shift to electric vehicles and bioenergy. There are also sizeable shifts in both the industry and buildings sectors, which each would consume around 1 000 Mtoe less energy in 2050 in the 66% 2°C Scenario. Differences in fossil fuel use account for the majority of this reduction (particularly coal in industry and natural gas in buildings), but electricity consumption is also markedly lower in the 66% 2°C Scenario in both sectors given the substantial effort to use energy more efficiently. Some of the difference is offset by a greater direct use of renewables in both sectors in the 66% 2°C Scenario, which is driven mainly by solar thermal with a smaller contribution from geothermal. This change is most notable in the industry sector. Direct use of renewables currently plays an increasing but modest role in the industry sector and their growth in the New Policies Scenario remains limited. In contrast, in the 66% 2°C Scenario, they would grow rapidly (at over 17% per year on average) to contribute nearly 7% of total industrial energy demand by 2050, an order of magnitude greater than in the New Policies Scenario.

Energy-related CO_2 emissions

The reduction in energy-related CO_2 emissions in the 66% 2°C Scenario would be much more pronounced than the changes projected in energy demand. Emissions would peak before 2020 in this scenario and exhibit an accelerating decline to the 2030s, when annual emissions would fall by just over 1 gigatonne per year (Gt/year). Between 2014 and 2050, the rate of decline in global CO_2 emissions would average just over 3.5% per year, and, by 2050, these emissions would be less than 9 Gt, more than 70% below current levels. This is a hugely ambitious pace of decline that would require robust policy support. To place it in context, global CO_2 emissions over the past 40 years grew at less than 2% per year and the fastest rate of growth sustained over a ten-year period was less than 3% (during the 2000s). In other words, the rate of emissions decline in the 66% 2°C Scenario would surpass the fastest rate of growth ever seen over an extended period and sustain this pace of decline over a period of 35 years.

All regions would need to contribute to CO_2 emissions reductions in the 66% 2°C Scenario, although there is a large degree of variation between them depending on their current level of emissions and the anticipated pace of economic growth over the next 35 years (Figure 2.3). Average CO_2 emissions per capita on a global basis would fall below 1 tonne per person just before 2050 (from around 4.4 tonnes per person today).

Figure 2.3 • Energy-related CO_2 emissions by region in the 66% 2°C Scenario



Key message • Global CO_2 emissions fall to less than 9 Gt in 2050, with all regions contributing.

As discussed in Chapter 1, the 66% 2°C scenario is formulated on the need to keep within a tight cap on CO_2 emissions. But this does not mean that, in order to stay within the temperature threshold, efforts are required only to reduce CO_2 while emissions of other greenhouse gases such as methane (CH_4) and nitrous oxide (N_2O) can continue to grow. The opposite is true: the 66% 2°C Scenario includes a dramatic reduction in all major sources of non-CO_2 gases both within and outside the energy sector. In the energy sector, on a CO_2 equivalent basis,[31] global GHG emissions fall by 35% between 2014 and 2030 (compared with CO_2 emissions that fall by just over

31 There are different ways to evaluate the effects of methane on global warming. CO_2 equivalent figures are generated on the basis of the 100-year global warming potential of fossil CH4 and N2O of 30 and 265 respectively.

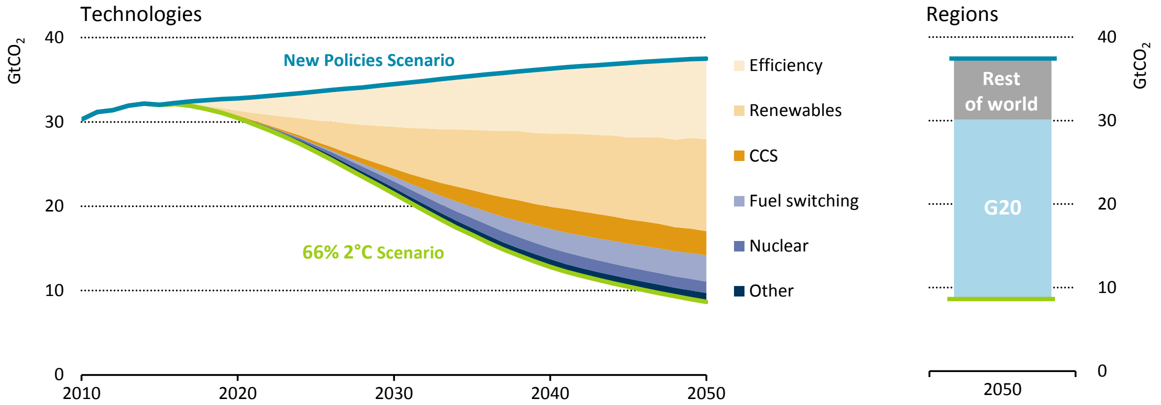
30% in the same period), with early action targeting CH_4 emissions released during fossil fuel production.[32] Without determined action on reducing energy sector non-CO_2 forcers, the CO_2 budget available to the energy sector would be reduced markedly, amplifying the required pace of reduction in CO_2 emissions and thus further complicating the energy sector transition.

Emissions trends in the 66% 2°C Scenario relative to the New Policies Scenario

The outlook for CO_2 emissions in the 66% 2°C Scenario represents a very sharp contrast with that of the New Policies Scenario. In the New Policies Scenario, which takes into account countries' pledges in their NDCs to the Paris Agreement, CO_2 emissions continue to increase to reach slightly more than 37 Gt by 2050. Cumulative energy-related CO_2 emissions between 2015 and 2050 in the New Policies Scenario are around 1 250 Gt, about 75% higher than the carbon budget consistent with a 66% chance of keeping the temperature rise below 2°C.

An unprecedented effort to mitigate CO_2 emissions would be required to remain within the carbon budget of the 66% 2°C Scenario. In absolute terms, much of the required savings would need to come from the countries with the highest levels of CO_2 emissions in the New Policies Scenario. For example, the G20 countries collectively account for around three-quarters of the cumulative emissions in the New Policies Scenario to 2050. The G20 therefore also accounts for around three-quarters of the 540 Gt reduction in cumulative emissions between the 66% 2°C Scenario and New Policies Scenario (Figure 2.4).

Figure 2.4 • Global CO_2 emissions abatement by technology and region in the 66% 2°C Scenario relative to the New Policies Scenario



Key message • G20 countries provide almost three-quarters of the emissions reductions in 2050 between the 66% 2°C and New Policies Scenarios.

The largest contributions to global energy-related CO_2 emissions abatement come from two sources: energy and material efficiency, which reduces both material and energy use;[33] and in the use of renewables in power generation, heat, and transport (i.e. biofuels). Both areas would be responsible for around one-third of the CO_2 savings in 2050 in the 66% 2°C Scenario, relative to the New Policies Scenario. Energy and material efficiency efforts would provide the largest contribution to emissions savings up to 2030. There are numerous additional energy efficiency

32 The World Energy Outlook 2017 will contain an analysis of the level of methane emissions, and the scope and costs of efforts to reduce them.

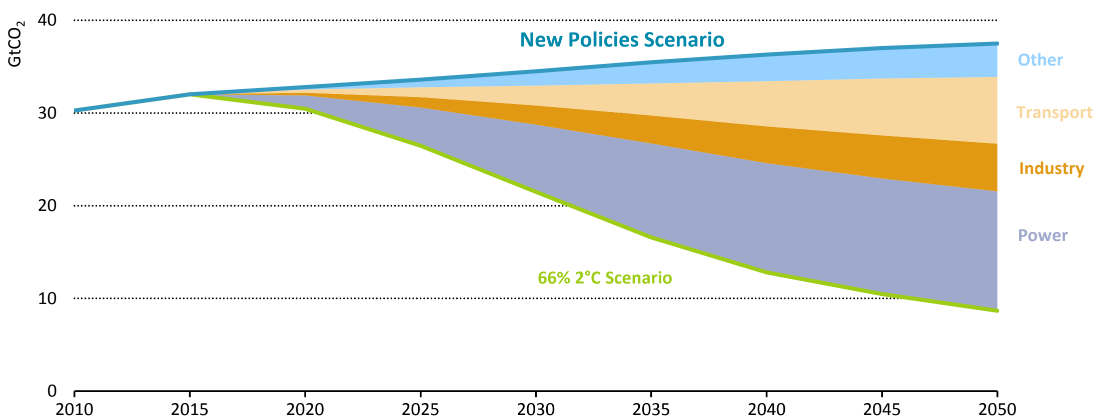
33 The emission reductions from efficiency measures include direct savings from lower fossil fuel demand and indirect savings as a result of lower electricity demand which reduces GHG emissions from power generation. The results take into account direct rebound effects as modelled in the IEA's World Energy Model. Direct rebound effects are those in which energy efficiency increases the energy service gained from each unit of final energy, reducing the price of the service and eventually leading to higher consumption.

measures, e.g. for appliances and lighting in buildings, boilers in industry and buildings, and fuel economy standards in transport, that are deployed in the near term in the 66% 2°C Scenario, but which are not adopted in the New Policies Scenario as existing policies are not sufficient to support their deployment. Supported by extensive new policy measures, the 66% 2°C Scenario also contains an array of ambitious improvements in material efficiency, none of which are implemented in the New Policies Scenario. These measures include light-weighting of products such as plastic bottles, paper and cars, and increased recycling and re-use of materials. While it would remain a challenge to mobilise stringent efficiency measures in such a short period of time, doing so has an immediate impact on emissions reduction in this scenario.

There has been an impressive scaling up of renewable energy options in recent years. In 2015, renewables, for the first time, accounted for more than half of all new electricity generating capacity installed worldwide. This momentum is maintained in the New Policies Scenario based on existing and planned policies for renewable energy. In the 66% 2°C Scenario, the deployment of renewables accelerates out to the end of the 2020s (and deployment maintains robust thereafter). Nevertheless, it takes a longer period for there to be a sizeable difference between the two scenarios in renewable energy supply (and consequently a longer period until there is a substantial difference in related emission reductions). Electricity generation from renewables increases on average by 7% per year over the next 15 years in the 66% 2°C Scenario, compared with 4.4% per year in the New Policies Scenario (which is similar to the average rate of growth of 4.5% seen over the past 15 years). Coupled with some degree of scale-up of negative emissions technologies in the power sector in the 66% 2°C Scenario, the contribution to emissions reduction from renewables therefore would become more pronounced over time.

Carbon capture and storage would become increasingly vital for reducing energy-related emissions in the power and industry sectors. CCS accounts for just over 10% of global CO_2 savings in 2050 in the 66% 2°C Scenario relative to the New Policies Scenario. Worldwide electricity generation from nuclear power nearly doubles in the New Policies Scenario over the period to 2050, while its contribution would triple in the 66% 2°C Scenario with nuclear providing 6% of the emissions savings in 2050. There is also a notable contribution from fuel switching (15% of the savings in 2050), which includes shifts from coal in the power sector and from oil in transport.

Figure 2.5 • Global CO_2 emission reductions by sector in the 66% 2°C Scenario relative to the New Policies Scenario



Key message • The power sector accounts for around half of the emissions savings in 2050.

The power sector provides the largest contribution to global CO_2 abatement, accounting for around half of the cumulative abatement relative to the New Policies Scenario between 2014 and 2050 (Figure 2.5). The rapid phase out of unabated coal plants (i.e. those not equipped with CCS), particularly older plants with lower conversion efficiencies, is very effective in curbing global CO_2 emissions in the early period, while in later periods, an increasingly large part of the additional CO_2 savings come from increased investment in renewable sources for power generation as electricity demand increases. By 2050, several G20 countries would have close to zero CO_2 electricty in the 66% 2°C Scenario, and the global average CO_2 intensity of electricity generation would be one-tenth of that in the New Policies Scenario.

The transport sector would provide the second-largest contribution to CO_2 savings, accounting for around 20% of the cumulative savings between 2014 and 2050 in the 66% 2°C Scenario. Transport makes less of a contribution in the early part of the projection period. While policies would underpin accelerated deployment of electric vehicles, it would take time – given their current low numbers on the road and the need for infrastructure build-up – to have a sizeable impact on oil demand and emissions reduction. Nevertheless, by 2030 there would be more than 750 million electric vehicles (motorbikes, passenger cars, trucks and buses) on the road and nearly 3 billion by 2050 – a twenty-fold increase from today's level. Nearly 60% of electric vehicles would be passenger cars, but electrification also extends to freight transport in the 66% 2°C Scenario. By 2050 nearly 50% of trucks would be electric and a large number of motorways would be equipped with electrified overhead (catenary) lines since batteries alone do not support long-haul journeys. Fuel efficiency standards and biofuel mandates in aviation and maritime transport also provide increasing contributions to emissions reductions over time and the use of biofuels would expand to nearly 12 mboe/d by 2050, a seven-fold increase on today's level.

The industry sector would provide around 17% of the cumulative emissions savings in the period to 2050. The introduction of CO_2 prices across all regions, alongside the use of wide ranging decarbonisation and efficiency mandates, results in the full realisation of material and energy efficiency potentials, a 40% increase in the use of electricity (especially for low-temperature heat), an unprecedented increase in the use of renewable heat, and the extensive deployment of CCS across a range of industrial processes.

Investment needs

From an investment perspective, the energy sector transition in the 66% 2°C Scenario would require not only more capital expenditure, but also a fundamental reallocation of capital compared with today's portfolio. Compared with current trends and those projected in the New Policies Scenario, a large, sustained increase in the capital flows for low-carbon energy options and efficiency measures would be an essential prerequisite. Meanwhile, continued investment in fossil fuel extraction (albeit at a lower level) would still be needed.

Over USD 120 trillion of energy-related investment worldwide in the period to 2050 would be required in the 66% 2°C Scenario (Table 2.5).[34] Around half of this investment is for supply-side technologies including fossil fuels, biofuels and electricity (generation, and transmission and distribution). The other half is for demand-side low-carbon technologies, including investment into more efficient technologies that moderate energy and material use in end-use sectors, which accounts for around one-third of total investment in the 66% 2°C Scenario. The remaining investment is for technologies that help to reduce direct energy-related emissions in the end-use sectors. In the transport sector, this includes the additional capital spent on electric or natural gas vehicles and trucks that displace the use of conventional vehicles, excluding the infrastructure investment needs related to this electrification. In the industry and buildings sectors, it includes investment for the use of renewable sources that can generate heat for direct

34 Cumulative investment numbers are undiscounted.

use, e.g. solar thermal, geothermal and biomass, as well as expenditure to install CCS in energy-intensive industries.

Table 2.5 • Cumulative global supply- and low-carbon demand-side investment in the 66% 2°C Scenario, 2016 – 2050

	Supply-side investment					Demand-side investment		Total
USD billion (2015)	Oil	Gas	Coal	Electricity	Biofuels	Efficiency	Other**	
World*	**7 346**	**7 456**	**731**	**39 576**	**2 221**	**39 071**	**26 207**	**122 607**
Of which: G20	4 853	4 708	641	28 944	1 963	30 509	22 449	94 066

*Includes inter-regional transport. **Includes investment in road transportation, CCS and direct renewables in industry and buildings but excludes investment in infrastructure.

Of the total level of investment in the 66% 2°C Scenario, around 13% would be required for the supply of fossil fuels. Most of this is needed for oil and gas extraction, despite the rapid reduction in oil demand in this scenario (averaging over 2% per year between 2014 and 2050). This is because the natural decline from producing oil fields is generally much higher than the decline of demand. The reduction in demand for natural gas is less pronounced than for oil in the 66% 2°C Scenario and continued investment in its development remains essential. In the New Policies Scenario, around 85% of oil and gas upstream investment is required simply to compensate for declines at existing fields. This provides a natural hedge against the risk of stranded assets in the upstream sector (see Implications of the 66% 2°C Scenario section). Continued investment in fossil fuel supply remains a necessary feature of the low-carbon transition in the 66% 2°C Scenario.

The largest portion of supply-side investment would be for power generation, the vast majority of which is focused on low-carbon technologies. Effectively no new unabated coal-fired power plants (i.e. those without CCS) would be built in the 66% 2°C Scenario, other than those currently under construction and the least-efficient coal-fired power plants would be phased out by 2030 in most regions and in all regions by 2035. Renewables would account for half of the near USD 40 trillion spent in the power sector, with a similar level of investment (just under USD 7 trillion) each spent on wind and solar (both solar PV and concentrated solar power) generation. G20 countries would account for the majority of the investment in low-carbon electricity.

On the demand-side, a cumulative USD 39 trillion would be spent on energy efficiency measures up to 2050. There are also impressive cost reductions anticipated in more efficient technologies in the 66% 2°C Scenario, but an average annual spending of over USD 1 trillion per year would still be required in order to ensure that primary energy demand remains broadly constant between 2016 and 2050. The level of investment into direct emissions reduction technologies in the end-use sectors is USD 26 trillion. The transport sector (principally the additional investment into electric vehicles for displacing conventional vehicles) would account for 65% of this cumulative total: the stock of electric passenger cars would need to grow by nearly 50% per year over the next 15 years to achieve the targets of the 66% 2°C Scenario. By 2050, there would be over 1.7 billion electric passenger cars on the road, compared with around 1.2 million today. The number of electric trucks would also need to expand rapidly, in particular after 2025. By 2050, almost 50% of trucks on the road are plug-in hybrid or full battery electric vehicles in the 66% 2°C Scenario.

Box 2.2 • Defining energy investment in IEA analysis

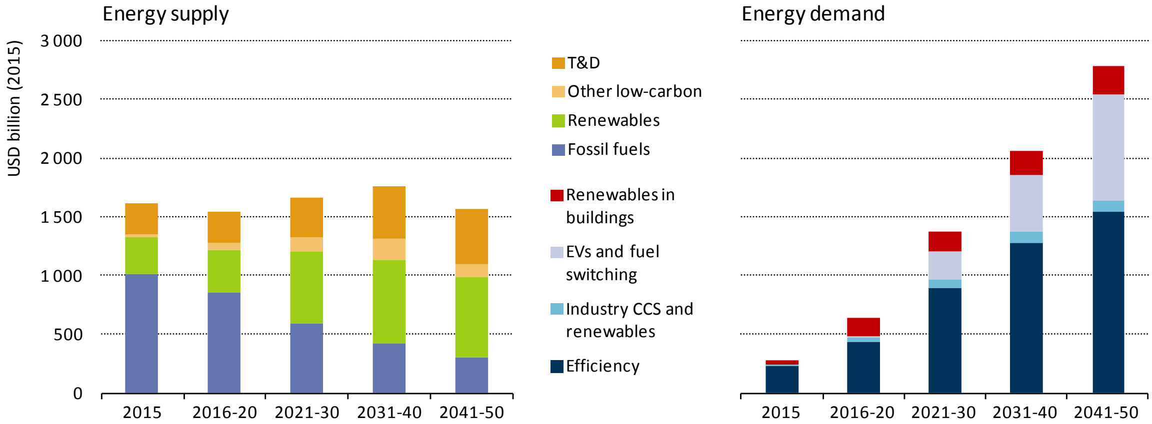
Investment figures in this chapter are generally split between supply- and demand-side investments. Supply-side investment covers capital expenditure to construct or refurbish assets that extract, process, transform or transport fossil fuels, bioenergy and power. It excludes the operating expenditure incurred in the daily functioning of these assets. The main items covered by these capital investments are the costs of engineering, procurement and construction, including all the equipment and other material required, as well as the labour costs associated with installing a device, machine or plant, or drilling a development well. They also include costs, such as planning, feasibility studies, external advisory services and all licensing and approvals (including environmental approvals), as well as acquiring the land for the project. They do not include research and development costs, or the costs of abandonment or decommissioning. The investments are booked in the year in which new energy supply commences; for a power plant, this is the first year of operation, while for upstream oil and gas projects, this can be over a period of years as production from a new source ramps up.

Demand-side investments include both energy efficiency measures and direct emissions reduction technologies such as CCS in industry, renewable technologies (e.g. solar thermal, bioenergy, geothermal) in the buildings and industry sectors, and alternative fuel vehicles (e.g. natural gas, electricity, hydrogen). In the industry and buildings sectors, costs cover similar elements to supply-side investments. However investments for energy efficiency and alternative fuel vehicles are more difficult to quantify. For efficiency, we analyse procurement capital, i.e. the money spent by end-users on energy-consuming products. However not all of this spending is included: only the amount that is spent to procure equipment that is more efficient than a given baseline. This baseline is established as the 2014 average efficiency of different products and sectors. In other words, this calculation reflects the additional amount that consumers have to pay for higher energy efficiency over the period to 2050. In a similar way, the investment in alternative fuel vehicles represents the additional cost for a vehicle over an equivalent 2014 conventional vehicle.

The volume of annual supply-side investments would be broadly constant over the period to 2050 in the 66% 2°C Scenario (Figure 2.6). There is a major shift, however, with expenditure related to fossil fuels (including both extraction and investment in fossil fuel plants without CCS) being reallocated to renewables and other low-carbon technologies (nuclear and CCS). In 2015, fossil fuels comprised almost 60% of supply-side investment, a share that would drop to less than 20% by 2050 in the 66% 2°C Scenario. Indeed, by 2025, investment in renewables exceeds total investment into fossil fuels in the 66% 2°C Scenario.

Investment in end-use sectors would need to see an even more radical transformation over the period to 2050. Total demand-side investment into low-carbon technologies grows by a factor of ten from less than USD 300 billion per year today to around USD 3 trillion by 2050 in the 66% 2°C Scenario. Demand-side investment to 2020 in the 66% 2°C Scenario would be dominated by the need to enhance energy efficiency and to deploy low-carbon options in buildings, using technologies that are commercially available today. Between 2016 and 2020 investment into energy efficient technologies is on average twice the level of 2015, and within five years, the level of investment in energy efficiency measures exceeds the total level of spending on fossil fuel extraction in 2015. An array of policies and measures drives this boost in the 66% 2°C Scenario, such as tighter minimum energy performance standards for a range of equipment, more stringent fuel efficiency standards and a widespread push for near zero-energy buildings. The level of investment in demand-side technologies that directly reduce emissions also surges over the period to 2050, growing by around 10% on average per year between 2015 and 2050 to more than USD 1.4 trillion.

Figure 2.6 • Average annual global energy supply- and demand-side investment in the 66% 2°C Scenario



Note: T&D = transmission and distribution; EVs = electric vehicles; CCS = carbon capture and storage.

Key message • The level of supply-side investment remains broadly constant, but shifts away from fossil fuels. Demand-side investment in efficiency and low-carbon technologies ramps up to almost USD 3 trillion in the 2040s.

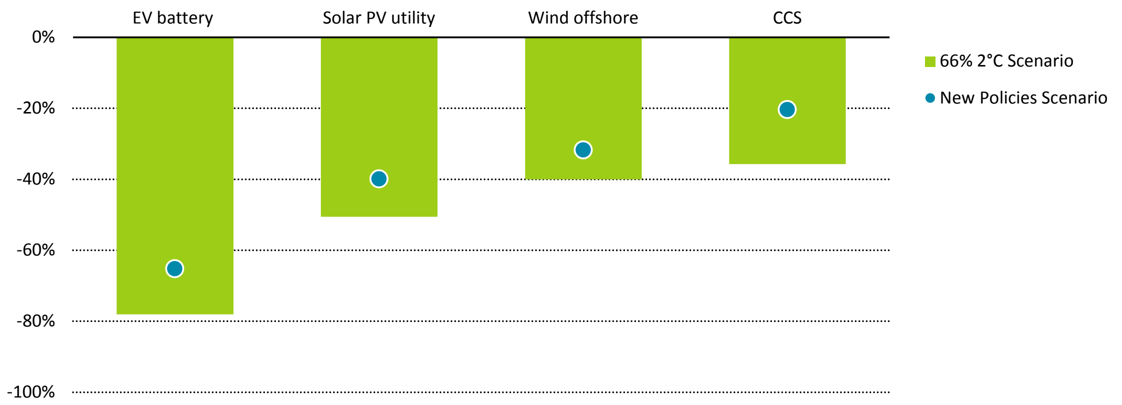
Investment trends in the 66% 2°C Scenario relative to the New Policies Scenario

Cumulative energy supply- and demand-side investment in the 66% 2°C Scenario is over USD 120 trillion, 25% more than the USD 99 trillion needed in the New Policies Scenario. There is also a marked difference in the destination of this capital between the two scenarios: in the New Policies Scenario, 65% of the total is spent on energy supply, compared with less than 50% in the 66% 2°C Scenario, largely because energy is used more efficiently in the 66% 2°C Scenario. Furthermore, in the New Policies Scenario, nearly 45% of total energy supply investment is spent on fossil fuel extraction. In the 66% 2°C Scenario, less than 20% of total energy supply investment would be for fossil fuel extraction. The contrary situation would be reflected for investment in electricity supply given the higher demand levels for electrification (even with ambitious energy and material efficiency adoption) in the 66% 2°C Scenario: nearly USD 40 trillion would be needed for electricity generation, transmission and distribution, 40% more than in the New Policies Scenario.

In the 66% 2°C Scenario, cumulative investment in power plants to 2050 would be USD 26 trillion, 50% higher than in the New Policies Scenario. In large part, this reflects the transition from fossil-fuelled power plants to low-carbon technologies, which are initially more expensive to build though generally are less expensive to maintain and operate. Wind power and solar PV exemplify this relationship, with higher upfront capital costs per unit of electricity generated than fossil-fuelled power plants, but zero fuel costs. Nuclear and CCS-equipped power plants are also more capital-intensive than unabated fossil-fuelled power plants. The underlying assumption is that, to facilitate the proliferation of more capital-intensive technologies in this scenario, market designs would need to be conducive for such investment. Overall, the increase in total investment is partially offset by the reduced expenditure for fuel, but, despite significant cost reductions in renewables-based electricity generation, the cumulative cost of the global power system (including transmission and distribution) to 2050 would be around 15% higher in the 66% 2°C Scenario.

Total energy supply investment in the 66% 2°C Scenario would be 10% lower than in the New Policies Scenario. This is partly because energy demand is lower and partly because of the more significant cost reductions for low-carbon technologies in the 66% 2°C Scenario (Figure 2.7). The array of ambitious policies and approaches enacted in the 66% 2°C Scenario accelerates the deployment of low-carbon technologies, and greater deployment means economies of scale and technology learning, pushing down costs especially through 2030 as many low-carbon technologies still offer vast potential for cost reductions. Thereafter, the pace of cost reductions levels off for many low-carbon technologies in the 66% 2°C Scenario, as the technologies mature. The cost of traditional fossil fuel supply technologies experience little, if any, reduction in either of the scenarios given their state of maturity, and because the effects of depletion (i.e. seeking to produce small and harder-to-access resource deposits) offset the technology learning that continues to occur.

Figure 2.7 • Cost reductions for selected low-carbon technologies in 2030 relative to 2015 in the 66% 2°C and New Policies Scenarios

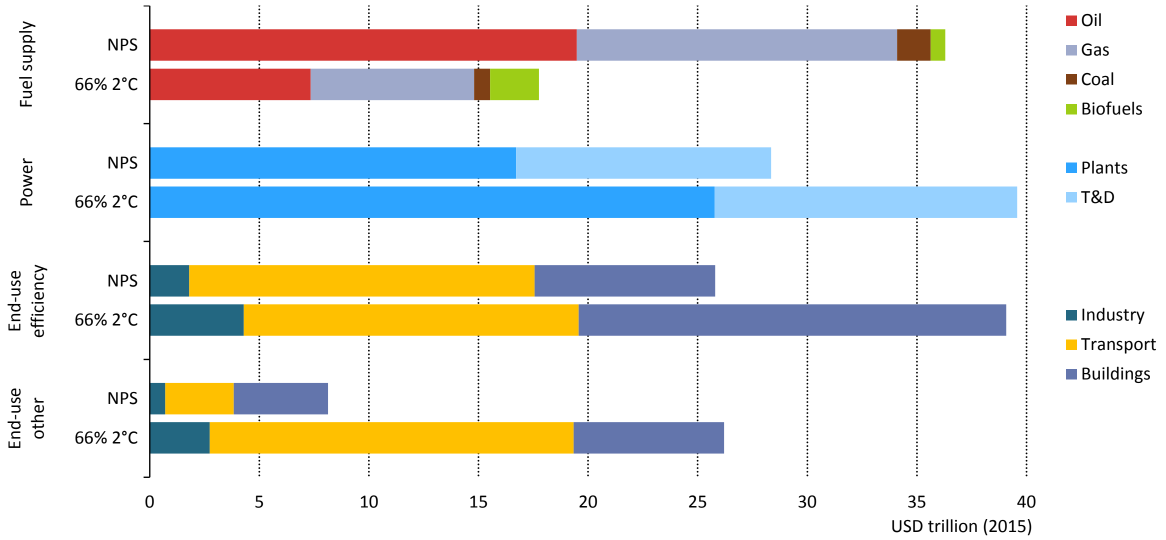


Key message • Enhanced policy efforts in the 66% 2°C Scenario would accelerate deployment of key low-carbon technologies which yields faster cost reductions.

While investment in energy supply would be lower in the 66% 2°C Scenario, investment in low-carbon demand-side technologies is over 90% higher (Figure 2.8). Much of the notable reduction in energy demand in the 66% 2°C Scenario compared with the New Policies Scenario is achieved by higher investment in more energy efficient technologies. Cumulative investment in energy efficiency in the 66% 2°C Scenario is therefore some 50% higher than the USD 26 trillion in the New Policies Scenario. Investment in energy efficiency in buildings is nearly 140% higher in the 66% 2°C Scenario, as a result of the need to curtail space heating and cooling demand in both new and existing buildings. This is achieved through the stringent enforcement of minimum energy performance standards and stringent building codes alongside rigorous retrofitting and deep renovation of existing buildings to yield a reduction in energy demand well beyond the levels seen in the New Policies Scenario.

In contrast, there is a slight decrease in the level of efficiency investment in the transport sector in the 66% 2°C Scenario relative to the New Policies Scenario, since improvements in efficiency are insufficient to generate the rapid and comprehensive emissions reductions required across the vehicle fleet in the 66% 2°C Scenario. But the lower investment in energy efficiency in transport is more than compensated for by a five-fold increase in the level of investment in direct emissions reduction technologies in the end-use sectors. In 2050, there are over 250 million electric cars on the road in the New Policies Scenario; in the 66% 2°C Scenario, there are over 1.7 billion. The early uptake of electric vehicles in the 66% 2°C Scenario accelerates technology improvements and mass production, and electric car battery costs fall to USD 80 per kilowatt-hour (kWh) in the early 2030s, a level not seen in the New Policies Scenario before 2050. Nevertheless, this is insufficient to offset the additional cost of an electric car compared with its equivalent conventional vehicle, and therefore results in an increased overall level of investment in transport. Similarly, investment in direct renewables both for the buildings and industry sectors in the 66% 2°C Scenario is around 80% higher than the New Policies Scenario, while there is an additional USD 0.7 trillion for CCS in the industrial sector.

Figure 2.8 • Global energy sector investment in the 66% 2°C and the New Policies Scenarios



Notes: NPS = New Policies Scenario; T&D = transmission and distribution. "End-use other" includes investment in road transportation, CCS and direct renewables in industry and buildings.

Key message • Investment shifts significantly from supply to demand-side in the 66% 2°C Scenario.

Box 2.3 • Raising the probability of reaching 2°C: a different energy world?

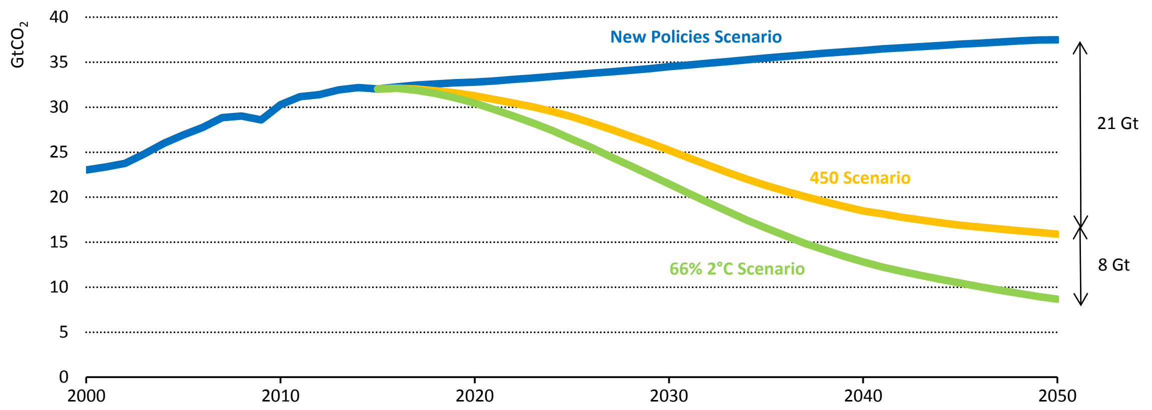
The IEA has for many years looked into the transition to a low-carbon energy sector that would be compatible with achieving the 2°C temperature rise limitation target using its 450 Scenario. This scenario was first developed for the *World Energy Outlook 2007*. Since then, it has been updated every year to illustrate the technology and investment requirements as well as the opportunities and challenges that lie ahead, serving as a means to track progress towards achievement of the 2°C temperature goal. The 450 Scenario is designed to achieve the 2°C temperature limitation objective by 2100 with a probability of 50%.

In the context of this study, the IEA for the first time explores a more ambitious pathway for reducing energy-related GHG emissions. The 66% 2°C Scenario, developed for the purpose of this study, aims to illustrate one energy sector development pathway that could be compatible with the goal of the Paris Agreement to limit the global mean temperature rise to "well below 2°C". It does so via analysis of a scenario with a 66% probability of limiting the temperature rise to below 2°C by 2100. Here we highlight the key differences between the 450 Scenario and the 66% 2°C Scenario in order to illustrate the additional energy sector challenges that arise from the different pathways.

The increase in probability from 50% to 66% implies a deep cut in the CO_2 budget that is allocated to the energy sector: the CO_2 emissions budget for the achievement of the 450 Scenario amounts to 1 080 Gt, 290 Gt above the budget that is available to the 66% 2°C Scenario, or roughly nine years at current emission levels. This variance is significant. The transition to a 450 Scenario would require energy-related CO_2 emissions to become net-zero by around 2100. To realise the 66% 2°C Scenario, CO_2 emissions would need to fall to net-zero by around 2060, i.e. 40 years earlier, unless negative emissions technologies could be deployed at scale (IEA, forthcoming).

Clearly, the emissions trajectory to 2050 in the 66% 2°C Scenario is a significant departure from that of the 450 Scenario. For the achievement of the 66% 2°C Scenario, energy-related CO_2 emissions need to drop to less than 9 Gt in 2050, which is 8 Gt below the level achieved in the 450 Scenario. Already by 2030, emissions need to be nearly 15% (3.7 Gt) below the level of the 450 Scenario for the more ambitious scenario to be achieved (Figure 2.9).

Figure 2.9 • World energy-related CO_2 emissions trends by scenario



Key message • Staying within the emissions budget of the 66% 2°C Scenario would require an additional CO_2 emissions savings of around 8 Gt by 2050 relative to the 450 Scenario.

The energy sector transformation associated with the 66% 2°C Scenario is significantly deeper than that of the 450 Scenario and the pace at which it has to be put in practice is faster (Table 2.6). Yet, the world of the 66% 2°C Scenario is not one of just more robust efforts with the same policy and technology levers of the 450 Scenario. To illustrate, we examine two key indicators of the energy transition. The first indicator is the energy intensity of economic activity (measured as energy use per unit of GDP), which is an important (yet imperfect) indicator for the efficiency of global energy use. The drop in energy intensity to 2050, relative to today, is very similar between the two scenarios, at 2.8% per year in the 450 Scenario and 2.9% per year in the 66% 2°C Scenario. The main reason is that much of the economic energy efficiency potential as it is known today is already being used as a cost-effective measure to meet the decarbonisation target of the 450 Scenario; the additional reduction in energy intensity of the 66% 2°C Scenario is therefore largely achieved through improving material efficiency in the industry sector.

The second indicator is the carbon intensity of energy use (measured as CO_2 emissions per unit of energy use), which is a key measure for assessing progress for the transition. It is this indicator that reflects most closely on the additional energy sector challenge of raising ambition from a 50% probability to a 66% probability of reaching the 2°C target: the pace at which the energy sector would need to decarbonise for the achievement of the 66% 2°C Scenario is one-third above that of the 450 Scenario. By 2050, the carbon intensity of energy use in the 66% 2°C Scenario would need to be around half of the level of an energy sector emissions pathway compatible with the 450 Scenario.

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Table 2.6 • Key indicators of the global energy sector transition in the 450 and 66% 2°C Scenarios

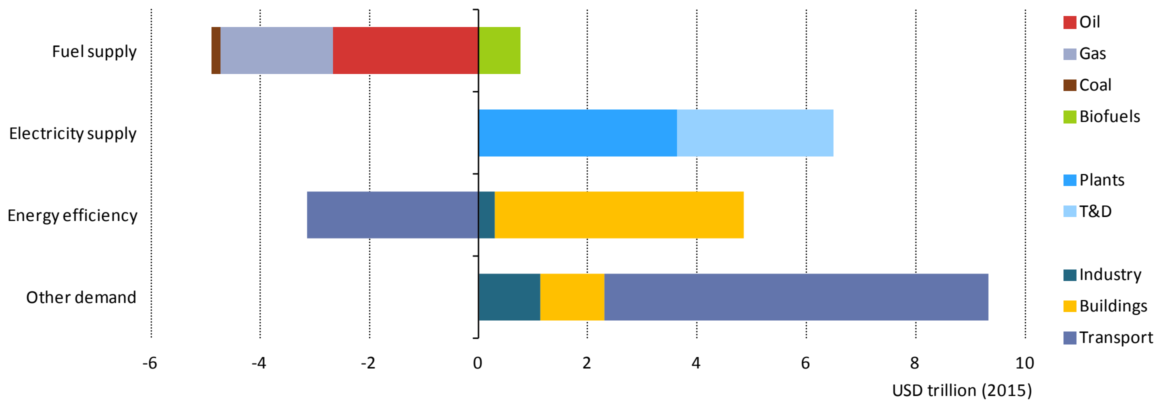
Indicator			450 Scenario		66% 2°C Scenario	
		2014	2030	2050	2030	2050
Primary energy demand	Energy intensity (toe/1 000 USD,MER)	0.192	0.125	0.082	0.120	0.077
	Carbon intensity (tonne CO_2/toe)	0.292	0.129	0.050	0.110	0.026
Power sector	Carbon intensity (gCO_2/kWh)	516	227	69	175	30
	Wind and solar PV capacity (GW)	527	2 850	5 366	3 761	7 131
Total final energy demand	Energy intensity (toe/1 000 USD,MER)	0.132	0.090	0.059	0.086	0.052
	Carbon intensity (tonne CO_2/toe)	1.81	1.53	1.12	1.38	0.65
	Share of electricity in energy demand	18%	21%	27%	23%	35%
Industry sector*	Carbon intensity (tonne CO_2/value added)	0.28	0.17	0.09	0.14	0.05
	Share of low-carbon fuels **	12%	24%	41%	29%	54%
Transport sector	Share of electric cars in car stock	0.1%	15%	47%	27%	69%
	Share of electric trucks in truck stock	0.0%	0%	0%	8%	46%
Buildings sector	Fossil fuel share in heat production***	69%	59%	47%	49%	20%
	Carbon intensity service sector (tCO_2/1 000 USD value added)	0.022	0.012	0.006	0.009	0.003

* Includes blast furnaces, coke ovens and petrochemical feedstock. ** Includes low-carbon electricity and heat and fossil fuels covered by CCS; *** Excludes traditional use of solid biomass.
Notes: MER = market exchange rate; gCO_2/kWh = grammes of carbon dioxide per kilowatt-hour.

The combination of the limited additional potential for energy efficiency, and the requirement to accelerate and deepen the reduction of carbon intensity, requires structural energy sector changes in the 66% 2°C Scenario that go well beyond those of the 450 Scenario. In the power sector, for the achievement of the 66% 2°C Scenario, the carbon intensity of electricity generation in 2050 would need to drop to less than half of the level of the 450 Scenario. This would require nearly 1 800 GW of additional wind and solar PV capacity, both for reducing the emissions intensity of electricity generation and for meeting higher electricity demand from increased electrification in end-use sectors. Much higher electrification of road transport is a key driver of higher electricity demand in the 66% 2°C Scenario, with levels for passenger vehicles considerably above those in the 450 Scenario. In addition, there would also be a need to electrify nearly half of all road freight trucks and to build the associated infrastructure including the catenary (overhead) lines needed in the 66% 2°C Scenario – a measure not required for the achievement of the 450 Scenario. Similarly, in the industry sector, the share of low-carbon fuels in total energy use would need to rise by one-third above the level of the 450 Scenario. In the buildings sector, the share of fossil fuels for residential heat supply would need to drop by almost 60% below the level of the 450 Scenario.

Achievement of the 66% 2°C Scenario requires energy sector investment of over USD 120 trillion over the period 2016 to 2050, which is around USD 14 trillion (or 13%) greater than the level of the 450 Scenario (Figure 2.10). The majority of the additional investment is required to increase the uptake of low-carbon technologies in end-use sectors above the level of the 450 Scenario, including electric cars and trucks, CCS in industry, and solar and geothermal heat supplies in the buildings sector. The rise in investment for electric cars and trucks is partially offset by lower investment needs to raise efficiency of conventional combustion engine passenger vehicles, which all but disappear by 2050 in the 66% 2°C Scenario. The second-largest additional investment is needed to accommodate a larger amount of low-carbon generation in the power sector.

Figure 2.10 • Global cumulative additional investment needs by type in the 66% 2°C Scenario relative to the 450 Scenario, 2016-50



Key message • Net investment needs in the 66% 2°C Scenario are USD 14 trillion above the 450 Scenario; the largest additional investment would be needed for low-carbon electricity supply and decarbonising end-uses.

Power sector in the 66% 2°C Scenario

The power sector is in the vanguard of the drive for decarbonisation; profound changes are already underway in many countries and this burgeoning transformation is reflected in the power system that we project in 2050 in the New Policies Scenario. Low-carbon technologies increase their share in the power mix from one-third in 2014 to more than half in 2050, led by solar and wind, and the least-efficient and often most polluting fossil-fuelled power plants are retired. The CO_2 emissions intensity of global power generation is 305 grammes of CO_2 per kilowatt-hour (gCO_2/kWh) in 2050 in the New Policies Scenario, down from 515 gCO_2/kWh today. Although electricity generation increases by more than 20 000 terawatt-hours (TWh) to meet rising demand in this scenario, annual CO_2 emissions from the power sector are only slightly higher than today, 14.6 Gt in 2050 versus the current 13.5 Gt.

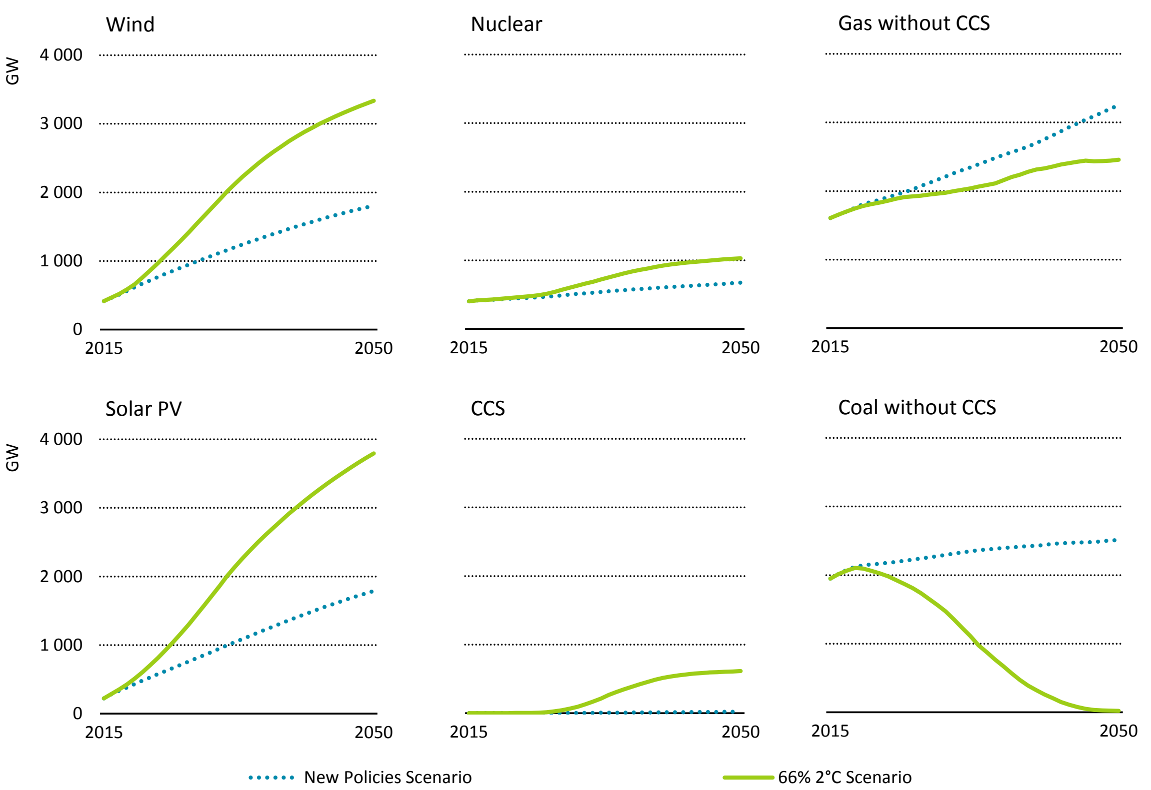
While the pace of change engendered by current and announced policies is noteworthy, it is not sufficient to achieve the level of emissions reduction required to meet climate goals. A much more ambitious track is presented in the 66% 2°C Scenario. For its achievement, the emissions intensity in the power sector would need to fall much faster and further, halved by the mid-2020s and down 95% in 2050, to around 30 gCO_2/kWh. CO_2 emissions from power generation would then decline to 1.7 Gt in 2050, delivering about 45% of the required global CO_2 emissions reduction, relative to the New Policies Scenario. The reductions in emissions and intensity in the 66% 2°C Scenario are largely driven by increasing carbon prices and strengthened policy support for low-carbon generation. But a major effort to redesign markets would also be needed, alongside rules and technologies to ensure the flexibility needed to accommodate large shares of variables renewables.

It will be imperative for electricity market designs and regulatory frameworks to evolve and assist the energy transition, particularly to enable the level of investment needed in low-carbon technologies and network infrastructure. Reforms would need to provide for the full participation of low-carbon generators in electricity markets, reflecting the value of various low-carbon technologies to the system to ensure a cost-effective transition, while also providing a degree of long-term revenue visibility to attract sufficient investment. The reliability of the power supply cannot be overlooked during the energy transition and may require market reform to ensure the adequacy of the power system (see Use of flexibility options section). The intelligent design and use of electricity network infrastructure would also be critical to managing the evolving relationship between electricity demand and supply, requiring regulatory frameworks to support the needed investment.[35]

Reshaping the power mix

Power generation capacity would take on an entirely new profile in the 66% 2°C Scenario, as policies and measures support a rapid increase in the deployment of renewables and other low-carbon technologies, reducing the need for electricity from fossil-fuelled power plants that are not equipped with CCS. To achieve the stringent targets of the 66% 2°C Scenario, by 2050, low-carbon options would need to reach more than 80% of installed capacity, with renewables making up almost 90% of total low-carbon capacity. Wind power and solar PV become the two leading technologies in terms of installed capacity in the 66% 2°C Scenario, both reaching roughly twice the level in 2050 of the New Policies Scenario (Figure 2.11). Global installed capacity of fossil-fuelled power plants without CCS plunges from 63% of the total in 2015 to 17% in 2050, as their role transitions from the foundation of the power system (as it is presently the case at a global level) to one focused on supporting the stability and reliability of the power supply.

Figure 2.11 • Global installed capacity by technology in the New Policies and 66% 2°C Scenarios



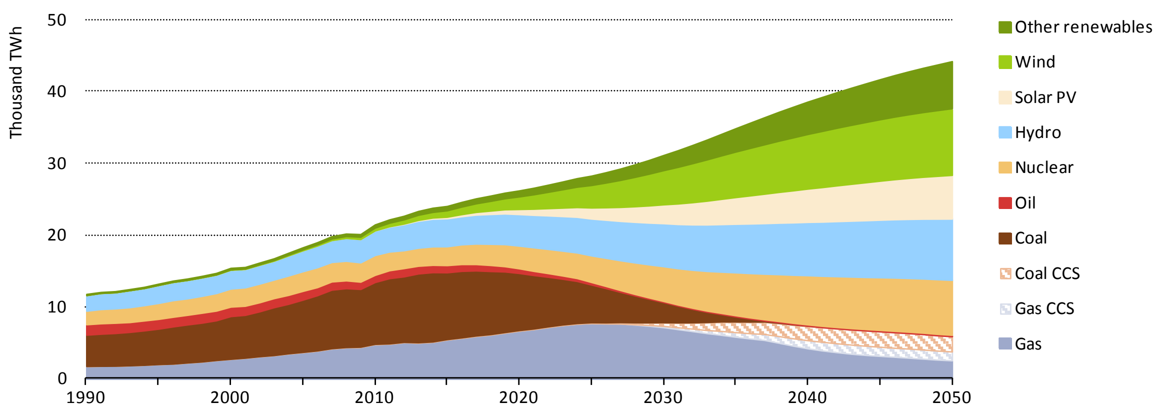
Key message • Wind and solar PV capacity would expand dramatically in the 66% 2°C Scenario, leading the decarbonisation push and replacing fossil-fuelled capacity as the foundation of the global power supply.

35 For more information on electricity market designs that support the energy transition, see the IEA's Re-powering Markets (IEA, 2016d).

Related to the evolving power plant fleet, the contribution of each source to the overall electricity supply reveals the full extent of the transition. By 2050, nearly 95% of global electricity generation in the 66% 2°C Scenario would need to come from low-carbon sources, rising rapidly from one-third today to almost 70% by 2030 (Figure 2.12). The share of renewables would need to accelerate rapidly to nearly 70% of generation in 2050, compared with 23% today. Wind and solar PV together steadily would make up an increasing share of power supply, reaching 35% by 2050. Nuclear generation would increase its share of global generation from 11% today to 17% in 2050, largely reflecting support for the technology in specific countries such as China, Korea, Russia and Japan as well as in India and the United States. This support more than offsets the reductions in other markets, including Canada and several countries in Europe. Generation from fossil fuel plants that are not abated with CCS would be substantially reduced: it is cut in half prior to 2035 and by more than 80% by 2050.

To keep pace with the overall emissions targets of the 66% 2°C Scenario, unabated coal-fired power plants, i.e. those without CCS, would need to be phased out as soon as possible. The least-efficient coal-fired power plants are phased out by 2030 in most regions, and by 2035 in all regions. In many cases, these plants are retired prior to reaching the end of their technical lifetime and, depending on the market conditions, can result in stranding a portion of the original capital investment (see Implications for stranded assets section). Existing highly efficient coal-fired plants continue to generate electricity for somewhat longer, but are almost completely eliminated by 2040 in the 66% 2°C Scenario. The required phase out of coal also means that effectively no new unabated coal-fired power plants would be built in the 66% 2°C Scenario beyond those that are already under construction today. Bridge technologies, such as efficient combined-cycle gas-fired power plants, would play an important role to drive down emissions through fuel switching from coal-fired power plants over the next decade, before falling back as the contribution from low-carbon technologies rapidly increases.

Figure 2.12 • Global electricity generation by source in the 66% 2°C Scenario

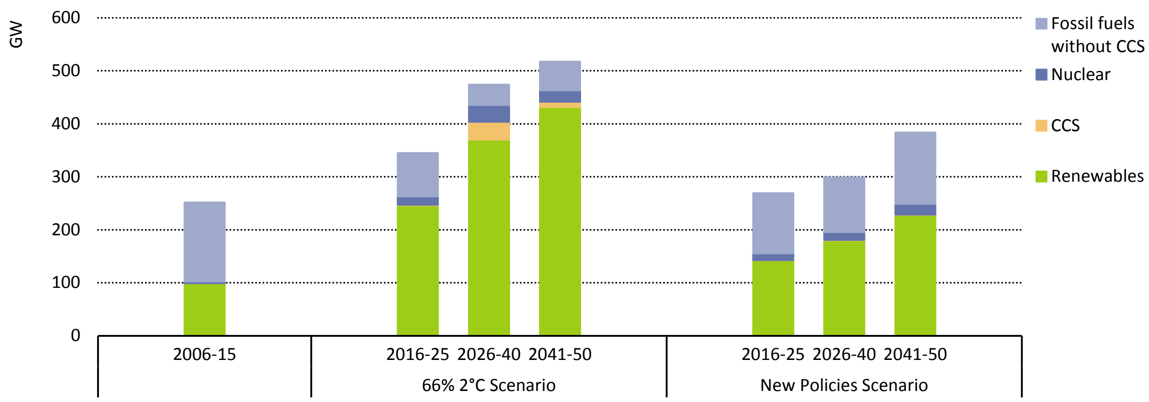


Note: TWh = terawatt-hours; CCS = carbon capture and storage.

Key message • The power generation mix undergoes a dramatic transformation to one based on renewables, nuclear and CCS, with unabated coal phased out and natural gas on the decline.

The massive build-out of renewables is critical to the low-carbon transition in the 66% 2°C Scenario and would need to occur at an unprecedented pace – going well beyond the historic rates of capacity additions and those projected based on Paris Agreement pledges (Figure 2.13). Overall, the pace of renewables-based capacity additions in the 66% 2°C Scenario would continue robustly through 2050, surpassing 400 GW per year towards the end of the period. This level is four-times the average of new capacity additions worldwide over the past ten years and close to double the average level of additions reached in the New Policies Scenario. Compared with record installations in 2015, the pace of solar PV capacity additions would need to double by 2020 and triple by 2030, reaching nearly 150 GW per year. This would also require the solar panel manufacturing capacity to dramatically increase. Alongside solar, wind power capacity additions would increase steadily to nearly 140 GW in 2030, well above the peak of 90 GW reached in 2040 in the New Policies Scenario. Beyond 2030, re-powering existing wind and solar PV projects drives continued market growth for both technologies. Hydropower also sees higher capacity additions, about 40% more than announced in the Paris pledges, helping to mitigate emissions and providing operational flexibility in electricity systems.

Figure 2.13 • Global average annual capacity additions by technology by scenario



Key message • The strong decarbonisation of the power supply requires an unprecedented build-out of renewables and other low-carbon technologies that must be sustained through 2050.

In order to achieve the emissions reductions in the 66% 2°C Scenario, nuclear and CCS technologies also would get a boost. Capacity additions of nuclear power would average 24 GW per year to 2050, similar to the average annual capacity additions during the 1980s, but 50% higher than in the New Policies Scenario. The additional growth in the 66% 2°C Scenario is led by stronger development in China, which had more than 20 GW under construction as of mid-2016, and India pursuing its goals as laid out in its NDC. Other long-time leaders in nuclear power generation also expand their fleets in this scenario, as part of their low-carbon strategies.

The achievement of the 66% 2°C Scenario would require some degree of development and deployment of CCS technologies in the power sector, which make up 8% of global electricity generation in 2050. At that point, CCS-equipped power plants would account for effectively all the remaining electricity generated from coal and one-third of the electricity from natural gas. Capacity additions of CCS-equipped power plants would average over 30 GW per year from 2026 to 2040, split between retrofits and new builds. The expansion of CCS in the 66% 2°C Scenario would be an important avenue to reduce CO_2 emissions in those countries that have a sizeable fleet of coal-fired power plants. In such cases, retrofitting coal-fired power plants with CCS equipment helps to reduce stranded assets in the power sector. The projected roll-out comes against the background of a limited number of large-scale CCS projects to date (15 across all applications as of 2016) and would also require the development of CO_2 storage resources.[36] But the development of CCS technologies for coal- and gas-fired power plants has important long-term benefits as it lays the groundwork for net-negative power plants, namely bioenergy with CCS (BECCS). This opens up the possibility of reaching more stringent climate targets beyond the level of the 66% 2°C Scenario, if sustainable biomass is available at sufficient scale (see Box 2.1

36 For more information on the current state of the industry, priorities and opportunities for CCS, see 20 Years of Carbon Capture and Storage (IEA, 2016e).

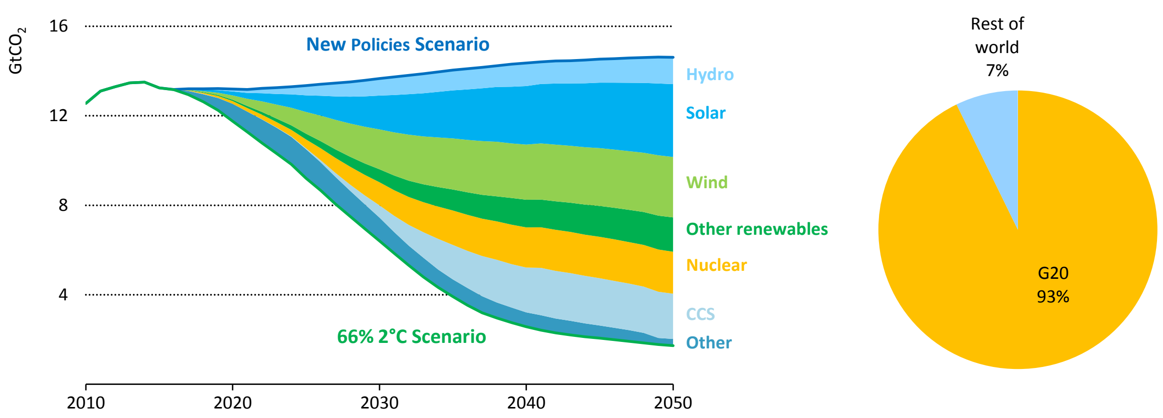
and Chapter 1). In the 66% 2°C Scenario, BECCS would start to gain momentum around 2040, in part to offset the remaining emissions from CCS-equipped fossil-fuelled power plants, on the path to net-zero emissions in the power sector. Nearly all of the build-out of CCS technologies is beyond that in the New Policies Scenario, as current and proposed policies are far less aggressive in terms of targeted CO_2 emissions reductions and available policy instruments.

CO_2 emissions abatement

Ambitious actions in the power sector would need to be ramped up right away to keep the overall climate target in sight. In the 66% 2°C Scenario, CO_2 emissions from the power sector worldwide would be less than half of current levels by 2030 and less than 15% of current levels by 2050, on the way towards zero. The G20 group, taken together, accounts for the vast majority of the emissions reductions compared with the New Policies Scenario, with many individual countries approaching net-zero emissions in the power sector by 2050.

In the 66% 2°C Scenario, renewable energy technologies taken together would account for about 60% of CO_2 emissions reduction to 2050 relative to the New Policies Scenario in the power sector (Figure 2.14). Solar PV and wind power, in particular, extend well beyond the New Policies Scenario, each accounting for about one-fifth of the total CO_2 emissions reduction from the power sector. The projections of the 66% 2°C Scenario build on recent momentum for solar PV and wind power technologies, namely driven by policy support and related cost reductions, but also due to their modular nature and short installation periods, which facilitate a rapid uptake. Additional use of hydropower, bioenergy, geothermal and concentrated solar power (CSP) contributes further to emissions reductions. Nuclear and CCS-equipped power plants account for the remaining one-quarter of emissions reduction by 2050 in the 66% 2°C Scenario, compared with the New Policies Scenario.

Figure 2.14 • Global CO_2 savings in the power sector in the 66% 2°C Scenario relative to the New Policies Scenario and the contribution of G20 group in 2050



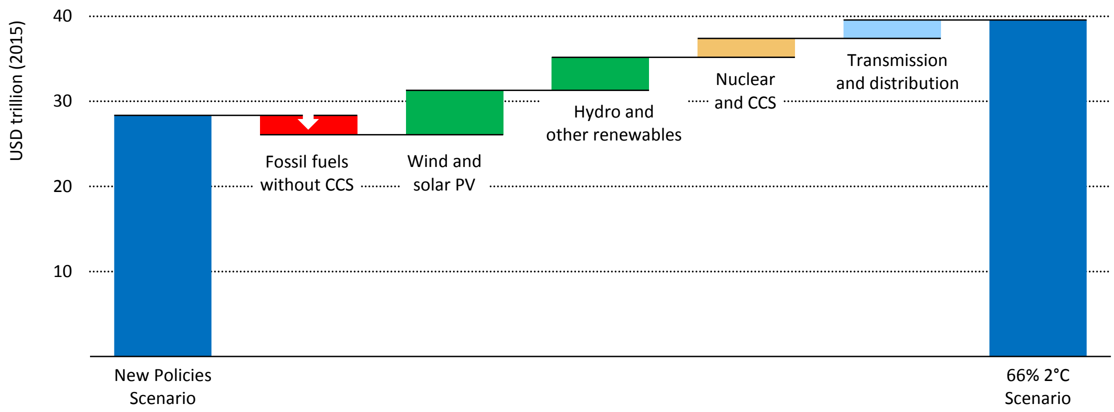
Key message • By 2050, the power sector nears full decarbonisation, with renewables taking the lead in the 66% 2°C Scenario. G20 countries would contribute the vast majority of the global CO_2 emission reductions.

Power sector investment

Cumulative investment through 2050 in the power sector would be USD 39.6 trillion in the 66% 2°C Scenario, 40% higher than in the New Policies Scenario (USD 28.4 trillion) (Figure 2.15). The majority of this increase stems from increased investment in new power generation capacity, which totals USD 25.8 trillion in the 66% 2°C Scenario, more than 50% higher than in the New

Policies Scenario. Renewables, led by wind power and solar PV, account for the largest share of the increase, with almost USD 20 trillion spent on their rapid deployment over the period to 2050. Beyond the USD 11.6 trillion spent in the New Policies Scenario, an additional USD 2.2 trillion would be needed for the necessary extensions and reinforcement of the electricity network during the energy transition, with more than 90% of the increase spent in support of the expanded use of renewables. Nuclear and CCS technologies would receive an additional USD 2.2 trillion in investment in the accelerated transition, in addition to the USD 2.2 trillion of investment in the New Policies Scenario.

Figure 2.15 • Cumulative investment worldwide in the power sector in the New Policies and 66% 2°C Scenarios, 2016-2050

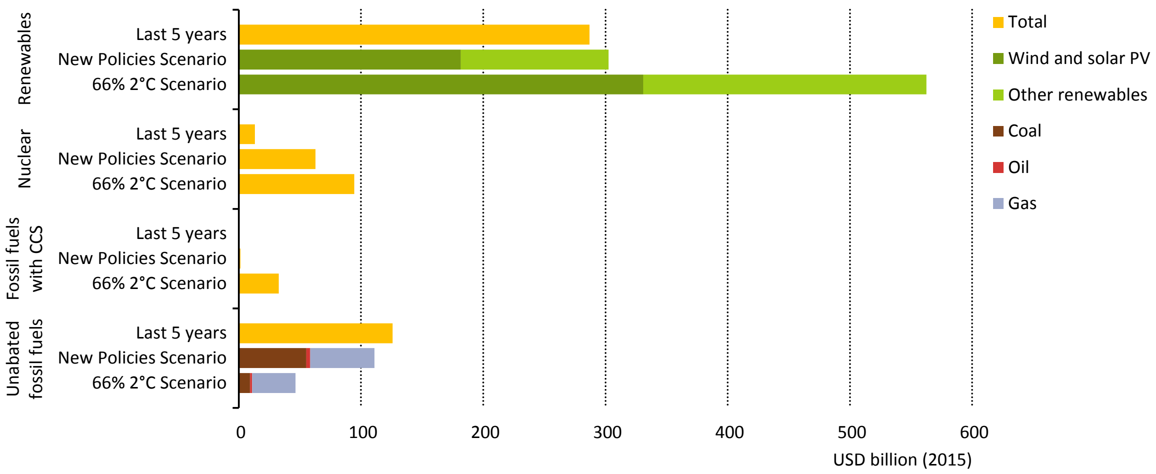


Key message • Cumulative power sector investment would need to increase by 40% in the 66% 2°C Scenario, with most additional investment going to build renewables and reinforce the grid to support them.

In the 66% 2°C Scenario, annual investment in new generation capacity peaks at about USD 900 billion in 2030, about twice the level of 2015 and USD 300 billion more than at any point in the New Policies Scenario. After 2030, annual investment steadily declines, as most systems start to approach a low-carbon power supply. The amount invested in renewables, on an average annual basis, is double the level experienced in recent years, which fuelled rapid deployment of wind and solar PV generation facilities (Figure 2.16). Annual expenditure for renewables peaks in 2030 at close to USD 700 billion. The investment represents a massive expansion of the renewable energy industry from manufacturing the equipment, e.g. wind turbine blades, PV panels and their related system components, to the sales and installation of new projects. Additional investment beyond that for new power plants will also be needed to build the industrial and manufacturing capacity for the supply of the technologies required to continue and expand their widespread deployment to decarbonise power generation.

While nuclear power and fossil-fuelled power plants equipped with CCS are important low-carbon technologies, they are less widely deployed and would need less investment than renewables in the 66% 2°C Scenario. Annual investment in new nuclear power capacity, at about USD 95 billion, is six-times more than in the past five years and 50% higher than in the New Policies Scenario. While CCS is a key technology for eventual net-negative emissions, the amount of investment required pales in comparison to that for renewables. The cumulative investment in CCS to 2050 is about equivalent to two years of average annual investment in renewables. Cumulative investment in fossil-fuelled power plants without CCS is about USD 1.6 trillion to 2050 in the 66% 2°C Scenario, 60% lower than in the New Policies Scenario. On an annual basis, this is about 40% of the average investment over the past five years (USD 130 billion).

Figure 2.16 • Recent and projected global annual average investment to 2050 in power plants by type in the New Policies and 66% 2°C Scenarios



Key message • In the 66% 2°C Scenario, average annual investment in renewables to 2050 would need to double compared with recent levels, along with increased investment in nuclear and CCS technologies.

Renewables cost and competitiveness

The unprecedented level of deployment of renewables in the 66% 2°C Scenario spurs technology improvements and process gains that enable several technologies to achieve low cost levels decades ahead of the pace set in the New Policies Scenario. Solar PV is one of the biggest benefactors of the accelerated transition and moves quickly down the cost curve. The global average capital costs of utility-scale solar PV fall by 50% by 2030 and reach an average cost level of USD 800 per kilowatt (kW), which is 20 years earlier than in the New Policies Scenario (Figure 2.17).[37] These reductions are in addition to the 40-75% cost declines seen in major markets since 2010. Cost reductions are also accelerated for other renewable energy technologies that are not yet fully mature, including offshore wind power and CSP. Both technologies achieve cost reductions of 40% by 2030, relative to today, two decades prior to reaching similar cost levels in the New Policies Scenario. The use of CCS technologies is stepped up in the 66% 2°C Scenario, supported by strong cost reductions through targeted research, development, demonstration and deployment.

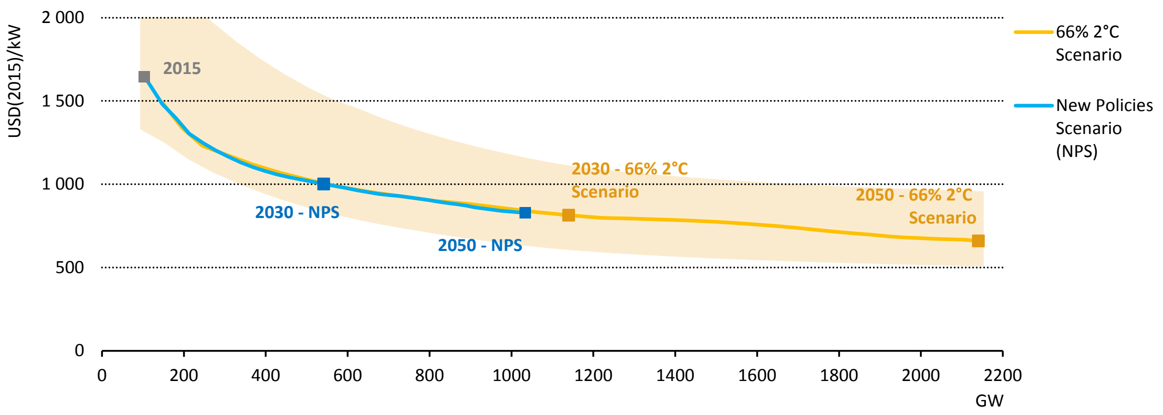
The rapidly falling costs of renewables improve their competitiveness with fossil fuels, especially in the 66% 2°C Scenario, where CO_2 prices are on the rise. Comparing the levelised cost of electricity (LCOE) from new power plants[38] indicates that the balance currently still tilts in favour of fossil fuels (Figure 2.18). However, recent auction bids in several markets suggest that renewables, particularly solar PV, are rapidly closing the gap with fossil fuels. By 2030, in the 66% 2°C Scenario, the balance for new projects clearly shifts towards renewables, helped by regional CO_2 prices that range from 50 to 150 USD per tonne of CO_2 emissions (USD/tCO_2). Beyond 2030, CO_2 prices continue to rise, further widening the gap of LCOEs between renewables and fossil fuels. The widening gap also helps new renewable energy projects to displace output from

37 For information on power plant cost assumptions, renewable energy technology learning rates and projected costs, see the Investment costs section of the World Energy Outlook website: www.worldenergyoutlook.org.

38 The LCOE is an indicator of the average cost per unit of electricity generated by a power plant, representing the minimum average price at which electricity must be sold for a project to "break even", providing for the recovery of all related costs over the economic lifetime of the project. The LCOEs presented reflect the full technology costs, based on a consistent set of assumptions designed to enable technology cost comparisons and contribute to the evaluation of competitiveness (when combined with value estimates).

existing coal- and gas-fired power plants, essential to achieving the deep power sector emissions reductions.

Figure 2.17 • Global average capital cost of utility-scale solar PV relative to installed capacity in the New Policies and 66% 2°C Scenarios

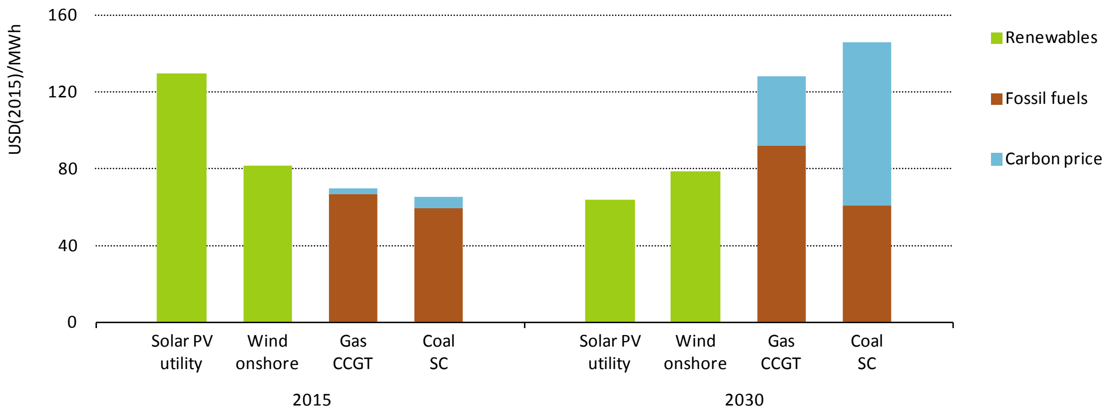


Key message • The accelerated deployment of solar PV in the 66% 2°C Scenario helps to achieve strong cost reductions by 2030, 20 years ahead of the schedule set in the New Policies Scenario.

While relative costs are an important consideration, the extent to which market forces contribute to the energy transition depends on the ability of renewables and other low-carbon technologies to attract investment without direct support. Gaining this fuller picture of competitiveness requires consideration of both the costs and value of technologies. In practice, this means that variable renewables – mainly wind power and solar PV – may need to reach lower LCOEs than fossil fuelled power plants in order to attract investment without government support. In addition, competitiveness can be a moving target, due to the fact that the market value of variable renewables declines as their share of the power mix increases.[39] In the presence of a rising CO_2 price, a declining market value also signals a lessening ability to mitigate CO_2 emissions, a motivating purpose for their deployment in the first place. Among low-carbon technologies, consideration of value tends to lead to more technology diversity. Some renewable energy technologies – including some forms of hydropower, bioenergy and CSP – are well-suited to shifting their output when it is most needed, a trait that becomes increasingly valuable over time in the 66% 2°C Scenario. As a result, while important, cost comparisons alone are insufficient to inform a cost-effective path to reduce emissions. The continued appeal of variable renewables therefore hinges critically on the flexibility of the electricity system, including demand-side response. These measures help make the best use of the varying output of wind and solar PV installations, aligning electricity demand with the available supply of electricity in real-time, which is the opposite of the conventional practices in the power sector today.

39 For more in-depth discussion of the competitiveness of renewables, see the special focus on renewable energy in *World Energy Outlook 2016* (IEA, 2016a).

Figure 2.18 • Global average levelised cost of electricity in the 66% 2°C Scenario



Notes: CCGT = combined-cycle gas turbine; SC = supercritical. Fossil fuel and carbon prices vary by region – the midpoint was taken as the basis for the LCOE calculations.

Key message • Renewable energy technologies beat fossil fuels on costs alone prior to 2030, as their costs fall and fossil-fuelled power plants become more expensive due largely to increasing CO_2 prices.

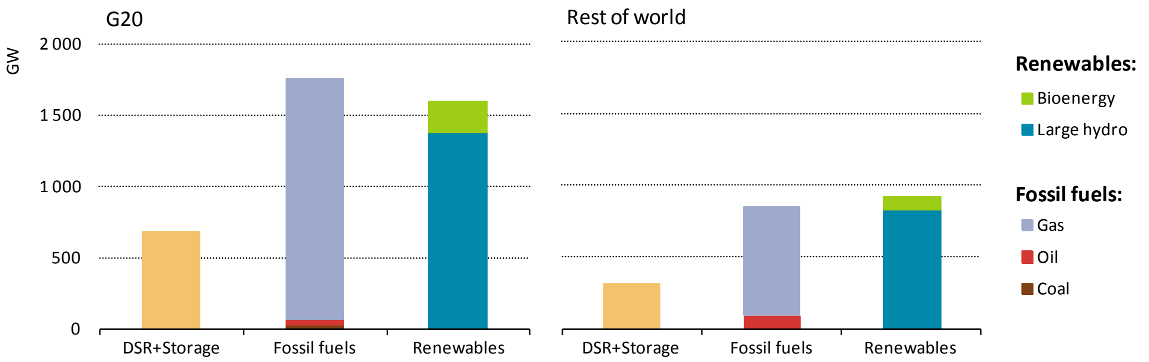
Use of flexibility options

The security and reliability of power systems depend to a high degree on the real-time balance of the demand and supply of electricity. Achieving this match and keeping the lights on requires the supply or demand of electricity, or both, to be flexible. To date, flexibility has almost exclusively been provided on the supply-side through the adjustable output of power plants. Fossil-fuelled power plants and hydropower have historically provided the bulk of flexibility in systems, with additional contributions from other technologies such as bioenergy-based and nuclear power plants (in specific markets).

In the 66% 2°C Scenario, demand-side technologies and energy storage become increasingly crucial to ensuring the security and reliability of the electricity supply. Hydropower continues to provide flexibility throughout the period to 2050, but as emissions get significantly reduced, the operations of fossil-fuelled power plants would need to be reduced to the maximum extent possible. In their place, demand-side response options and energy storage technologies would be needed to effectively balance supply and demand, while integrating increasing amounts of electricity generated from variable renewable energy technologies. By 2050, solar PV and wind power represent 35% of global power generation, with higher shares in many regions, including the United States, European Union and India. To integrate such large shares of variable renewables, we estimate that more than 990 GW of flexibility would be needed from demand-side response measures and energy storage. In particular, G20 countries rely heavily on these flexibility measures (representing 680 GW) in the 66% 2°C Scenario to integrate higher shares of variable renewables and limit the use and related emissions from fossil-fuelled peaking power plants (Figure 2.19).[40]

40 For more in-depth discussion of the integration of variable renewables and the role of flexibility options in the outlook, see the special focus on renewable energy in *World Energy Outlook 2016* (IEA, 2016a).

Figure 2.19 • Flexibility options to ensure the reliability of electricity supply in the 66% 2°C Scenario, 2050



Key message • Demand-side response options and energy storage are required alongside flexible power plants to successfully integrate rising shares of variable renewables, especially in G20 countries

Electricity market designs, in addition to enabling investment in low-carbon technologies and the network, will be critical to supporting an expanding suite of flexibility options, including demand-side response measures and energy storage. One area for reform is to allow market participation for all forms of flexibility, enabling wider competition across technologies that span both the supply- and demand-sides of the power system. Another critical element is the potential for additional revenue streams to supplement revenues for energy sold to the grid, reflecting the value of flexibility and contributions to the reliability of the system. Doing so would support the deployment of all forms of flexibility, including demand-side response measures and energy storage, as well as preventing important providers of flexibility (such as gas-fired power plants) from retiring early and potentially increasing the cost of the transition due to stranded assets. This transition has already started in some wholesale electricity markets, where methods to provide additional revenue streams, including capacity mechanisms, are being tested as a means of incentivising essential investment. Without market access and additional revenue streams, the necessary investments in the flexibility of the power system may not be forthcoming and, in turn, threaten the overall security of the electricity supply.

End-use sectors in the 66% 2°C Scenario

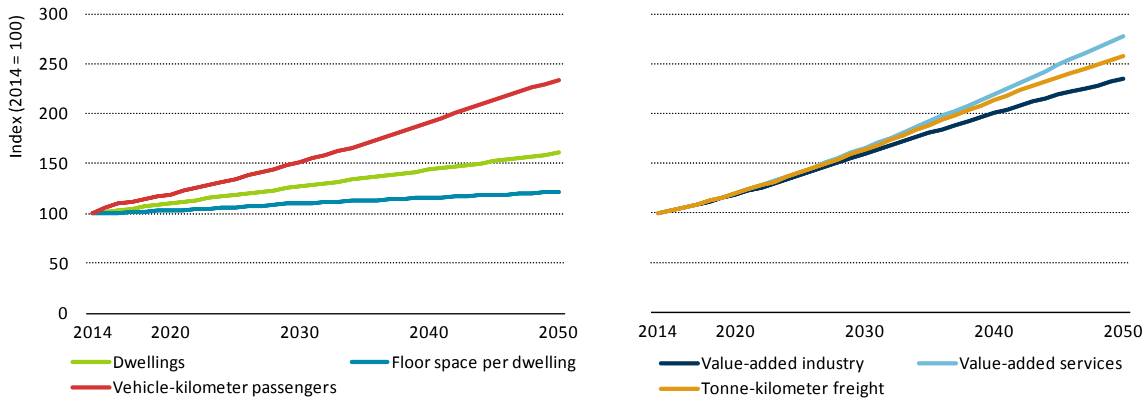
Overview

The world's need for energy is driven by demand for energy services across the various end-use sectors, the main ones being industry, transport and buildings.[41] The industry sector is an important engine of economic growth and is responsible for almost 40% of final energy demand today. The transport sector encompasses personal as well as commercial activities by roads, airplanes, ships and rail, and requires energy, in particular oil, for doing so. Transport accounts for 27% of final energy demand today, and, notably for the topic of this analysis, for almost 40% of direct fossil fuel use in end-use sectors. The buildings sector encompasses residential, commercial and public buildings and is responsible for nearly one-third of final energy demand today, and, importantly, for over half of global electricity demand.

41 Energy end use is the sum of consumption by the various end-use sectors: industry (including manufacturing and mining, blast furnaces and coke ovens, and petrochemical feedstocks); transport (including for individual and commercial purposes); buildings (including residential and services) and other (including agriculture and non-energy use).

With rising economic and population growth, demand for energy services from all end-use sectors is expected to continue to grow through 2050 (Figure 2.20). [42] Economic growth implies rising industrial output in monetary terms at an aggregated level, although deep structural changes are expected to occur over the next decades. Demand for mobility is also set to rise, both for individual and commercial activities, particularly in developing countries. Rising population and income are also expected to continue to push up demand for modern energy services in the buildings sector, such as water heating, lighting, air conditioning and the electricity required to power an increasing range and number of appliances.

Figure 2.20 • Outlook for socio-economic (left) and economic (right) drivers in the 66% 2°C Scenario



Key message • Activity levels across all end-uses are expected to rise steadily, pointing to rising demand for energy services.

In all of these respects, G20 countries will continue to play a key role in setting global trends. With an expected share of 75% in global GDP growth, this diverse set of countries will also see some of the strongest increase for energy services. Over the period to 2050, 60% of growth in global floor space in residential buildings is projected to be in G20 countries; around three-quarters for growth in demand for personal mobility[43] and in value added from the industry sector.

Table 2.7 • Energy intensity improvement by sector and region in theNew Policies and 66% 2°C Scenarios

Sector	New Policies Scenario		66% 2°C Scenario	
	G20	Rest of World	G20	Rest of World
Industry	-54%	-36%	-66%	-55%
Transport	-57%	-52%	-74%	-72%
Buildings	-58%	-54%	-70%	-62%

Note: Energy intensity refers to the total sectoral energy consumption divided by GDP in PPP terms.

Policy efforts to curb the growth in energy demand in end-use sectors have been ramping up in recent years. Recent IEA analysis shows that efficiency-regulated energy use in 2015 covered 30% of global final consumption and that the average stringency of regulation has increased by 23% since 2005 (IEA, 2016f). This is notable and energy efficiency measures, together with structural effects within the industry sector and across the economy as a whole, continue to constrain the

42 Assumptions for economic and population growth are the same across the IEA scenarios in this study. For further analysis of the macroeconomic implications of the IEA scenarios, see OECD (forthcoming).

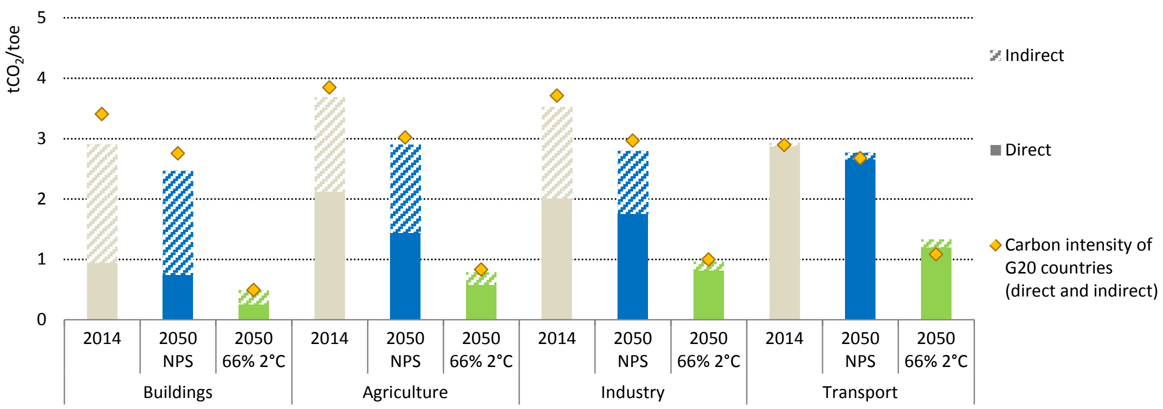
43 Measured in vehicle-kilometres driven by passenger cars.

level of growth projected in the New Policies Scenario, bringing down the energy intensity of the various sectors (Table 2.7). Nonetheless, energy demand across end-use sectors still increases by around 40% by 2050 in the New Policies Scenario and the improvement in energy intensity falls short of what would be required to achieve the 66% 2°C Scenario.

The intensity with which we use energy, relative to economic growth or other activity variables is a useful yet imperfect aggregate measure of efficiency. The intensity with which we emit carbon, relative to energy consumption, is another critically important indicator of the energy transition. Today, on a global level, energy use in final consumption is associated with around 3 tonnes of CO_2 per tonne of oil equivalent use (directly or indirectly), reflecting the current high dependency on fossil fuels in all end-use sectors: coal (particularly in industry), oil (particularly in transport) and natural gas (particularly in buildings) and the generally carbon-intensive nature of fuels used to generate electricity and heat in most countries (Figure 2.21). Existing and planned policies, as considered in the New Policies Scenario, point to important improvements. The carbon intensity of final consumption in the New Policies Scenario drops by around 15% to 2050, to which the projected shifts in the fuel mix towards lower carbon fuels for power and heat production also contribute.

But much more would be needed in the 66% 2°C Scenario: by 2050, the carbon intensity of the buildings sector would need to be reduced by another 80% below the level of the New Policies Scenario; by two-thirds in the industry sector; by half in transport and by more than 70% in agriculture. In the 66% 2°C Scenario, such improvements would bring down the direct CO_2 emissions of all end-use sectors combined dramatically: by 2050, emissions would be three-times lower than today. Indirect CO_2 emissions would also drop, by a factor of seven, as the CO_2 content of electricity generation falls by a factor of more than 15 on a global average, relative to today.

Figure 2.21 • Global carbon intensity by sector in the New Policies and 66% 2°C Scenarios



Notes: toe = tonnes of oil equivalent; NPS = New Policies Scenario.

Key message • Existing and planned policies lead to a drop in carbon intensity, but much more radical improvements would be needed to achieve the 66% 2°C Scenario.

A drop in carbon intensity of the scale needed for the 66% 2°C Scenario would require a deep transformation in the way demand for energy services is met across all end-use sectors. Radical energy efficiency improvements (e.g. drastically raising the retrofit rates of buildings, better electric motors in industry, appliances in buildings, boilers in industry and buildings, and fuel economy standards in transport) are critical in the short term. These would need to be accompanied by major structural changes in the way industrial processes are designed in order to improve material efficiency (e.g. through the re-use of post-consumer scrap in iron and steel production, increased recycling and light-weighting in chemicals, petrochemical, and pulp and paper). In combination, these measures would essentially stabilise global final energy consumption (compared with a 2.2% annual growth since 2000) in the 66% 2°C Scenario. In aggregate, G20 countries would register a decline in final energy consumption, so that, by 2050, this returns to the level seen in 2009.

Achieving the emissions reductions required in the 66% 2°C Scenario would require not only efforts to curb demand, but also profound changes in the way that demand is met. In practice, this means major efforts to reduce the direct use of fossil fuels, notably by increasing the use of renewable technologies, where relevant and possible (e.g. biomass boilers in industry, solar water heaters in buildings, biofuels in transport), and by increasing the electrification of heat supply and road transport vehicles (e.g. replacing boilers by heat pumps, increasing the penetration of electric passenger and freight vehicles).[44]

Such transformative actions would fundamentally change the fuel mix: in the 66% 2°C Scenario, the share of coal in final energy demand would drop from 14% today to 6% in 2050 and the share of oil from 38% today to 17% (Table 2.8). Only natural gas retains about its current share, reflecting its importance in the industry sector and potential role to reduce emissions from international shipping. In addition, reducing the carbon intensity of the industry sector requires large-scale deployment of CCS in the 66% 2°C Scenario.

Table 2.8 • Global final energy demand by fuel in the 66% 2°C Scenario

Mtoe	2014	2020	2030	2040	2050	CAAGR* 2015-50	Difference in 2050 to NPS**
Coal	1 407	1 347	1 064	770	601	-2.3%	-869
Oil	3 740	3 843	3 264	2 404	1 687	-2.2%	-2 839
Gas	1 423	1 536	1 527	1 435	1 383	-0.1%	-1 138
Electricity	1 710	1903	2 319	2 917	3 366	1.9%	99
Heat	274	295	290	277	266	-0.1%	-45
Bioenergy***	1 157	1 237	1 497	1 705	1 855	1.3%	494
Other renewables	37	78	242	433	563	7.9%	340
Hydrogen	0	0	4	13	21	n.a.	20
Total	**9 747**	**10 240**	**10 208**	**9 955**	**9 741**	**0.0%**	**-3 938**
% fossil fuels in TFC	*67%*	*66%*	*57%*	*46%*	*38%*		*-25%*
% renewables in TFC+	*8%*	*11%*	*22%*	*34%*	*44%*		*27%*
% low-carbon heat demand++	*9%*	*12%*	*25%*	*43%*	*55%*		*37%*
Memo: *% low-carbon electricity supply*	*33%*	*41%*	*68%*	*89%*	*94%*		*43%*

*Compound average annual growth rate. **New Policies Scenario. *** Includes traditional and modern use of solid biomass. + Includes indirect renewables contributions, excludes traditional use of solid biomass. ++ Includes indirect renewables contributions and fossil fuels covered by CCS, excludes traditional use of solid biomass. Note: TFC = total final consumption.

At a sectoral level, the transformation of final energy use in the 66% 2°C Scenario requires success in overcoming two major policy and technology challenges that remain unresolved in the

44 Activity levels could also be part of policy actions. For example more public transport could move demand for mobility from private to public (IEA, forthcoming).

New Policies Scenario: decarbonising the transport sector and heat production. Transport accounts for less than 30% of final energy demand today, but contributes a disproportionally high share of direct CO_2 emissions (around 45%). This reflects the continued reliance on oil-based fuels in most transport modes, such as road, aviation and shipping; the exception being rail where electricity constitutes nearly 40% of energy demand. Alongside a near-term push to dramatically reduce the fuel consumption of conventional vehicles across all transport modes, the main means to decarbonise transport in the 66% 2°C Scenario are a deep electrification of road transport (including passenger and freight vehicles) and a substantial uptake of advanced biofuels in aviation and shipping. By 2050, nearly 60% of all fuels in the transport sector would need to be low carbon (from 3% today).

Box 2.4 • Smart Cities: Opportunities to start from scratch

The world's population will grow by one-third by 2050, mostly in emerging and developing countries and will be concentrated in cities. The United Nations estimates that an additional 2.5 billion people will live in urban areas by 2050, 6.4 billion in total. This has enormous implications for the long-term outlook for energy, as the rapid socio-economic development in urban areas affects people's lifestyles: demand for personal mobility, appliances and space cooling equipment rises, among others. If trends continue along historic patterns, it risks amplification of common urban problems such as congestion, accidents and air pollution. But increasing urbanisation also creates opportunities for policy makers in developing countries to foster improved urban conditions with effective efficiency standards for buildings and more efficient ways to satisfy mobility demand by establishing "smart cities".

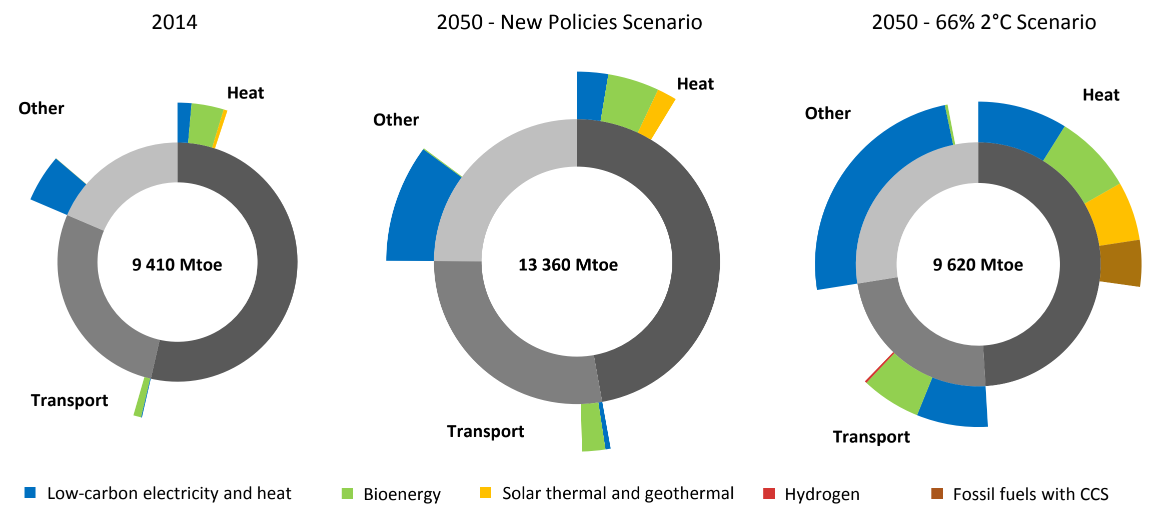
Smart cities can improve services such as energy, water and waste management through the installation of smart meters and using waste to produce energy. Through digitalisation of the energy sector, they can also contribute to efficiently managing energy services in buildings, as well as mobility. Planning for smart cities is also a good opportunity to compare options to meet heating and cooling demand in buildings. For example, with sufficient density of demand, district heating and cooling can be a viable option. However, district systems have high capital costs and long payback periods, meaning that their design as a component of urban planning needs to be effectively integrated. District cooling using ice storage is an additional storage option for the power sector as a flexible means to integrate high shares of variable renewables.

Effective urban planning also can help to curb transport energy demand growth by facilitating "smart mobility". Early co-ordination between urban and traffic planners is important, in particular where the development of a public transport system is envisaged, but also because it can help to ensure that dedicated spaces for pedestrians and public transit networks are available. Smart mobility goes beyond the use of information and communication technologies to optimise traffic flows. Improving awareness is also vital as smart transport depends on the sharing of best practice behaviours. Innovative transport solutions such as collective taxis, car sharing or car-pooling that show promise and can ease traffic congestion and the need for parking. But smart cities require significantly more effective approaches to shift modes to walking, cycling and public transportation – elements which go beyond the analysis in the 66% 2°C Scenario.

"Smart cities" programmes have already been launched in some countries. For example, in 2015 India set out the "Smart Cities Mission". China has established over 285 pilot "Smart Cities" and Japan has launched its "Future City" programme in 2011.

Heat demand in the buildings and industry sectors represents around half of total final energy consumption today (Figure 2.22). Heat demand is currently linked to 9.7 Gt of direct CO_2 emissions from fuel combustion and 2.7 Gt of indirect CO_2 emissions from electricity and district heating, or almost 40% of total energy sector emissions. In the buildings sector, heat is needed mainly for space and water heating as well as cooking. In the industry sector, it is used in a large variety of processes. The nature and scale of heat demand varies significantly between countries. These differences relate to climatic conditions; efficiency of the buildings stock and heating equipment; level of economic development and access to modern energy services; and availability of fresh water and industrial structure. Heat demand can directly or indirectly be satisfied by various fuels: fossil fuel combustion in boilers and stoves; the use of electricity and heat from district heating (which are indirectly linked to CO_2 emissions); and renewables (bioenergy, solar thermal, geothermal). In the 66% 2°C Scenario, increasing the share of near zero-energy buildings in new constructions to 40% (from 1% today) and mandates for stringent retrofits of the entire stock by 2050 would be the key means to reduce heat demand in buildings. In addition to further strong improvements to the efficiency of conventional boilers, the wider use of low-carbon technologies (e.g. biomass boilers in industry, solar water heaters in buildings) and the expanded use of electricity to meet heat demand would increase the low-carbon share to more than half of heat demand in 2050 compared to less than 10% today (Figure 2.22). This share would be considerably higher than in the New Policies Scenario, where low-carbon technologies satisfy less than 20% of heat demand by 2050.

Figure 2.22 • Global final energy consumption by end-use and fuel in the New Policies and 66% 2°C Scenarios



Note: The category "Other" includes final energy consumption in industry, buildings and agriculture excluding heat.

Key message • The uptake of low-carbon technologies across all end-uses would need to rise significantly over existing efforts to meet the challenges of the 66% 2°C Scenario.

Box 2.5 • Hydrogen: Panacea to achieve a broader energy transition?

The fuel mix in global energy supply in the 66% 2°C Scenario in 2050 would differ dramatically from today's mix. Overall the energy sector would switch away from fossil fuels, their share in primary energy demand would fall to less than 40% by 2050, compared with 81% today. But this transition would be more than just a shift from one fuel to another; it would require entirely new ways of making the energy system work. At its essence, a shift from a stock-system to a flow-system would be needed, bringing about challenges to the way energy systems operate. While electricity is the main energy carrier that facilitates the transition in the 66% 2°C Scenario, there could be alternative routes towards a deeply decarbonised energy system, one option being wider hydrogen uptake.

Like electricity, hydrogen needs to be produced from low-carbon fuels to be considered a low-carbon energy carrier. Hydrogen can serve multiple purposes along the entire energy sector value chain on a pathway to decarbonisation. For example, a high share of variable renewables in the power sector requires development of demand-side response measures and storage at scale for its successful integration. Hydrogen could serve as storage ; it is currently the storage technology with the longest possible duration until full discharge (besides pumped hydropower), which could enable seasonal storage of electricity.

The use of hydrogen as a storage option for electricity could facilitate the energy sector transition towards the use of more renewables in electricity generation. But hydrogen could play a much wider role and support the low-carbon transition also in the end-use sectors, in particular for transport, chemical synthesis (e.g. associated with CCU[45] in methanol production) or heat production in industry (and, to a lesser extent, in buildings). In transport, electrification is the main route assumed in the 66% 2°C Scenario to phase out the use of oil in cars and trucks. But the use of electricity for road transport, in particular for trucks, still faces significant barriers, such as driving range. Hydrogen is not limited in this respect and could be an alternative. In addition, some means of heat production (mainly in the industry sector) cannot switch from fossil fuels to renewables and electricity because of the need for very high temperatures. Hydrogen could play a complementary role here, either by partially substituting for natural gas in the distribution network or by producing a synthetic gas. In addition, in the buildings sector, electricity and low-temperature heat could be supplied in a decentralised way through a combination of an electrolyser with a fuel cell, so that excess heat released by the fuel cell while producing electricity can be used to meet buildings heat demand.

In the 66% 2°C Scenario, hydrogen contributes only around 1% of final energy demand by 2050, mostly in demonstration projects in transport. The immature level of hydrogen technology *vis-à-vis* other low-carbon options, high upfront investment costs and the lack of available infrastructure are key factors for this modest contribution. Significant further technology development would be necessary on the supply and demand-sides for the hydrogen option to become widespread. Cost related to hydrogen technologies (e.g. electrolysers, fuel cells, tanks) have declined over the last decade and technology performance has improved. But much deeper cost cuts and more support for the technology roll-out would be required if the potential benefits of hydrogen are to play a more central role in reaching climate goals.

Recently 13 companies formed the “Hydrogen Council” and are planning to spend around USD 10 billion in the next five years on hydrogen-related technology.[46] But R&D spending would need to be much larger for hydrogen to play a mainstream role in the energy transition. Hydrogen has been part of the IEA Technology Collaboration Programme for the past 40 years, with the aim to accelerate hydrogen implementation and widespread use. In 2016, 29 projects in France were selected to be supported by public funding under the “hydrogen territory” call for proposals process. These projects aim to demonstrate the technical feasibility of hydrogen on a territorial scale and include hydrogen mobility as well as production. Japan’s ENE-FARM programme has supported the deployment of around 140 000 residential fuel cell units. Japan aims to deploy 1.4 million residential units by 2020 and 5.3 million by 2030.

Electrification is a key mechanism to accelerate the decarbonisation of end-uses in the 66% 2°C Scenario. Energy efficiency can reduce, but not eliminate energy demand growth, and renewables cannot provide all heat and transport fuel needs due to resource constraints (e.g. bioenergy) and technology limitations (e.g. solar thermal for high temperature industrial applications). As the power sector decarbonises, electricity gradually becomes a low-carbon energy carrier. This makes the use of low-carbon electricity an integral part of the decarbonisation pathway of the 66% 2°C Scenario; the share of electricity in end-use energy demand rises above the level seen in the New Policies Scenario (Table 2.9). The largest change

45 CCU = carbon capture and use using CO_2 as a raw material.

46 http://hydrogeneurope.eu/wp-content/uploads/2017/01/20170109-HYDROGEN-COUNCIL-Vision-document-FINAL-HR.pdf.

occurs in the transport sector, where passenger and freight transport are electrified at scale. Average GDP per capita outside the G20 group is projected to remain around 40% below that the G20 average in 2050. For this reason, the market penetration of new or innovative technologies with higher upfront investment costs (including those that rely on electricity) is expected to be generally faster in the G20 group in the 66% 2°C Scenario.

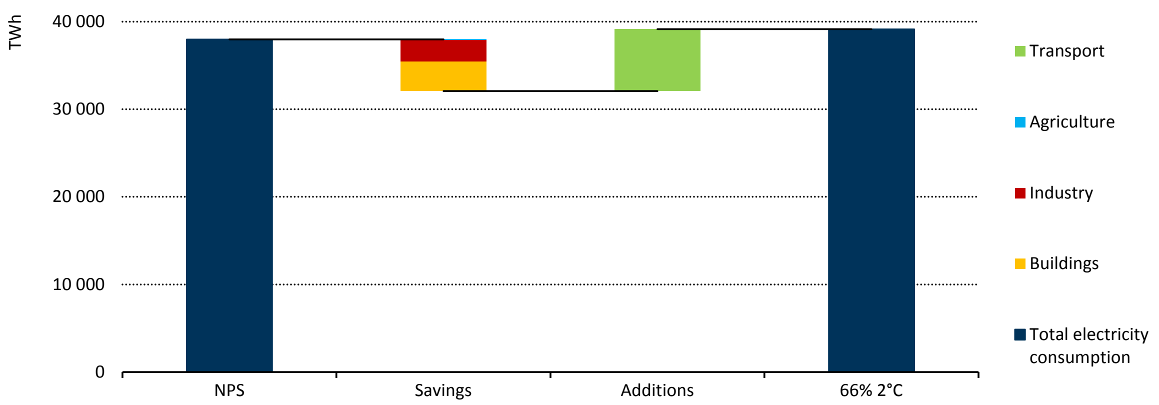
Table 2.9 • Electrification of end-use sectors in the New Policies and 66% 2°C Scenarios

Sector	Indicator	2014		New Policies Scenario		66% 2°C Scenario	
		G20	Rest of world	G20	Rest of world	G20	Rest of world
Industry	Share of electricity in TFC	20%	18%	24%	19%	26%	22%
	Share of electricity-based heat supply	*3%*	*3%*	*6%*	*4%*	*11%*	*9%*
Transport	Share of electricity in TFC	1%	0.6%	5%	1%	43%	30%
	Share of electric vehicles in total PLDVs	*0.1%*	*<0.1%*	*11%*	*5%*	*72%*	*53%*
Buildings	Share of electricity in TFC	33%	19%	50%	34%	55%	40%
	Share of electricity for space heating	*13%*	*11%*	*18%*	*16%*	*22%*	*28%*

Notes: TFC = total final consumption; PLDVs = passenger light-duty vehicles.

A strong increase of electrification would not necessarily be associated with higher electricity demand. Even if the increased use of heat pumps and electric boilers in the buildings sector leads to higher electricity consumption to meet heat demand in some regions, energy efficiency and electricity savings for other applications mean that electricity use in buildings in the 66% 2°C Scenario would be around 15% lower relative to the New Policies Scenario (see Buildings section). Similarly, in the industry sector, the share of electricity-based heat supply would grow, but overall electricity demand would be lower than in the New Policies Scenario. At a global scale, in 2050 in the 66% 2°C Scenario, electricity demand would be only 3% higher than in the New Policies Scenario, as the reduction in buildings and industry would be offset by increases in the transport sector (Figure 2.23).

Figure 2.23 • Global change in electricity demand by sector in the 66% 2°C Scenario relative to the New Policies Scenario, 2050



Key message • Electrification in 2050 rises across end-use sectors, but more efficient electricity use in industry and buildings means that additional electricity demand is diluted.

Industry

The decarbonisation challenge of the industry sector in the 66% 2°C Scenario is stark. It would require targeted measures that are integrated and tailored to a multitude of industrial activities. To meet the ambition of the 66% 2°C Scenario, a wide array of low-carbon technologies and processes would need to be adopted at a faster pace and larger scale than ever before, setting industrial production activities globally on a radically different path of development (Table 2.10). The transformation depicted in the 66% 2°C Scenario is spurred by carbon prices in all regions on the order of USD 80 - 190 per tonne of CO_2 in 2050, alongside other policy measures such as mandatory energy management systems, minimum energy performance standards, inter-regional energy intensity targets per sector and policies that support the ambitious early adoption of CCS, which is central to the achievement of the industry sector's decarbonisation goals.

In the 66% 2°C Scenario, energy demand in the G20 region would decouple from the rise in industrial production, with the region's aggregate industrial energy demand starting to decrease by the mid-2020s. This trend is sharply different from the one in the New Policies Scenario, where industrial energy use keeps rising throughout the projection period. In the 66% 2°C Scenario, many G20 economies, including China, would see energy demand from industry peak by 2020, although in others, notably India and Indonesia, it continues to rise through 2050.

The trend in industrial energy demand in the 66% 2°C Scenario reflects a combination of measures: material efficiency, which reduces material needs to provide the same service; energy efficiency, which reduces energy demand; and changes in production routes. Increased material efficiency, a relatively low cost strategy, requires some changes to industrial processes (e.g. light-weighting of products such as plastic bottles, paper and cars) and consumer behaviour (e.g. increased recycling and re-use of materials).[47] The implications of improved material efficiency for energy consumption vary by sector: in the G20 region, in 2050, it has the effect of reducing production levels by approximately 20% in steel, 10% in aluminium, 7% in cement, 3% in paper and 5-15% in high-value chemicals.

Electrification with low-carbon electricity is a key decarbonisation option in the 66% 2°C Scenario. In G20 countries, electricity demand to provide industrial heat would triple by 2050 (Figure 2.24). Heat pumps, to provide low-temperature heat, would be responsible for over 80% of this increase. Most heat pumps are used in the less energy-intensive industries, such as food processing and textiles, and in the chemicals and petrochemicals sector. This would be a considerable change from current patterns of industrial heat provision: today, most low-temperature heat is supplied from fossil fuel boilers, while the use of heat pumps is very limited. Although heat pumps would only account for about 15% of total electricity demand in the industry sector in G20 countries by 2050 in the 66% 2°C Scenario, the electricity consumption of heat pumps at the global scale would nevertheless be twice the level of total electricity demand in Japan in that year. Overall, total electricity demand for heat in industry would be 30% higher in 2050 in the 66% 2°C Scenario than in the New Policies Scenario in the G20, and the uptake of heat pumps three-times higher.

47 A detailed study of the material efficiency in energy-intensive industries is presented in the *World Energy Outlook 2015* (IEA, 2015).

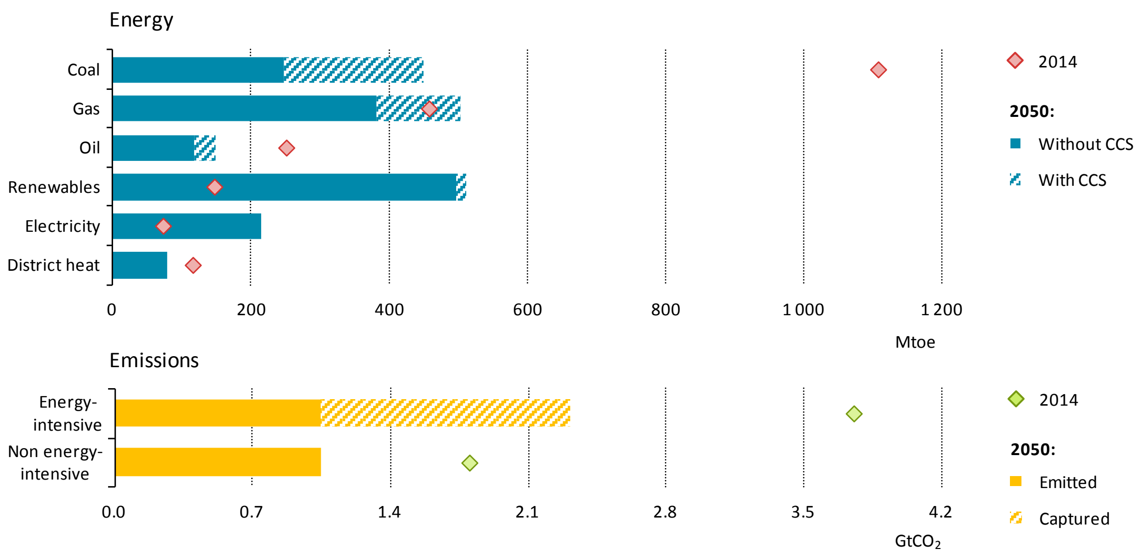
Table 2.10 • Global energy and CO_2 energy intensity reductions and key additional technology levers in the industry sector in the 66% 2°C Scenario relative to the New Policies Scenario

Sub-sector*	Reductions in the 66% 2°C Scenario relative to the New Policies Scenario		Technology levers
	Energy intensity	Carbon intensity	
Cross-cutting	-24%	-66%	Energy efficiency deployment up to its economic potential. Minimum energy performance standards for electric motors by 2025 (min. IE4), including variable speed drives in suitable load systems. System-wide measures in industry systems, such as predictive maintenance and proper systems sizing.
Iron and steel	-26%	-65%	Recycling of all available scrap. Material efficiency improvement through increased manufacturing and semi-manufacturing yields and re-use of post-consumer scrap. Switch of steel production from blast furnace to smelting reduction processes including CCS.
Cement	18%**	-82%	Greater use of alternative fuels in kilns, in some cases above 50% of fuels inputs. Improvement of cement-to-clinker ratio to at least 65% for all regions by 2050. CCS deployment, including for biomass (BECCS).
Chemical and petrochemicals	-3%***	-55%	Material efficiency improvement through increased recycling and light-weighting. Electrification of low-temperature heat demand through the deployment of heat pumps. Direct use of renewable technologies (e.g. solar thermal), mainly to satisfy needs for utilities. CCS deployment in production processes including ammonia, methanol and olefins.
Aluminium	-14%	-17%	Maximum deployment of secondary aluminium production. Material efficiency improvement through increased manufacturing and semi-manufacturing yields and re-use of post-consumer scrap. Fuel switching from coal/oil to gas in some processes, such as alumina refining.
Pulp and paper	-30%	-81%	Material efficiency improvement through increased recycling and light-weighting. Greater integration of bioenergy in the production process. Electrification of low-temperature heat demand through deployment of heat pumps. CCS deployment, including for biomass (BECCS).
Other industries	-27%	-62%	Greater use of bioenergy in new and existing applications and substantial investment in solar thermal and geothermal technologies to supply low-temperature demand. Electrification of low-temperature heat demand through deployment of heat pumps.

* Includes energy consumption and CO_2 emissions from blast furnaces and coke ovens, as well as petrochemical feedstocks. ** Positive value represents an increase in energy intensity in the 66% 2°C Scenario that stems from the additional energy need associated with CCS deployment. *** If petrochemical feedstocks were excluded, the sectoral energy efficiency improvement relative to the New Policies Scenario would be around 10%.

Notes: IE4 = super premium efficiency level according to the International Electrotechnical Commission (IEC) classification. CCS = carbon capture and storage. BECCS = bioenergy with carbon capture and storage. Energy intensity and CO_2 energy intensities refer respectively to the amount of energy divided by the physical production (total high-value chemicals production for the chemical and petrochemical sector) and the total direct CO_2 energy emissions from the industry sector. Intensities are given by unit of total industrial added value for the "other industries" category and at the total industry level in USD 2015 at market exchange rate.

Figure 2.24 • Heat demand energy mix in industry (top) **for the G20 region and related direct CO_2 emissions by sector** (bottom) **in the 66% 2°C Scenario**



Key message • Besides energy efficiency, renewables, electrification and CCS are all necessary to shift industrial heat demand to low-carbon.

The net result of these changes on energy demand is that global industry-related CO_2 emissions in the 66% 2°C Scenario would fall by almost 60% to 2.7 Gt in 2050. The global trend is broadly mirrored by that of G20 countries, where energy-related emissions from the industry sector would peak at around 5.6 Gt before 2020 and fall by around 60% below today's level by 2050. Relative to the New Policies Scenario (where emissions continue to grow), the industry sectors of G20 countries would save around 75 Gt of cumulative CO_2 emissions over the period to 2050, accounting for about 80% of global savings from the industry sector.

The trends for industry sector emissions in the 66% 2°C Scenario vary considerably by region, depending on the predominant industries and the status and outlook for industrial development. The different pathways can well be illustrated by comparing the outlooks for China and India, which are important countries for achieving the overall emissions reduction relative to the New Policies Scenario. In China, the key challenge would be to decarbonise existing industrial infrastructure; in India, the task in the 66% 2°C Scenario would be to develop new low-carbon industrial facilities. Much of the importance of China and India in reducing industrial emissions to the level projected in the 66% 2°C Scenario is related to their high production base (e.g. China and India make up about 50% of both the world's steel and cement production in 2050).

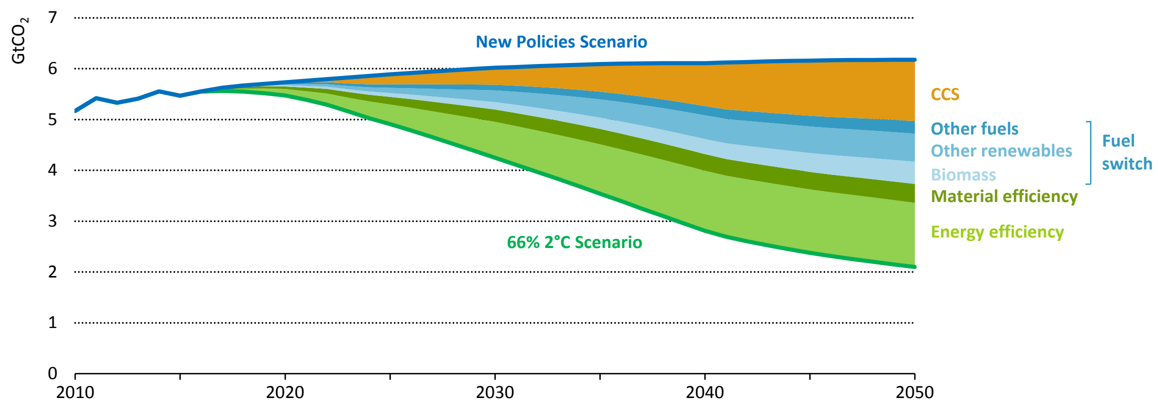
By sub-sector, the main reductions in industrial CO_2 emissions in G20 countries through to 2050 arise from the manufacturing of iron and steel (44% of emissions reductions), followed by cement (18%) and chemicals (12%). The cement and paper sub-sectors would have to become almost carbon neutral in the G20 region by 2050 in the 66% 2°C Scenario, which underscores the size of the challenge. In iron and steel, emissions reductions stem from a combination of increased recycling through the deployment of electric arc furnaces and large-scale deployment of CCS. In the cement sector, emissions reductions would mainly be achieved from the switch to low-carbon fuels (such as bioenergy) and because CO_2 prices as in the 66% 2°C Scenario would facilitate the integration of CCS into the production process. The decarbonisation routes are similar in pulp and paper, although integrating CCS is not as cost-competitive as in cement, meaning that the deployment rate of CCS is lower. In regions with already significant industrial production, CCS is mostly an option for retrofit; in regions in which industrial activity is currently expanding, CCS is integrated mostly in greenfield projects.

In the G20 group, energy efficiency plays the largest role towards a low-carbon industrial sector in the 66% 2°C Scenario, followed by fuel switching and CCS (Figure 2.25). In addition, process-related CO_2 emissions in industry would need to decline from above 1 700 million tonnes (Mt) CO_2 today to below 800 Mt CO_2 in 2050. Most of the latter decrease is due to improvements in the cement-to-clinker ratio and favourable penetration rates of CCS in cement making. Process emissions in the aluminium sector would fall by almost half due to advanced technological process change in smelting, starting from the mid-2030s.[48]

Overall, CCS appears to be a key technology enabling otherwise challenging emissions reductions in the industry sector. It would account for around one-fourth of industry's cumulative CO_2 emissions savings, relative to the New Policies Scenario, and would avoid almost half of the coal-related and about a quarter of the gas-related CO_2 emissions in the G20 group in 2050. Its deployment at scale would need to start in earnest around 2020 and span across industrial sectors. In the cement sector, CCS would be responsible for the majority of energy-related CO_2 emissions savings, while it would save around 45% of the emissions in the steel sector. This poses practical challenges with regards to the siting of future industrial activities, which would either need to be located close to sites where CO_2 can be stored, or to be connected to a CO_2 transportation network (which does not yet exist). CCS also forms the basis for potential future development of bioenergy carbon capture and storage (BECCS), which could facilitate negative emissions mainly in the cement sector (and, to some extent, in the pulp and paper sector) as a means to offset remaining emissions elsewhere.

Large-scale deployment of CCS in industry, at the level required in the 66% 2°C Scenario, would require a considerable near-term push to improve its commercialisation prospects, with an immediate need for further research, development, demonstration and deployment. In the 66% 2°C Scenario, China and India play a key role in CCS deployment, contributing around 60% of the global CO_2 emissions captured in industry by 2050, given their importance for global industrial activities.

Figure 2.25 • G20 region energy-related CO_2 emissions reduction in industry by measure



Notes: "Other fuels" mainly refers to the electrification of demand in industry, but in some instances also includes CO_2 abatement of fuel switching from coal/oil to gas. Material efficiency refers to those levers that impact overall raw material production.

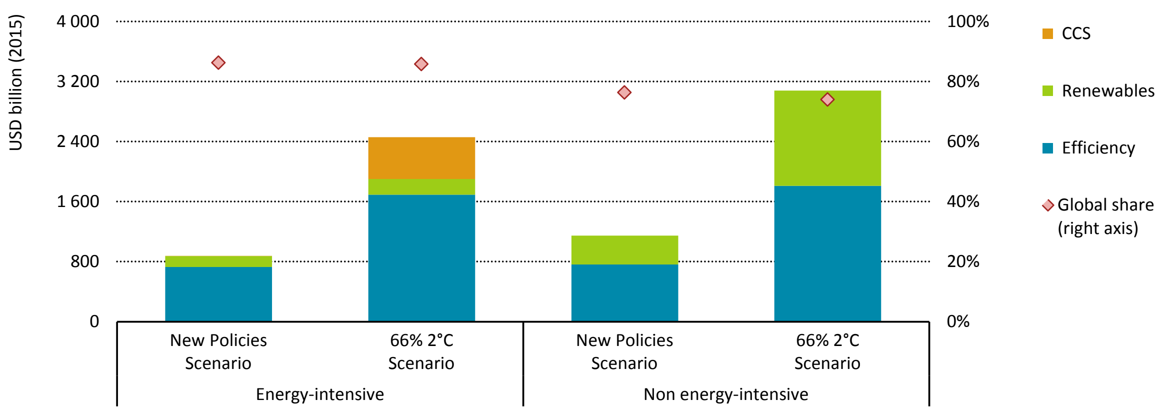
Key message • Combined and aggressive deployment of efficiency, fuel switching and CCS would be necessary to reach the emissions reductions of the 66% 2°C Scenario in the industry sector.

48 Advanced process refers to the usage of Hall-Héroult inert anodes for the smelting of aluminium, which would result in considerably decreased CO_2 emissions compared with traditional processes.

In terms of investment, the 66% 2°C Scenario would require an additional USD 3.4 trillion of cumulative investment in the industrial sector in G20 countries to 2050 (three-quarters of the global increment), compared with the level in the New Policies Scenario (Figure 2.26). More than half of the additional investment would be for energy efficiency measures. This would be followed by about USD 1 trillion for renewable energy deployment in industry, mostly for low-temperature heat via solar thermal and geothermal technologies in the less energy-intensive industries. CCS deployment would require an additional USD 0.6 trillion in energy-intensive industries in G20 countries, where most energy-intensive industries are currently located. Since industrial facilities often have long lifetimes (and retrofitting existing high-emitting infrastructure can be difficult and expensive), delaying the transition to a low-carbon pathway in industry risks imposing significant additional costs, if climate targets are to be met.

Under the assumptions of the 66% 2°C Scenario, the measures to improve energy and material efficiency, and boost the use of renewable energy sources to satisfy heat demand in industry, would be largely cost-effective over the lifetime of the investment, facilitated by substantial carbon price signals. Yet, payback periods can be long, and mobilising the high upfront investment is challenging in a sector where investment decisions today typically demand a payback of less than three-to-five years. Even with high carbon prices, targeted policies and measures would therefore be essential to improve the visibility and viability of low-carbon technologies and processes for investment planning. Such measures would include raising awareness and stimulating the adoption of technologies and practices to expand the use of renewables for heat production. Another important avenue would be to promote best practice efficiency options in industry, for example by strengthening incentives and requirements for effective energy assessment and management systems. In addition to cross-border carbon pricing schemes, international sectoral agreements and benchmarking across industries can also help to enable emissions reductions.

Figure 2.26 • Cumulative investment in the industry sector in the G20 region in the New Policies and 66% 2°C Scenarios, 2016-50



Note: CCS in non energy-intensive industries includes other energy transformation, such as CCS in refineries, oil and gas extraction activities, coal-to-liquids and gas-to-liquids.

Key message • Efficiency measures make up the bulk of investment needs in the industry sector.

Transport

Demand for mobility and freight activity is on a rising trend and the expectation is for further growth. The passenger vehicle stock worldwide is expected to expand two-and-a-half times to reach more than 2.5 billion by 2050, with more than 80% of the increase occurring in the G20 countries. Both aviation and shipping activities are expected to more than triple by 2050 and road freight activity (measured in tonne-kilometres) to rise over two-and-a-half times.

Meeting such demand growth without compromising energy security and environmental goals is a key policy challenge. In the New Policies Scenario, energy demand for transport fuels grows by more than 40% to 2050, to 3 700 Mtoe. More than 50% of the rise in energy demand is met by oil-based fuels, which grow from around 51 mb/d today to nearly 63 mb/d in 2050. Further growth of oil demand is constrained by fuel economy standards, particularly for passenger vehicles. But the limited availability of such standards for other transport modes, notably road freight, and the lack of commercially viable alternatives for oil means that, by 2050, oil demand from transport in the New Policies Scenario is one-quarter above today's level. In this scenario, the contribution of alternative fuels such as natural gas, biofuels and electricity to total transport demand remains just below 20%, even though electric cars make significant in-roads in passenger transport.

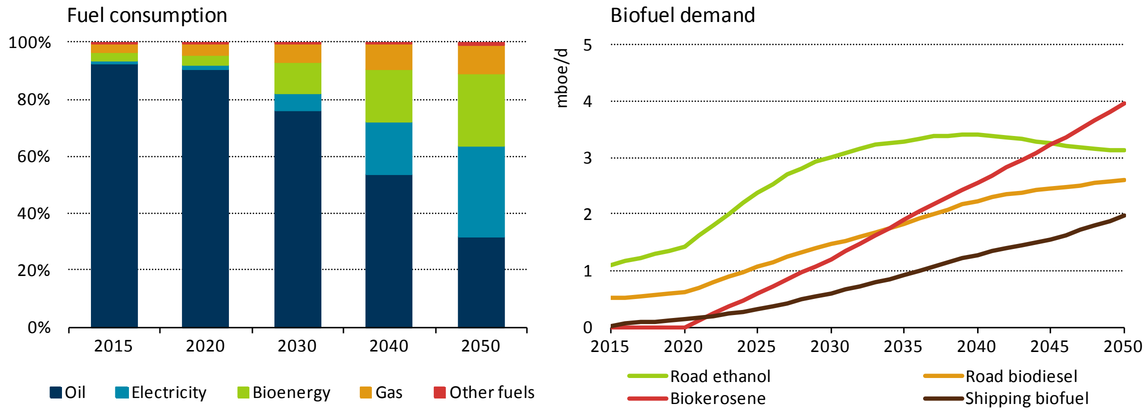
Table 2.11 • Global energy and CO_2 intensity reductions and additional policy actions in the transport sector in the 66% 2°C Scenario relative to the New Policies Scenario

Mode	Reductions in the 66% 2°C Scenario relative to the New Policies Scenario		Policy actions
	Energy intensity	Carbon intensity	
All modes			Carbon pricing/taxes to offset the decline in oil prices. Stringent vehicle efficiency and emissions standards. Agricultural and forestry land-use planning.
Passenger vehicles	*-44%*	*-76%*	Purchase rebate or purchase tax exemption*. Differentiated vehicle taxation based on efficiency performance. Free access to toll road and urban centres*. Biofuel blending targets. Incentives for R&D and infrastructure deployment (e.g. electric vehicle charging stations).
Buses and coaches	*-72%*	*-78%*	Right sizing and integrating bus and emerging mobility services to high capacity public transport. Public procurement promoting low-carbon vehicles.
Trucks	*-65%*	*-73%*	Differentiated vehicle taxation based on GHG emission performance. Support to infrastructure deployment (catenary lines). Greening financing, purchase rebate or purchase tax exemption*. Harmonisation and wide diffusion of fuel economy and emissions standards across countries. Biofuel blending targets.
Rail	*-59%*	*-88%*	Support full electrification.
Aviation	*-32%*	*-82%*	Blending mandates and incentives for R&D for advanced biofuels. Optimise routing, minimise flight distances and cut aircraft waiting times through improvements in air traffic management.
Shipping	*-46%*	*-57%*	Incentives to promote the development of advanced biofuel technologies for aircraft and ship engines. Fuel efficiency and emission standards for maritime and air transport at international level.

* For low-carbon vehicles.

To facilitate the transition to a low-carbon transport sector, the 66% 2°C Scenario relies on a strong and integrated policy framework, which takes into account the specificity of each transport mode and goes well beyond existing policy efforts (Table 2.11). Strengthened vehicle efficiency standards, set at an international level, would be crucial to cut emissions from all modes of transport. But standards alone are unlikely to be sufficient to ensure the adequate development of low-carbon transport options. Differentiated vehicle purchase taxes (also known as fee-bates) would complement vehicle efficiency regulations by providing clear pricing signals, rewarding the most efficient technologies. Effective planning and development of the required infrastructure to support the built-up of recharging stations for electric vehicles and Electric Road Systems for electric trucks (such as catenary [overhead] lines), carefully designed public transport networks and an integrated strategy for biomass supply and transformation are all crucial elements of the 66% 2°C Scenario. Additionally, a carbon price (taking the form of a fuel tax) would be required to offset the decline in oil prices and to avoid rebound effects.[49] Multi-modality, which allows taking advantage of the least-emitting transport mode for passengers and freight movement, is also an option that would require policy support (Box 2.4).

Figure 2.27 • Global transport fuel mix and biofuel demand by type in the 66% 2°C Scenario



Note: mboe/d = million barrels of oil equivalent per day.

Key message • Transport oil demand would fall drastically in favour of electricity and biofuels in the 66% 2°C Scenario; road ethanol would peak before 2040 as the conventional car fleet declines.

The net impact of such robust strengthening of policy ambition is that, in the 2°C 66% Scenario, transport-related energy demand would peak at around 2 750 Mtoe by the mid-2020s and then fall to 2 250 Mtoe in 2050, almost 15% lower than today. The composition of the transport fuel mix would change entirely: oil demand would decline steeply to a mere 15 mb/d in 2050 and its share in the transport fuel mix would fall to less than one-third (Figure 2.27). Alongside efforts to improve the efficiency of all types of vehicles, the main reason for this drop is a switch towards electricity and biofuels. In 2050, virtually all cars sold worldwide would either be hybrid or electric. Transport electricity use would increase significantly and account for around one-third of global fuel demand by 2050 (from 1% today); electricity would become the main means to satisfy road passenger and road freight demand. The use of biofuels would also expand and reach almost 12 mboe/d in 2050, from 1.6 mboe/d today. Trends differ across biofuel types in the 2°C 66% Scenario. Ethanol is an important transition fuel for passenger vehicles; but its use starts to

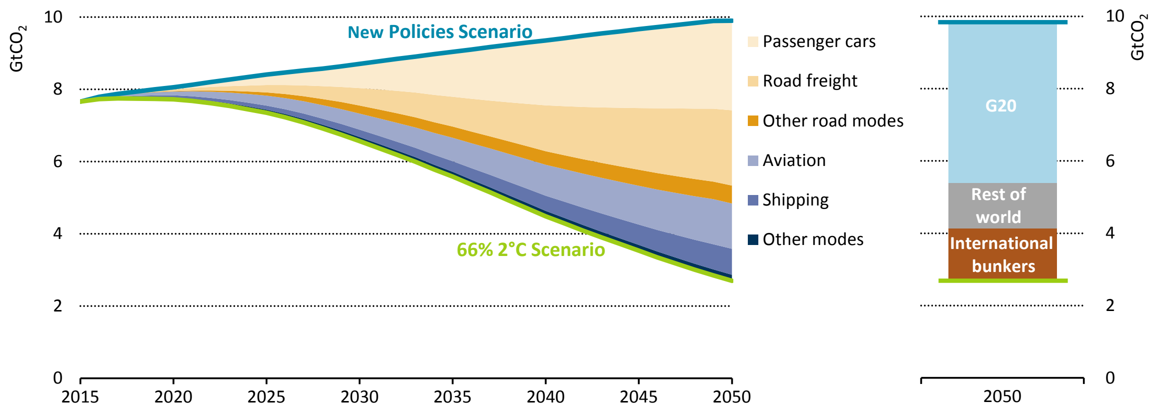
49 Rebound effects occur when lower energy prices, due to less energy demand, lead to a reduction of household energy expenditures. The available money can then be spent on other energy-consuming products or activities, such as driving more or flying more often. Supporting the transition to zero emission mobility through taxes may take the form of a fuel tax as in the 66% 2 °C Scenario, but could also take more complex forms, complementing and partly shifting fuel taxes with charges reflecting road usage and other externalities, to offset the decline in oil prices and to avoid rebound effects.

decline by around 2040 as battery costs fall and electric cars and motorbikes accumulate in the vehicle stock, freeing up some of the limited sustainable biomass potential for other uses. Instead, biofuels become the fuel of choice in transport modes where alternatives to oil are scarce, such as aviation and shipping; and in road freight, where the build-up of the required catenary lines is a key bottleneck for deployment of electric trucks.

This major transformation would lead to a cumulative reduction of CO_2 emissions of 112 Gt, relative to the New Policies Scenario, of which two-thirds occurs in G20 countries. The radical decoupling between transport activity growth and CO_2 emissions would require contributions from all transportation modes – passenger cars account for about one-third of the emissions reduction, road freight for one-quarter, aviation for one-fifth and shipping for one-tenth (Figure 2.28). But the means to achieve such a deep and rapid transition to a highly efficient and low-carbon transport system are different by mode and region.

In the 66% 2°C Scenario electrification of the vehicle fleet is the key route assumed to decarbonise road transport for both passenger and freight vehicles, coupled with a switch to biofuels and energy efficiency measures. The share of electricity in road transport demand rises to more than 40% in 2050, up from close to zero today. Electric engines are more than twice as efficient as conventional gasoline engines and electric vehicles can shift transport sector emissions from millions of mobile conventional sources to a much smaller number of stationary sources in the power sector. If the power generation is from low-carbon sources, as in the 66% 2°C Scenario, then electric vehicles could make a major contribution to the reduction of GHG emissions.

Figure 2.28 • Contribution to global CO_2 reductions by transport mode in the 66% 2°C Scenario relative to the New Policies Scenario

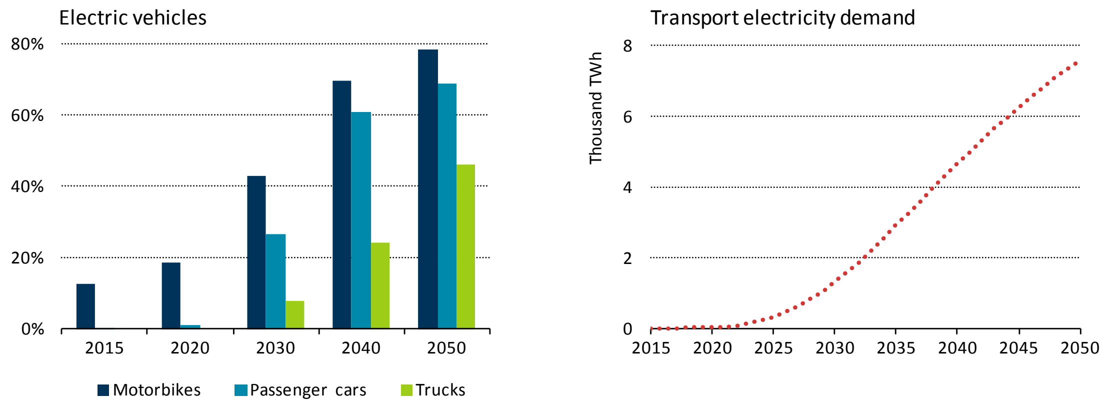


Key message • CO_2 emissions reductions would accelerate after 2030 as sales of electric vehicles rise and biofuels make in-roads in aviation and shipping.

Electrifying road transport at the pace and scale required in the 66% 2°C Scenario is an enormous task: the share of electric cars in passenger car sales would rise from less than 1% today to almost 70% in 2050, more than six-times higher than what is achieved under existing and planned policies in the New Policies Scenario (Figure 2.29). This is primarily a challenge for the G20 group, which hold more than 85% of the global passenger car stock in 2050: the largest increase in electric car sales in the 66% 2°C Scenario occurs in the large vehicle markets such as China, India, the United States and the European Union. The main exception among G20 countries is Brazil, which relies more on a very efficient fleet of flex-fuel and pure ethanol engine cars.

The deep transformation of transport required in the 66% 2°C Scenario would involve electrification beyond passenger cars alone: there are 1 billion electric motorbikes on the world's roads by 2050 in the 66% 2°C Scenario (from less than 250 million today, most of which are in China) and more than 200 million electric freight vehicles. While the majority of the latter are light commercial vehicles, used for local delivery in cities, the electrification challenge needs to extend to heavy freight traffic operating over longer distances. So the most frequented highway routes would need to be equipped with electrified overhead lines in the 66% 2°C Scenario to fuel plug-in hybrid trucks, as battery ranges otherwise would not permit long-haul journeys.[50] A successful transformation of road freight transport as in the 66% 2°C Scenario would also require improved logistic networks to optimise truck utilisation, e.g. platooning and backhauling, and integrate long-haul delivery with local delivery, e.g. adjust timing to avoid trucks to travel during congestion hours.

Figure 2.29 • Share of electric powertrains in global vehicle stock by type and global electricity demand for transport in the 66% 2°C Scenario



Note: TWh = terawatt-hours.

Key message • Electric engines would make big in-roads in passenger and freight road markets, inducing a sharp increase in electricity demand.

In aviation and shipping, key elements of curbing CO_2 emissions in the 66% 2°C Scenario are fuel efficiency improvements of the fleets and the large-scale use of biofuels. The average fuel consumption of ships and aircraft would fall by around two-thirds in the 66% 2°C Scenario between now and 2050, thanks to the large-scale deployment of technology improvements such as open rotor, geared turbofan and counter-rotating fan, as well as better traffic management in aviation and data-enabled load optimisation in navigation. In addition, drop-in[51] biofuels from non-edible vegetable oil and lignocellulosic material could substitute for almost 4 mb/d of oil in aviation and 2 mb/d in shipping by 2050 in the 66% 2°C Scenario, up from a combined 0.7 mb/d in the New Policies Scenario. Natural gas additionally supports the decarbonisation of shipping, with liquefied natural gas (LNG) replacing more than 1.5 mb/d of oil by 2050.

By enabling behavioural changes, urban planning can also be a cornerstone to reduce emissions from transport in an increasingly urbanising world, e.g. through a dense and interconnected network of cycle lanes, low-carbon public transportation and charging stations. Development of smart mobility might also help to transform traditional transportation patterns. On the one hand,

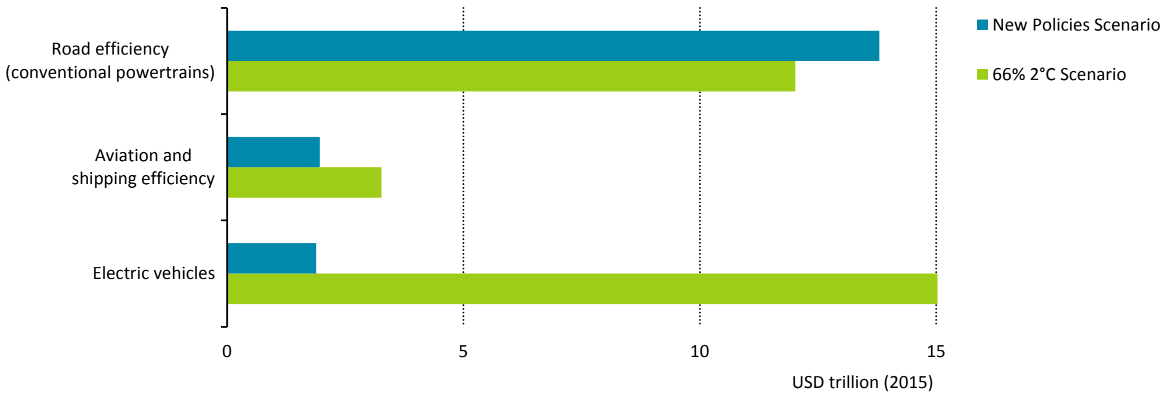
50 Alternatively, a carefully co-ordinated build-out of a hydrogen supply and fuelling infrastructure in tandem with the rollout of fuel cell trucks could provide a cost-effective alternative to overhead lines, depending on the potential for technology learning in electrolysers, fuel cells and other key hydrogen technologies.

51 Drop-in biofuels are made of the same molecules as conventional fuels, so they can be blended at a high rate in common engines without any modifications.

car sharing and car-pooling could reduce the overall vehicle kilometre; on the other hand, autonomous vehicles and lower fuel consumption could lead to an increase of the activity.[52]

The transformation of the transportation sector in the 66% 2°C Scenario would require a cumulative investment of USD 32 trillion between 2015 and 2050, USD 13 trillion more than in the New Policies Scenario (Figure 2.30). This includes energy efficiency investment in road, aviation and shipping sectors and investment for new powertrains, such as pure electric vehicles. Over half of this investment would be dedicated to new electric vehicles and the remainder to energy efficiency.[53] The lion's share of energy efficiency investment would need to be dedicated to road transport to meet stringent fuel economy and emissions standards, although investment in improving the efficiency of road vehicles would actually be lower than in the New Policies Scenario. The reason is that because of the rise in electric mobility, there are fewer highly efficient conventional vehicles on the road in 2050 in the 66% 2°C Scenario than in the New Policies Scenario. Investment in aviation and shipping would jump by two-thirds in order to improve fuel efficiency, relative to the New Policies Scenario. In addition, biofuels investment would rise sharply to meet the larger demand for biofuels in particular in shipping, aviation and road freight.

Figure 2.30 • Global cumulative transport investment in in the New Policies and 66% 2°C Scenarios, 2016-50



Note: Excludes investment in recharging infrastructure.

Key message • Additional investment needs in the 66% 2°C Scenario stem mainly from the electrification of the fleet.

Electrification of transport accounts for the bulk of the overall investment requirement (of which more than three-quarters of the required investment is for passenger cars, given the substantial shift to electricity, and freight transport captures the remainder with the rise of electric trucks), but this sum is mitigated somewhat by significant reductions in the cost of batteries. Battery cost in the 66% 2°C Scenario falls at a much faster rate than in the New Policies Scenario, with the unit cost reaching the assumed floor cost of USD 80/kWh[54] for battery electric vehicles by the early

52 These effects have not been included in the analysis of the 66% 2 °C Scenario, but are discussed in *Energy Technology Perspectives 2017* (IEA, forthcoming).

53 Represents the additional cost compared with an average combustion engine vehicle today and includes a large set of incremental as well as breakthrough improvements. For road vehicles, examples are hybridisation, higher capacity batteries (e.g. lithium oxygen) and super-fast charging stations. For aviation, examples are light-weighting, drag reduction, engine improvement and new motorisation such as open rotor. In navigation, it includes minimising drag and improving engine operation.

54 This floor cost value is based on a US Department of Energy analysis that assumes overcoming chemistry challenges, favourable systems engineering and high production volumes (Sarkar, 2016). See also the discussion in the *World Energy Outlook 2016* (IEA, 2016a).

2030s, around 20 years earlier than in the New Policies Scenario. The reason is that the policy push to electrification facilitates additional cumulative sales of more than 2 billion electric cars in the 66% 2°C Scenario, relative to the New Policies Scenario. In addition to these investments, the electrification of road transport implies significant investment across the whole chain value, from R&D in battery capacity and robustness, to the upgrade of the grid to meet possible local surplus demand and the deployment of charging stations for cars and catenary lines for trucks. Their quantitative assessment would require a further analysis.

Buildings

Today, the buildings sector accounts for around one-third of global final energy demand; almost 75% of which was in G20 countries.[55] Roughly three-quarters of the global total is required to meet heat demand while the remaining quarter is mainly electricity for lighting, appliances and space cooling. Satisfying heat demand currently accounts for about 4.5 Gt of CO_2 emissions, which represent around half of the total emissions in the buildings sector (including direct and indirect CO_2 emissions). Almost all of the sector's direct CO_2 emissions arise from heat production from coal, oil and natural gas boilers (around 1% of direct CO_2 emissions arise from the use of kerosene for lighting). Today, fossil fuels account for more than one-third of total energy use in buildings.

The outlook for the buildings sector is one of rapid growth. In the period to 2050, the global number of dwellings is expected to swell (by around 60%) and the size of the average individual building also rises. As a result, total floor space area of dwellings is expected to double, pushing up demand for energy services such as space heating and cooling. The increase in floor area is expected to be significant in the G20 group as a whole, at around 80% to 2050, but not as rapid as in non-G20 countries, which include many fast-growing emerging economies. Until 2050, the value added by the services sector, an important driver of consumption, almost triples, and more than 80% of the increase comes from the G20 group.

Such trends are expected to push up energy demand in the buildings sector. In the New Policies Scenario, total global energy demand in this sector rises by one-third, with half of the growth in the G20 group. The intensity of energy demand in the buildings sector falls, but continued reliance on fossil fuels in this scenario means that the sector's carbon intensity barely improves. Further steps to reduce emissions from the buildings sector, to the level required in the 66% 2°C Scenario, would require major additional policy action in three main areas. First, adopting and implementing effective policies that would make end-use appliances as efficient as possible. Second, a push for near zero-energy buildings for new construction (covering around 40% of all new buildings from today to 2050, the other 60% of new buildings by 2050 being compliant with buildings codes), along with deep retrofits of the overall existing buildings stock by 2050 (to reduce space cooling demand). Third, decarbonising the remaining supply of heat to the buildings sector by replacing fossil fuels with electricity, district heating and renewables. These policies are directed to spur the necessary reduction in the energy intensity of each end-use, or their carbon intensity, or both (Table 2.12). Decarbonising power and heat generation are a vital additional step towards achieving net-zero CO_2 emissions in the buildings sector: indirect CO_2 emissions currently represent around two-thirds of the sector's CO_2 emissions.

The net effect of implementing this very ambitious package of policies and measures is that, in the 66% 2°C Scenario, energy consumption from the buildings sector would peak in the early 2020s and just about return to the level of today in 2050. This is the result of some offsetting trends, with lower demand for space heating and lighting being counterbalanced by continued

55 The buildings sector includes energy used in residential, commercial and institutional buildings. Household and services energy use includes space heating and cooling, water heating, lighting, equipment, appliances and cooking equipment.

growth in all other buildings-related end-uses, for which the effect of higher income levels and gradually improving access to modern energy services in developing countries outpaces efficiency and conservation efforts. In G20 countries as a whole, energy demand in the buildings sector drops by around 10% by 2050.

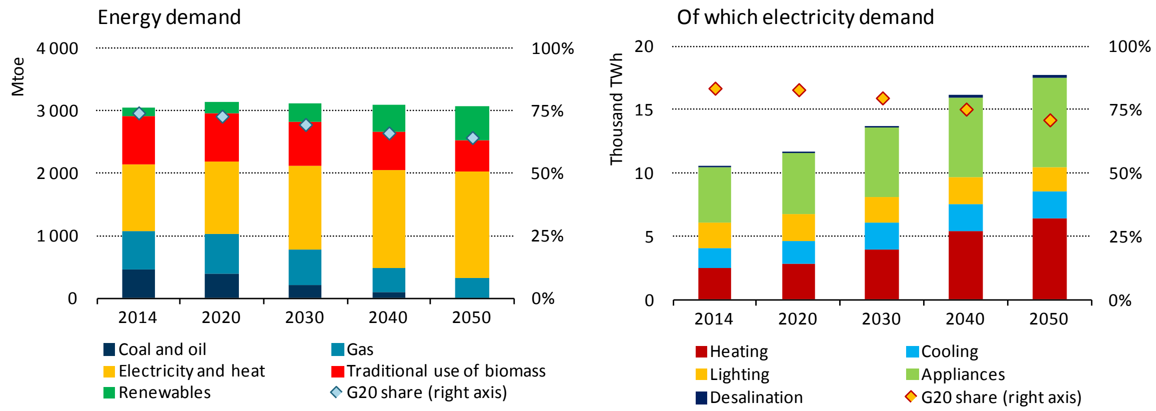
Table 2.12 • Global energy and CO_2 intensity reductions and additional policies in the buildings sector in the 66% 2°C Scenario relative to the New Policies Scenario

End-use	Reductions in the 66% 2°C Scenario relative to the New Policies Scenario		Policy actions
	Energy intensity	Carbon intensity	
Space heating	-33%	-79%	New buildings: increase the share of near zero-energy buildings on average from now to 2040 to 40% (from 1% today) and ensure other new construction complies with building codes. Existing stock: mandate stringent measures to ensure deep retrofit of the entire stock by 2050 (from less than 10% today). Mandates seeking to maximise buildings energy performance for both new and existing buildings. Phase out fossil fuel boiler sales by 2025 in all regions, except where natural gas is a major provider today. Extensive support and mandates for direct use of renewables (solar and geothermal), efficient electrification and efficient district heating in dense urban areas.
Water heating	-16%	-84%	Phase out of fossil fuel boiler sales by 2025 in all regions, except where natural gas is a major provider today. Extensive support and mandates for direct use of renewables (solar and geothermal), efficient electrification and efficient district heating in dense urban areas.
Cooking	-15%	-74%	Phase out fossil fuel stoves sales by 2025 in all regions; exceptions: regions where natural gas is a major provider today; developing countries, where LPG enables more access to modern energy services in rural areas.
Lighting	-40%	-92	Phase out kerosene lamps sales by 2025. Enhance deployment of electricity and clean off-grid technologies, e.g. solar lamps. Require lighting performance at current LED efficacy levels or higher for all lighting sales by 2025.
Appliances	-25%	-90%	Phase out of sales of the least-efficient major appliance by 2025.
Space cooling	-46%	-93%	New buildings: increase the share of near zero-energy buildings to 40% (from 1% today) and ensure other new constructions comply with building codes. Existing stock: mandate stringent retrofits to ensure deep retrofit of the entire stock by 2050 (from less than 10% today). Phase out least-efficient cooling systems sales by 2025.

Notes: NPS = New Policies Scenario; LPG = liquefied petroleum gas. Energy intensity and carbon intensity for the buildings sector refer respectively to the amount of energy divided by the global population and the total CO_2 emissions (direct and indirect) linked to the buildings sector.

Successful decarbonisation of the buildings sector in the 66% 2°C Scenario would also require changes in the fuels and technologies used. The rapid rise in the use of renewables and electricity for heating purposes would precipitate a major revolution in the sector's fuel mix (Figure 2.31). The required level of decarbonisation of the 66% 2°C Scenario would require the share of fossil fuels in the sector to drop to around 10% by 2050, compared with 35% today. Electricity use in the 66% 2°C Scenario would increase by two-thirds to 2050, with heat applications and other electricity end-uses (e.g. appliances and space cooling) each accounting for around half of the increase; about 3% is for desalination purposes. The change in energy demand in the 66% 2°C Scenario is particularly notable for G20 countries, which would see their share in worldwide buildings energy demand shrink from around three-quarters (and almost 85% for electricity) to around 65% (70% for electricity) in 2050. Countries outside G20 have higher projected growth for hot water needs (met either by electricity or solar water heaters) as well as for space cooling and appliances.

Figure 2.31 • Global energy demand by fuel and electricity demand by end-use in the buildings sector in the 66% 2°C Scenario



Note: Mtoe = million tonnes of oil equivalent.

Key message • Electricity demand would nearly double and account for half of energy demand in buildings in 2050.

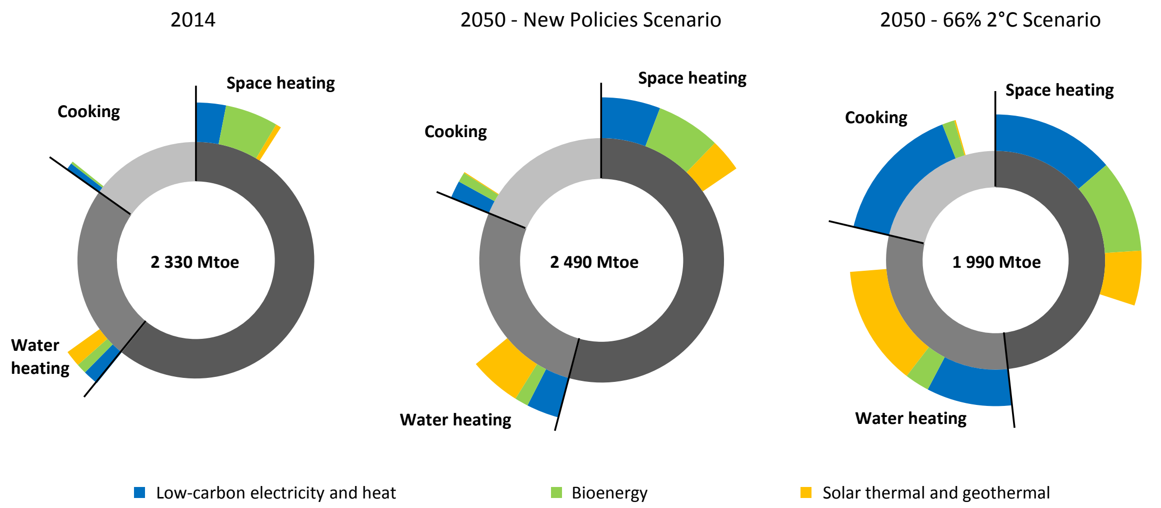
The composition of electricity demand in the buildings sector in the 66% 2°C Scenario reveals some diverging trends. Compared with the New Policies Scenario, there would be electricity savings of 5 400 TWh in 2050 as a result of more robust efficiency measures for lighting, appliances and space cooling, but these would be partially offset by an additional 2 000 TWh of electricity needed to satisfy increasing use of electricity for heating purposes. In some sub-sectors, despite aggressive efficiency efforts, electricity demand would continue to rise. For example, overall average electricity consumption per unit of large appliance would decrease strongly (e.g. refrigerators, freezers, washing machines, dishwashers and dryers). But rising ownership rates and a growing amount of small appliances and equipment would lead to an increase of over 60% of electricity use related to appliances through to 2050 in the 66% 2°C Scenario (compared with a doubling of electricity consumption in the New Policies Scenario). Electricity demand for space cooling would see one of the highest growth among all end-uses, despite efficiency efforts. In India, for example, electricity demand would increase by almost a factor of four to 2050, of which around a quarter is related to space cooling, despite the adoption of aggressive minimum energy performance standards and stringent building codes. The net result is that, at a global level, electricity demand in the 66% 2°C Scenario would be 15% lower than in the New Policies Scenario. Together with a reduction in carbon intensity of power generation, this would reduce indirect CO_2 emissions by 6.1 Gt in 2050.

The strong worldwide push for near zero-energy buildings in new constructions (40% of the additional buildings by 2050) and deep retrofit of the existing buildings stock means that, in the 66% 2°C Scenario, global heat demand (mostly for space and water heating) in the buildings sector would decline by 10% below today's level by 2050. This is a radical reversal of present trends: it compares with an increase by 10% in the New Policies Scenario (Figure 2.32). the G20 group – which today accounts for 70% of the world's dwellings and more than 85% of space heating demand – would be responsible for the entire decline in the 66% 2°C Scenario (countries outside G20 would still have a higher heat demand in 2050, compared with today's level). The overall decline masks different trends: while global energy demand for space heating would decline by one-quarter below today's level in 2050, heat demand for water heating and cooking with modern fuels would increase by over 25%. The latter largely reflects population and economic growth in developing countries: sub-Saharan Africa accounts for a third of the increase.

The fuel mix to satisfy heat demand in the 66% 2°C Scenario in 2050 would be entirely different from today, with bioenergy (including the traditional use of solid biomass), electricity and other renewables (solar thermal and geothermal) supplying three-quarters of total heat demand, and much of the remainder being natural gas. This would bring down the fossil fuel share to 15% from 45% today (compared with 45% by 2050 in the New Policies Scenario). Although the share of bioenergy in heat demand (mainly traditional use of solid biomass for cooking which is particularly inefficient) would be higher than that of electricity, the number of consumers reliant on electricity would actually be higher, as the efficiency of heat pumps is higher than that of other equipment. In 2050, around 40% of households would rely on electricity for space heating, 35% for water heating and 80% for modern forms of cooking.

Direct use of renewables also contributes to meeting heat demand. By 2050, in the 66% 2°C Scenario, 20% of global households would use renewables (mostly bioenergy) for space heating and some 40% solar water heaters. In the 66% 2°C Scenario, many African and Asian countries would move directly to renewable options for water heating purposes.

Figure 2.32 • Heat demand by fuel and end-use in the buildings sector in the New Policies and 66% 2°C Scenarios



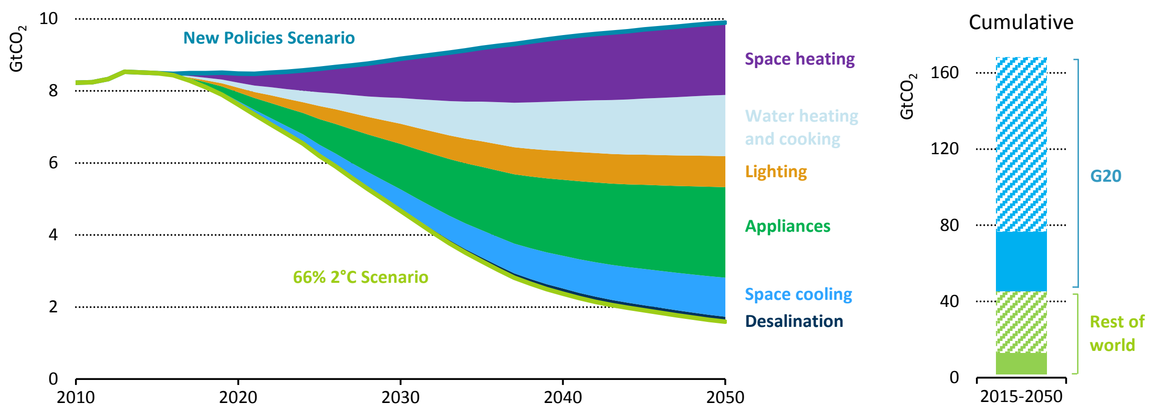
Note: Traditional use of solid biomass is accounted for separately from the three end-uses.

Key message • The use of low-carbon technologies for heat demand in the buildings sector would need to rise significantly over existing efforts, despite lower heat demand from energy efficiency.

Moving to near zero-energy buildings for new construction and deep retrofits of the existing buildings stock is a huge challenge; the required pace of change to 2050 amplifies the scale of what is required. Tight, robustly enforced efficiency standards for equipment, appliances and lighting would be needed to restrain energy demand growth in the residential and services sector, as well as to spur technology advances. Best practice and effective codes to promote energy-wise design and construction of new buildings have proven useful in many parts of the world, but would need to continue to evolve and to be strengthened significantly to put the buildings sector on track to achieve the 66% 2°C Scenario.

Dramatically improving the energy performance of today's stock of buildings poses particular challenges. The required decline of space heating demand by 25% through 2050 in the 66% 2°C Scenario, relative to today, compares with an expected annual growth of 0.35% in the New Policies Scenario. The latter is already below historic growth trends: space heating demand grew by 0.5% per year on average over the last 15 years. The lower growth projected in the New Policies Scenario is mostly due to relatively modest increases in floor area in countries with cold climates. But, given the generally slow turnover of the building stock, this also implies that in these countries, about 70% of today's building stock will still exist in 2050. The absence of long-term incentive schemes for retrofitting in most countries creates a lock-in effect that, unless overcome through robust policy intervention, will continue to deter improvement in the energy performance of existing buildings. Achievement of the 66% 2°C Scenario would therefore require widespread retrofit and insulation measures, supported by financing models to overcome barriers related to the significant capital outlays and long payback periods (more than ten years, albeit in relation to buildings lifetimes that can exceed 100 years).

Figure 2.33 • Total CO_2 emissions reduction (direct and indirect) **by end-use in the buildings sector in the 66% 2°C Scenario relative to the New Policies Scenario and cumulative CO_2 savings by region**



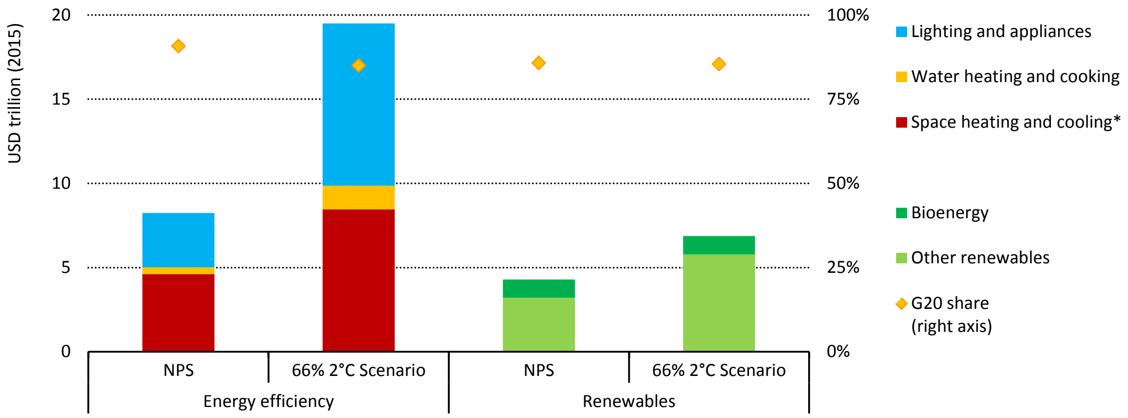
Note: Hatched area in the figure on the right represents indirect CO_2 emissions savings within the region.

Key message • Much greater policy action is needed across all parts of the buildings energy use to put the sector on track to achieve the needs of the 66% 2°C Scenario.

As in other end-use sectors, the picture of the buildings sector that would emerge from our projections in 2050 in the 66% 2°C Scenario is one that is very different from today (Figure 2.33). The contribution of the G20 group towards direct and indirect emissions savings would be particularly large, as their share in these emissions would drop from almost 85% today to around 60% in 2050 in the 66% 2°C Scenario. At less than 1 Gt by 2050, global direct CO_2 emissions would be almost four-times lower than the current level. China would provide the largest contribution to direct CO_2 emissions savings, as coal to meet demand for heat in buildings would be replaced by other fuels. The United States and the European Union today account for 40% of global heat demand met with modern fuels in the buildings sector and, in our projections, would be the second- and third-largest contributors to direct CO_2 emissions savings. By 2050, the buildings sector would represent around 20% of total CO_2 emissions (including indirect) in the 66% 2°C Scenario. Energy efficiency gains in buildings would contribute to these savings, but a large part of the decline in CO_2 emissions also reflects the reduction in carbon content of the power sector.

Investment in more efficient buildings, equipment (e.g. LED lighting, appliances, induction stoves, heating and cooling systems) and renewables-based heat systems (e.g. bioenergy boilers, solar water heaters) would require investment of more than USD 25 trillion in the 66% 2°C Scenario, over twice the level of the New Policies Scenario (Figure 2.34). About 85% of the cumulative investment is in G20 countries. The bulk of the investment is to improve the efficiency of energy use – including insulation and retrofits as well as more efficient appliances and heating systems – and about a quarter is for expanding the use of renewables to serve heating needs.

Figure 2.34 • Cumulative investment for efficiency and renewables by end-use in the buildings sector in the New Policies and 66% 2°C Scenarios



*Space heating and cooling energy efficiency investments include also retrofit and insulation investments.

Key message • The 66% 2°C Scenario would require twice the level of investment in energy efficiency and renewables than the New Policies Scenario.

The investment in renewables is for energy services related to heat production, such as biomass boilers and solar water heaters. Efficiency expenditures for heat-related applications include improvements in the building envelope, high-performance heat pumps, more efficient boilers and heating/cooling equipment. These account for around 60% of the cumulative investment with the rest being for efficiency improvements in end-uses that rely on electricity such as appliances and lighting.

The variety of potential stakeholders making investment decisions related to energy use in the buildings sector is very wide, ranging from the administration of a major city that decides how to equip its schools with water heating systems, to a landlord who buys space heating units for a rental apartment and to a homeowner who selects a new light bulb. Awareness of the energy and GHG emission aspects of their decisions varies, as does their assessment of the costs involved and their potential interest in pursuing such efforts. Where the owner reduces the carbon intensity of a home, the impact will be felt directly: household energy expenditures in 2050 in the 66% 2°C Scenario are lower than in the New Policies Scenario (see next section). But some of the required investment has long payback times, which can be a barrier to consumers and requires improved access to finance. In other cases, where the owner of a building is not the tenant, pursuing efforts to retrofit the building does not necessarily deliver direct benefits to the owner (although the value of the property could rise as a result of the efforts taken), but rather to the tenant whom benefits from lower energy bills. Overcoming such split incentives is a key policy challenge in addition to the adoption of the measures of the 66% 2°C Scenario.

Implications of the 66% 2°C Scenario

The primary objective of the 66% 2°C Scenario is to reduce energy-related GHG emissions to an extent that it would put the world on track towards achieving climate goals. But energy affects the entire economy and multiple stakeholders, which means that any energy policy to tackle climate change has implications for the achievement of other policy goals. In this section, we explore the implications of the 66% 2°C Scenario for the energy industry (with a focus on stranded assets) as well as for selected energy policy goals beyond climate change, in particular for energy security, air pollution and energy access.

Implications for stranded assets

A rapid and profound energy sector transition as required under the 66% 2°C Scenario would have significant consequences for the energy industry. The sizeable expansion of renewables, efficiency and other low-carbon technologies would bring with it many new jobs that support the manufacturing of components, the installation of new projects, retrofits, and maintenance of installations. The renewable energy industry is already a large employer, and this would be expanded along the transition path. Fossil fuel consumption, meanwhile, would fall dramatically in the 66% 2°C Scenario. A key question is whether these reductions would lead to severe losses for companies and investors in the fossil fuel industry, or whether the transition to a low-carbon economy could be managed smoothly with zero or minimum losses. There are multiple strands to this debate that are inter-related but too often conflated, and, partly as a result of loose terminology, there is a high degree of confusion surrounding discussions of the potential value of losses resulting from climate change policy. It is therefore relevant to differentiate between the various impacts and losses that could be incurred by the energy industry, which include:

- The extent of existing fossil fuel reserves that will be left unexploited as a result of climate policy ("reserves left in the ground" or "unburnable fossil fuels").
- The capital investment in fossil fuel infrastructure which ends up failing to be recovered over the operating lifetime of the asset because of reduced demand or reduced prices resulting from climate policy ("stranded assets").
- The potential reduction in the future revenue generated by an asset or asset owner assessed at a given point in time because of reduced demand or reduced prices resulting from climate policy ("carbon bubble").

The carbon bubble, occasionally also referred to as a reduction in the "remaining book value" of assets as a result of climate policy, is an important consideration for understanding the impacts of the low-carbon transition. This calculation has a wide number of moving parts to be considered, many of which are quite subjective. For example, to calculate the losses for assets resulting from climate policy, it is necessary to compare the book value between a scenario that contains climate policy and for one that does not; estimates of losses are very sensitive to the specific "counterfactual" scenario chosen. There is also uncertainty surrounding the possibility that market participants could substantially modify the type and nature of their asset portfolios in response to different climate policies; estimates of losses are therefore not static over time. The calculation also requires a detailed knowledge of prices, demand, costs (including the cost of capital), project-specific discount rates and any potential alternative sources of revenue (such as government support to ensure sufficient capacity is maintained in the system).[56] Without considering all of these elements, any estimate of the carbon bubble for a specific sector is likely to be flawed.

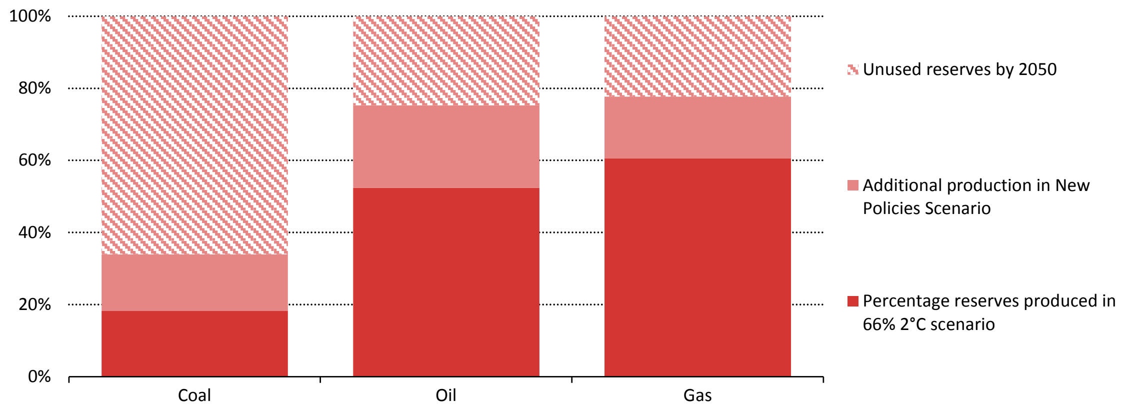
56 The calculation is further complicated when estimating the carbon bubble for assets that do not necessarily generate any obvious revenue streams, such as in the buildings or transport sectors.

Potential losses incurred on invested capital, i.e. stranded assets, pose a critical concern for companies, investors and policy makers. For each asset taken out of service before it has been able to recover the original capital investment, the parent company's total capital is reduced, potentially lowering its ability to make future investments. Here, our analysis therefore focuses on the impacts of climate policy on fossil fuel reserve utilisation and stranded assets (as defined above) in the power, upstream and refining sectors, the sectors in which stranded assets are likely to be largest. While there are also potential risks for stranding of midstream gas infrastructure, including pipelines and LNG terminals, given the increase in natural gas consumption through to the mid-2020s in the 66% 2°C Scenario, this issue appears less pressing than for the other sectors examined.

Unburnable fossil fuels

Current reported fossil fuel reserves worldwide consist of around 1 000 billion tonnes of coal, 1 700 billion barrels of oil and 215 trillion cubic metres of gas.[57] The CO_2 emissions that would result from combusting these reserves total around 2 800 Gt of CO_2, over three-times the remaining CO_2 budget in the 66% 2°C Scenario (880 Gt). This leads to the oft-quoted finding that two-thirds of today's fossil fuel reserves need to be "left in the ground" to avoid dangerous climate change.

Figure 2.35 • Proportion of fossil fuel reserves produced in the 66% 2°C and New Policies Scenarios, 2015 - 2050



Key message • Close to 80% of remaining coal reserves, 50% oil reserves and 40% gas reserves would not be produced before 2050 in the 66% 2°C Scenario. Remaining reserves would not be fully utilised in the New Policies Scenarios as well.

This is a simplification for a variety of reasons. The outlook for each fossil fuel varies markedly in the 66% 2°C Scenario: coal consumption would drop by over 65% between 2014 and 2050, oil by around 55% and natural gas by less than 20%. This is because the combustion of coal results in significantly more CO_2 emissions than from oil and gas per unit of energy supplied, the energy density of oil is significantly higher than that of coal (hence its widespread use in the transport sector) and the substitutability of the various fossil fuels is decidedly different, depending on the purpose to which they are serving. Comparing cumulative fossil fuel production in the 66% 2°C Scenario up to 2050 with the remaining reserves of each fuel individually, we find that around 40% of gas, 50% of oil and over 80% of steam and coking coal current reserves would be "unburnable" (Figure 2.35). However this calculation overlooks that most of today's proven

57 Here we use "reserves" loosely to mean "published proven reserves", recognising that not all the published numbers should be considered as proven under international classification schemes such as SEC, PRMS or UNFC.

reserves are not produced by 2050 in any scenario even in the absence of stringent climate policies. In the New Policies Scenario, for example, less than 40% of coal reserves and 80% of oil and gas reserves are produced between 2014 and 2050. In other words, over 60% coal reserves and 20% of oil and gas reserves are not produced before 2050 in the New Policies Scenario. The world's proven reserves are not synonymous with those lined up for development, though this is the definition implied by most international classification systems. Continued exploration for and development of new resources remains essential in the 66% 2°C Scenario.

Stranded assets

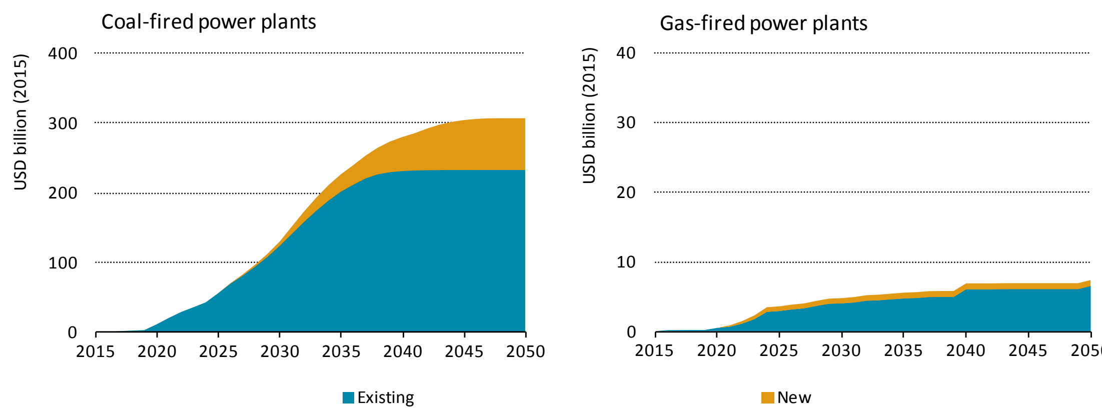
Stranded assets can occur for a number of reasons related to market conditions, technology and performance risk, as well as changes in regulations or policies. They can occur for all types of technologies, including low-carbon technologies. Low-carbon technologies and, in particular, renewables are often supported by policies that provide consistent revenue streams, such as feed-in tariffs in the power sector. In such cases, retroactive policy changes that reduce these revenue streams could lead some of the initial capital investment to be stranded.

When considering the potential value of stranded assets, it is important to recognise the difference between assets that are prematurely shut down due to adverse demand evolution, and assets that are prematurely shut down and lose part of the capital spent on their development. In other words, it is possible for an asset to be shut before it reaches the end of its technical lifetime, but for it still to have recuperated all of the capital invested into it. The degree of capital recovery when an asset is retired requires a detailed understanding of investment and operating costs, utilisation and production rates, commodity prices and other potential revenue streams that it generated over its lifetime. In this section, we build our analysis of stranded assets on the detailed modelling of all these parameters for the different parts of the energy sector in the IEA's World Energy Model (WEM) (see methodology in Annex A) and focus on those assets that may not recoup their capital due to the additional climate policies put in place in the 66% 2°C Scenario.

In the *power sector*, stranded assets in the 66% 2°C Scenario would total USD 320 billion worldwide over the period to 2050 in terms of fossil fuelled power plants that would need to be retired prior to recovering their capital investment. Coal-fired power plants account for the vast majority of the total (96%), as many of them would be phased out in the 66% 2°C Scenario (Figure 2.36). Gas-fired and oil-fired power plants would be far less affected, partly because they are critical providers of flexibility for many years to come and partly because they are less capital intensive than coal-fired power plants. A detailed analysis underpins these estimates of stranded assets in the power sector, based on simulated costs and revenues for each of the 87 fossil fuelled technologies represented in each region of the IEA's WEM. Each technology was further broken down by the year it was completed. For example, for the subcritical coal-fired power generation capacity that was put into service in 1995 in the United States, market-based revenues were simulated for each year of its operational life, marrying historic data and projected market conditions concerning the mix of technologies in operation, fuel and CO_2 prices. The amount of capital recovered in each year for that capacity could then be calculated (annual revenues less operating costs) and tallied over the 30-40 year operational life.

Three-quarters of the total stranded assets in the power sector are related to plants already in operation today that are retired during the transition before recovering their original investment. The remaining USD 80 billion of stranded capital in the power sector is associated with plants that would be built over the projection period, nearly all of which are already under construction. The level of new power plants that would become stranded is limited by the fact that the 66% 2°C Scenario embodies a well-planned emissions reductions schedule: market players have certainty of the coming transition and invest accordingly. The apparent risk is that stranded assets become larger with more limited visibility about the policy direction, or an unanticipated switch in policy direction or the intensity of emissions reduction (Box 2.6).

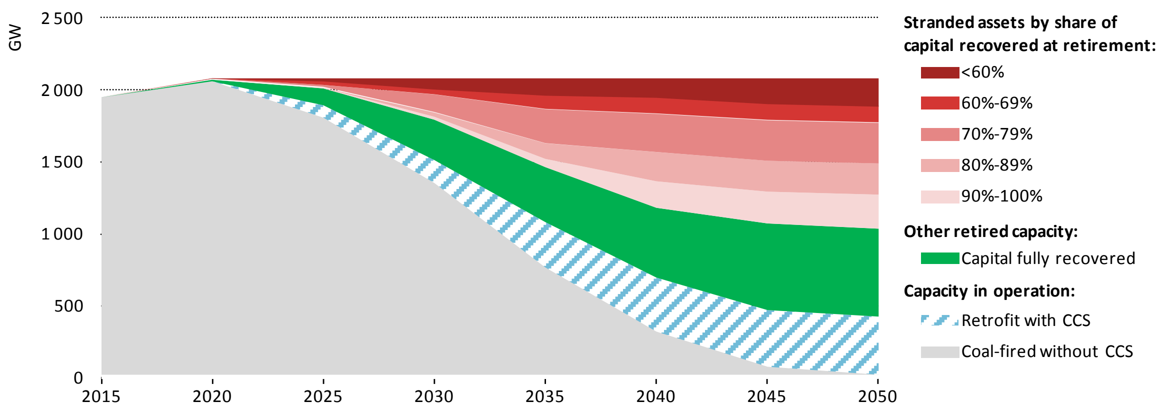
Figure 2.36 • Cumulative stranded assets in the power sector in the 66% 2°C Scenario, 2015-2050



Key message • Global stranded capital would surpass USD 300 billion by 2050 in the 66% 2°C Scenario, most of it related to coal-fired power plants.

In the 66% 2°C Scenario, the installed capacity of the global fleet of coal-fired power plants without CCS would fall from some 1 950 GW today to near-zero by 2050, with the exception of some combined heat and power plants. This is a considerable departure from the path in the New Policies Scenario, where unabated coal-fired power plants remain a fixture of power systems through 2050. However, while the phase out of coal capacity is dramatic, not all retirements indicate stranded capital. Of the total capacity that is phased out by 2050, some 600 GW – about 40% of the total – would have fully recovered its initial capital investment, another 450 GW would have recovered more than 80% of its capital and some 200 GW would have recovered less than 60% (Figure 2.37).

Figure 2.37 • Global coal-fired power plants currently in operation or under construction in the 66% 2°C Scenario



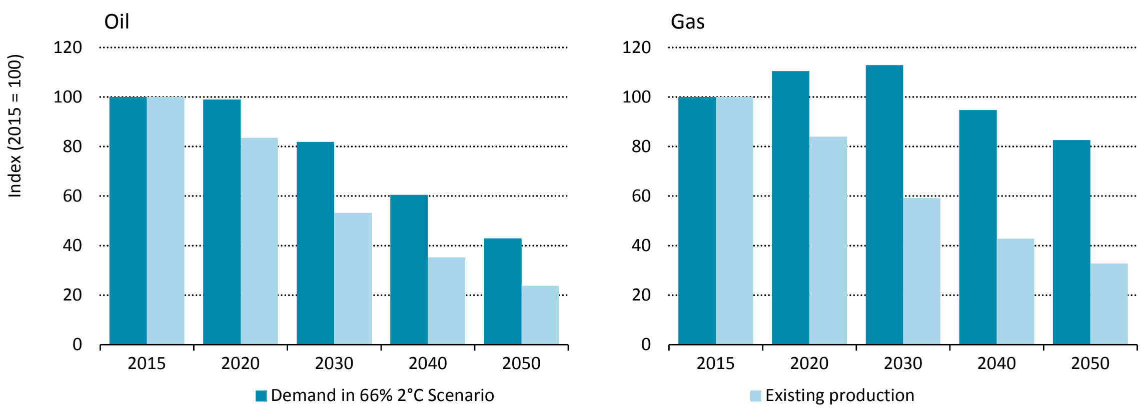
Note: NPS = New Policies Scenario.

Key message • Coal-fired power plants in operation or under construction are either retrofitted with CCS or phased out by 2050 and two-thirds of retired capacity fail to fully recover the initial capital investment.

The development and deployment of CCS technologies provides a level of asset protection for fossil fuelled power plants. Power plants can be designed and built with the option to be retrofitted with CCS technologies; for example, providing the necessary space to add carbon capture equipment at a later date. Retrofitting fossil fuelled power plants helps to extend the original asset's operational life as CO_2 prices rise and emission limits fall. In doing so, CCS technologies reduce the amount of stranded assets in the power sector and the associated financial strain on energy companies. Where the operations of coal-fired power plants without CCS soon become incompatible with the emissions trajectory of the 66% 2°C Scenario, the continued operation of fossil fuelled power plants equipped with CCS would be fully compatible through to 2050.

The *fossil fuel upstream sector* is, besides the power sector, the one that carries the main risk for stranding assets as a result of climate policy. In our analysis, stranded assets in the upstream sector refer to production facilities, including coal mines, oil and gas wells and processing plants, that fail to recover their capital investment as a result of climate policy.[58] For oil and gas, the relationship between the decline in demand in the 66% 2°C Scenario and production declines from existing fields provides a crucial backdrop to the stranded assets discussion. In the 66% 2°C Scenario, the maximum annual decline for oil demand in any year would be just over 3.5% per year, while the maximum decline in gas demand would be less than 2.5% per year. As examined in *WEO-2016*, the observed decline rate for conventional oil fields that have passed their peak in production is around 6% per year, and if all investment were to cease entirely, this decline rate would accelerate to the natural decline rate, which is closer to 9% per year (IEA, 2016a). The average global decline rates for gas fields are broadly similar. In order to keep oil and gas production at the levels required in the 66% 2°C Scenario, these declines would need to be offset by developing new reserves in known fields, and by discovering and developing new oil and gas resources (Figure 2.38).

Figure 2.38 • Global oil and gas demand, and observed decline in current oil and gas supply in the 66% 2°C Scenario



Key message • The decline in currently producing fields is greater than the anticipated decline in oil and gas demand in the 66% 2°C Scenario.

In the 66% 2°C Scenario, between 2014 and 2050, around 350 billion barrels of new oil resources and reserves would need to be developed to ensure a smooth match between supply and demand. Similarly, around 115 trillion cubic metres (tcm) of new gas resources and reserves would need to be developed. In the New Policies Scenario, oil and gas demand grows to 2050 and so around 850 billion barrels of new oil resources and reserves need to be developed and around 180 tcm of gas. The 500 billion barrel and 65 tcm differential between the two scenarios provides some boundaries for the discussion about stranded assets in the upstream sector. It is

58 The upstream sector encompasses oil and gas extraction as well as coal mining.

investment in these volumes that runs the most risk of becoming surplus to requirements. In particular, a portion of the resources that are developed in the New Policies Scenario, but that are not developed in the 66% 2°C Scenario, have already had money spent on their discovery and appraisal. The capital already spent proving up these reserves, i.e. the exploration costs, would not be recovered in the 66% 2°C Scenario and could therefore be considered stranded. Of the 500 billion barrel and 65 tcm differential between the two scenario projections, around 300 billion barrels and 30 tcm consists of proven, but undeveloped, reserves. It is not simple to assign their value, particularly since the costs were incurred many years ago, but we estimate the expenditure incurred to be around USD 400 billion for oil and USD 120 billion for gas.

Beyond these exploration costs, there is no reason why other upstream oil and gas assets should become stranded in the transition, provided the process is one in which a consistent and credible course towards decarbonisation is pursued. As with the power sector, if the path towards the 66% 2°C Scenario is clear and visible to investors, there would be little reason for oil and gas companies to develop new resources in the expectation of a much higher trajectory for demand and prices.

Coal is hit harder than oil or gas in terms of the decline in demand in the 66% 2°C Scenario. Indeed, the decline in demand would be greater than the natural decline in coal production from existing mines. A portion of existing coal mining capacity would therefore need to be shut-in before the mines are fully exhausted – these are at risk of becoming stranded assets. In quantifying this, it is important to recognise that over the lifetime of a mine, the costs of labour and the fuel and power required for the mining equipment far outweigh the capital expenditure necessary. For example, while capital often comprises around 50-75% of the total costs of a new oil project, it can represent less than 15% of total expenditure for a new greenfield coal mine. In the 66% 2°C Scenario, around 1 400 million tonnes of coal equivalent (Mtce) capacity, one-quarter of current production, is closed between 2014 and 2050 before the mines are fully depleted. The value of stranded assets in the upstream coal sector is less than USD 12 billion, significantly lower than stranded capital in the power and oil and gas sectors. This is because the majority of mines that are shut have already recovered their invested capital well before they are closed. Of more concern is the impact that closing this level of mining capacity would have on direct mining jobs. In the 66% 2°C Scenario around one million direct mining jobs would be lost due to the premature closure of assets, around 20% of current global coal mining employment.

Besides stranded assets in the upstream sector, with the drop in oil demand in the 66% 2°C Scenario, there is also a risk that some oil refineries would become stranded assets. However, while there is over 65 mb/d refinery at risk of closing by 2050 in this scenario (around two-thirds of total capacity today), this is unlikely to result in any significant stranded investment. Most of the current refineries that would need to close in the 66% 2°C Scenario in early years are in developed countries: these were largely built some time ago and have already recuperated the capital invested into them. Some refining capacity has been built more recently (within the past ten years), but this is mostly located in the Middle East and Asia. Refineries in these regions remain robust even in the 66% 2°C Scenario thanks to the availability of cheap feedstock or relatively resilient demand. In total, the value of stranded investment in the refining sector in the 66% 2°C Scenario would be around USD 20 billion.

Box 2.6 • Delayed action on climate change and stranded assets

The level of stranded power plant and upstream fossil fuel assets analysed in the 66% 2°C Scenario hinges on the assumptions that the transition starts immediately at the pace and level needed; that all market participants act rationally; and that the policy and market signals related to the low-carbon transition are credible and visible. As investors adjust to lower demand and price levels of the 66% 2°C Scenario, they avoid loss-making investment that could bear the risk of becoming stranded. In the following, we construct a “disjointed transition case”, in which we examine the possibility that climate action is delayed until 2025 and an abrupt and unexpected step-change in mitigation policies occurs in 2025, whatever the reason. The assumption is that to 2025, operators invest expecting that prices and demand will continue to rise as in the New Policies Scenario. In 2025, a sudden shift in climate policy is assumed to occur, with policy makers seeking to ensure that cumulative energy sector CO_2 emissions between 2015 and 2100 remain as in the 66% 2°C Scenario (790 Gt). Once these policies are enacted, the pace of the emissions reduction is then faster than in the 66% 2°C scenario to make up for the lack of effort over the preceding ten years. This is a hugely disruptive case for energy markets and the abrupt change in 2025 would pose enormous challenges to the industry. For example, from 2025, oil demand would need to fall by around 4% per year to 2050, one-third greater than the rate seen over the same period in the 66% 2°C Scenario. Gas demand would need to decline 50% faster than in the 66% 2°C Scenario, while the pace of decline for coal would be over twice as fast. For a transition to materialise at such a pace, massive policy intervention would be required, leading to an unprecedented ramp up of capacity for low-carbon infrastructure.

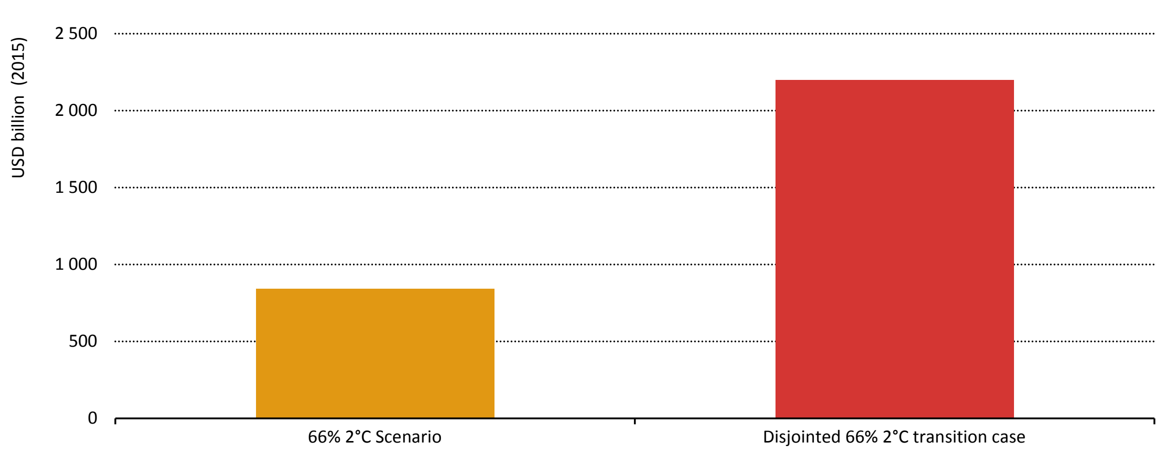
The implication for stranded assets would accordingly be substantial; the combined effect across all sectors would be a rise by a factor of nearly three over the level of the 66% 2°C Scenario. In the power sector, stranded assets would be some USD 80 billion higher to 2050, 25% beyond the level in the 66% 2°C Scenario. The assets most at risk of becoming stranded in the 66% 2°C Scenario would be those currently in operation that were affected by the immediate impact of price reductions from 2015. In the disjointed case, the ten-year period between 2015 and 2025 where prices and demand follow the New Policies Scenario, provides an extended opportunity for these assets to recuperate their capital investment. Over the 2015 to 2025 period, however, some countries would continue to invest in new unabated coal-fired power plants. While these plants can operate normally to 2025, their operations would plunge thereafter, stranding the majority of their invested capital. On balance this latter effect leads to an increase in the overall level of stranded assets in the power sector.

The increase in upstream oil and gas stranded assets in the disjointed case is much larger, given the required pace of decline of demand. While a significant part of the sudden reduction in demand that occurs in 2025 would again be absorbed by declining output from existing fields, two types of stranded assets would still arise (in addition to the stranded exploration capital discussed above). First, as was the case with the power sector, projects developed between 2015 and 2025 that were expecting prices to follow the New Policies Scenario outlook could fail to recover their invested capital. Larger scale and higher cost assets reliant on high and rising oil and gas prices over a prolonged period after 2025 would be most at risk. In addition, part of the prolonged reduction in demand would be absorbed by shutting in fields that have already been developed. The stranded exploration capital would largely be similar to the 66% 2°C Scenario, but total stranded oil investment would be above USD 1 trillion and there would be over USD 300 billion stranded natural gas assets.

Coal assets would again be less affected; indeed the level of stranded assets in the disjointed case is actually lower than in the 66% 2°C Scenario. This is because many of the mines that get stranded in the 66% 2°C Scenario result from investments made between 2008 and 2012, a period when the outlook for the coal market and coal prices appeared to be much more promising than it does today. Many of these mines have relatively high breakeven costs and so the capital at risk is higher than for mines we would assume to come online in the future. A price path following the New Policies Scenario to 2025 covers most of the critical timeframe for these high-cost mines to recoup the capital invested into them. The disjointed case therefore leads to stranded coal assets of around USD 7 billion, most of which stems from projects that were recently commissioned or are scheduled to come online over the medium term.

Taken together, it is evident that a disjointed energy sector transition would significantly increase the value of cumulative stranded assets, demonstrating the importance of early action on emission reductions to avoid unnecessary losses (Figure 2.39).

Figure 2.39 • Cumulative stranded assets in the 66% 2°C Scenario and the disjointed 66% 2°C transition case



Key message • A disjointed energy sector transition would increase stranded assets by a factor of three, relative to the 66% 2°C Scenario.

Implications for energy security and import bills

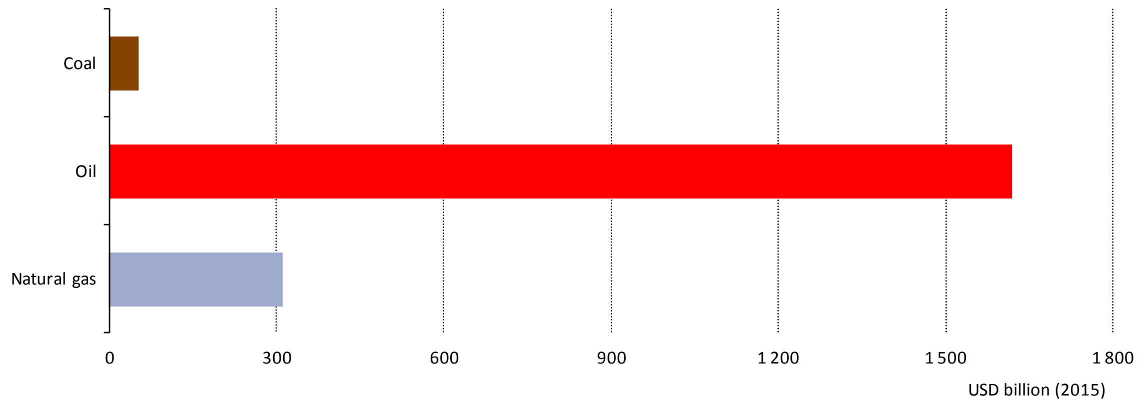
The energy security implications of the 66% 2°C Scenario vary by fuel. Security of electricity supply, an issue that often takes a back seat in energy security discussions, becomes a key energy security concern, as electricity becomes the most used energy carrier thoughout the economy and as most of this electricity is produced by variable renewables. This raises the oft-discussed issue of ensuring adequate system reliability by enhancing flexibility in the power system with a combination of improved networks, energy storage, demand-side response measures and flexible power plants (discussed in the power section above and in detail in the *World Energy Outlook 2016*).[59] In the 66% 2°C Scenario, the rising share of variable renewables is accommodated through the effective management of the demand for electricity supply and a rising amount of energy storage at utility or decentralised level, in order to guarantee system reliability. But to facilitate the necessary investments, and to ensure the reliability of power supply at all times, wider reforms to the design and operation of electricity markets will often be necessary. Electrification and the advent of a "smarter", more responsive energy system will also require constant vigilance from policy makers on issues of cybersecurity.

Energy security deliberations span well beyond the power sector, as, for many countries, it relates to their reliance on imports to satisfy domestic energy demand. Such concerns have two main dimensions: the actual physical level of imports dependency and the monetary value that is associated with it. The latter is a particularly important measure, as fossil fuel import bills can be

59 For further details on the integration of variable renewables in the power sector, see *World Energy Outlook 2016* (IEA, 2016a).

a major economic concern. Although the 66% 2°C Scenario is not designed specifically to this end, its aggressive pursuit of a path to facilitate achievement of climate goals helps to achieve the desirable co-benefit of improving the balance of payments of net importers. Within the G20 group, the net-importing countries stand to benefit from reduced import bills, with the value of oil imports falling by over USD 1 600 billion, gas-imports by around USD 300 billion and coal imports by around USD 50 billion (Figure 2.40).

Figure 2.40 • Net savings in imports bills for fossil fuel importing G20 countries in the 66% 2°C Scenario relative to the New Policies Scenario, 2050



Key message • Fossil fuel import bills would fall in the importing countries of the G20 group in the 66% 2°C Scenario.

Naturally, the other side of this equation is that revenues for fossil fuel producers and exporters are reduced relative to the New Policies Scenario. In the 66% 2°C Scenario, these revenues remains very substantial: net export revenues of fossil fuel exporters in the G20 group amount to a cumulative USD 17.7 trillion for oil and gas over the years to 2050, compared with a cumulative USD 13.4 trillion for the previous 35 years. Revenues at this scale would provide the opportunity for exporters to reduce vulnerabilities by taking steps to limit their dependence on fossil fuel revenue, as Saudi Arabia is doing with its sweeping Vision 2030 reform programme. It is, nevertheless, clear that in the world of a 66% 2°C Scenario, the export market for fossil fuel producers is much smaller than one based on the projections of the New Policies Scenario. Without additional compensating measures, such as through structural reforms, this is likely to result in economic pressure for the countries concerned.[60]

Implications for household energy expenditure

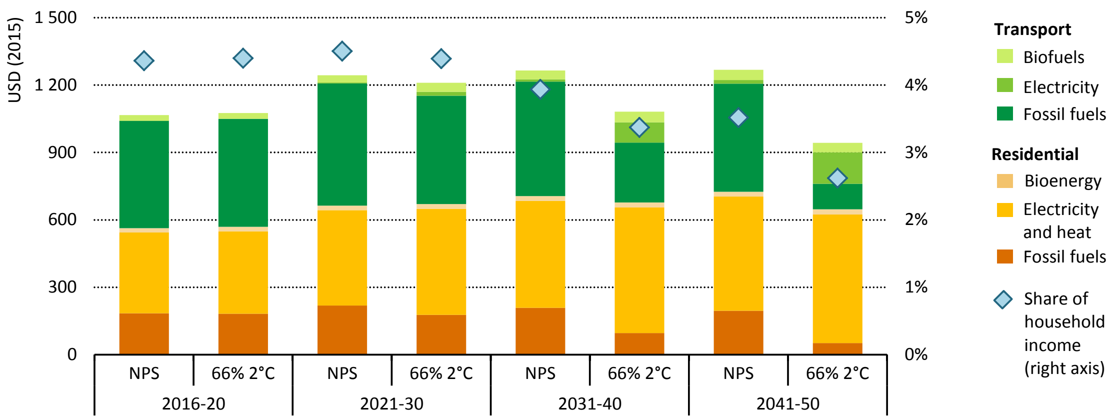
The investment required to reduce emissions in the industry, transport and buildings sectors would be significantly higher in the 66% 2°C Scenario than in the New Policies Scenario. The purchase of more efficient appliances, boilers and other equipment, the insulation of buildings or the purchase of electric cars brings about higher upfront investment needs. The increase of investment limits the ability of households (which are responsible for a large part of the investment made) and firms to invest in other activities. Given that household consumption, in general, is a particularly important driver of economic growth, this is a major policy consideration.

Yet, there is another side to the story. For households, the share of disposable income that is allocated to energy expenditures varies by country, depending, for example, on the level of

60 For more analysis of structural policy reforms, see OECD (forthcoming).

taxation and extent of domestic energy resources. But energy expenditures, in particular for oil-based transport fuels, can be an important burden on household budgets. Aggressive efficiency measures as assumed in the 66% 2°C Scenario offers some important relief. With the deployment of more efficient technologies, as well as low-carbon technologies (such as renewables-based heat or electric cars), energy expenditures for fuel use are generally much lower. In the 66% 2°C Scenario, on a global average, household energy expenditure for fuel consumption drops below the level of the New Policies Scenario during the 2020s, and below today's level during the 2040s, freeing up additional resources (Figure 2.41). However, upfront additional investments would remain still well above the New Policies Scenario, which would require the development of appropriate financing models.

Figure 2.41 • Global average household energy-related fuel expenditures in the New Policies and the 66% 2°C Scenarios



Note: NPS = New Policies Scenario; 66% 2°C = 66% 2°C Scenario.

Key message • After 2030, average household energy expenditures in the 66% 2°C Scenario would be lower than today.

Implications for air pollution

The energy sector is the largest emitter of air pollution, including harmful pollutants such as sulfur dioxide (SO_2), nitrogen oxides (NO_X) and fine particulate matter (smaller than 2.5 micrometres) ($PM_{2.5}$), which are responsible for about 6.5 million premature deaths each year (IEA, 2016c).[61] The pursuit of strategies to reduce GHG emissions from the energy sector can have important co-benefits for mitigating air pollution. For example, at a global level, combustion-related SO_2 emissions mainly relate to the power sector. A power sector strategy to displace unabated coal-fired power generation with non-emitting fuels (such as renewables and nuclear power) can therefore reveal important reductions of SO_2 emissions. In the 66% 2°C Scenario, this could cut energy-related SO_2 emissions by almost 60% in 2050, relative to the level of the New Policies Scenario (Figure 2.42).

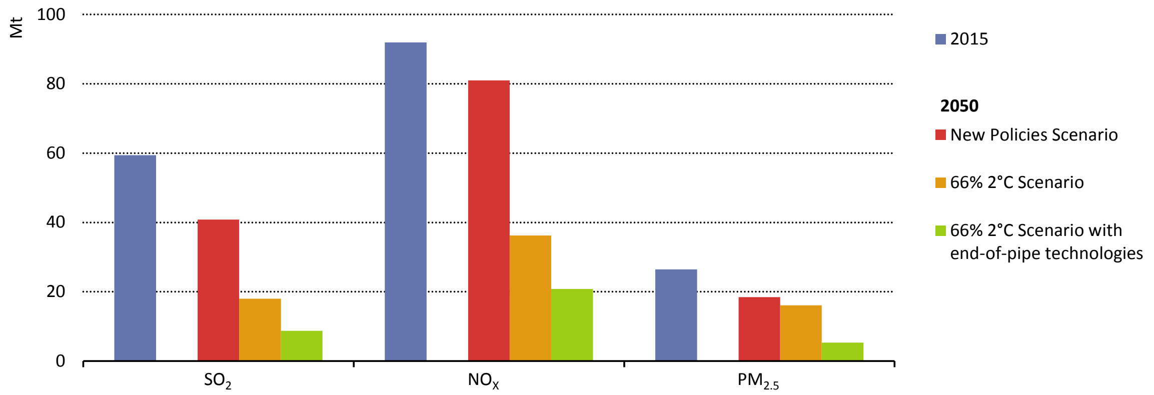
Combustion-related NO_X emissions, large parts of which are, at a global level, related to the transport sector, would also be drastically reduced in the 66% 2°C Scenario. The switch to electric cars, both for passenger and road freight applications, is a key means for combustion-related NO_X emissions to drop by 55 % in 2050, relative to the level reached in the New Policies Scenario. This

61 Recognising that air pollutant emissions cannot simply be calculated by applying emissions factors to fuels (as emissions are typically very process dependent), the IEA's assessment of air pollutant emissions is conducted using a link of its World Energy Model with the Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) model of the International Institute for Applied Systems Analysis (IIASA). Results for air pollutant emissions in this study are based on *Energy and Air Pollution: World Energy Outlook Special Report*, which includes an in-depth discussion of the applied methodology (IEA, 2016c).

reduction is particularly important in urban areas, where traffic is a major source of air pollution and, given proximity of human exposure, is a significant cause of premature deaths.

Fine particulate matter ($PM_{2.5}$) is one of the most harmful substances among the various air pollutants. There are multiple sources: in developing countries, $PM_{2.5}$ emissions are often linked to the traditional use of biomass in inefficient cookstoves; in developed countries, they stem from industrial facilities and power plants, as well as road traffic. While a decarbonisation strategy for the energy sector is a key ingredient for their reduction, an entire phase out of $PM_{2.5}$ emissions would require wider efforts, including energy access policies in developing countries and strategies to avoid traffic in urban areas. In some cases, the pursuit of climate targets can create conflicts with air pollution targets if the latter are not being adequately taken into account. For example, while the use of wood burning stoves for residential heating is a favourable option for the achievement of climate targets, it can contribute to indoor air pollution if appropriate standards are not put in place.

Figure 2.42 • SO_2, NO_X and $PM_{2.5}$ emissions by scenario, 2015 and 2050



Key message • Large-scale deployment of low-carbon technologies could mitigate not only CO_2 emissions, but also SO_2, NO_X and $PM_{2.5}$ emissions.

While important, the pursuit of a decarbonisation strategy alone is not sufficient to mitigate air pollution. The deep pollutant emissions reductions required to minimise adverse impacts on human health require more stringent pollution control policies to facilitate the uptake of advanced air pollution control technologies. Their adoption would further reduce emissions beyond the level reached in the 66% 2°C Scenario.

Implications for energy access

Access to modern energy services – electricity and clean cooking facilities – is a crucial factor in human development. Every advanced economy has required secure access to modern energy services to underpin its development and foster prosperity. While many countries are focussing on energy security and decarbonising their energy mix, many others are still trying to secure sufficient energy to meet basic human needs. In developing countries, access to affordable and reliable energy services is a building block to reduce poverty, improve health and increase productivity, and is a necessary step to promote economic growth. Today, billions of people lack reliable access to either electricity or clean cooking facilities, or both.

Even among G20 countries, energy access remains a crucial problem: around 300 million people (6% of the population) have no access to electricity today, many of which are in India and Indonesia. This is around a quarter of the global population without access. Maintaining access to electricity for those already with access is also a challenge. For many who currently have access to an electricity connection, the supply is not reliable and the steady delivery of electricity in many countries is a daily challenge. Major strides have been taken: in 2015, the government of China announced achievement of universal electricity access, culminating the largest national electrification programme in history. In India, the electrification rate reached 81%, almost doubling the 43% rate of access in 2000. But, at a global level, the situation is not expected to improve much further in the next few decades unless more vigorous action is taken, especially outside the G20 group. In the New Policies Scenario, more than 780 million people are projected to remain without access to electricity in 2030 globally, of which 66 million are in G20 countries. By 2040, while G20 countries are almost fully electrified, more than half a billion people still remain without access at a global level.

In addition to the lack of electricity access, there are around 1.4 billion people in G20 countries who still rely on the traditional use of biomass for cooking today, or 30% of the population of the G20 group. This represents around half of the more than 2.7 billion people without modern cooking access in the world. For cooking, the outlook is worse than for electricity access in our projections, with nearly 1.9 billion people still without access in 2040 in the New Policies Scenario. This is largely because in several regions, growth of cooking access solutions does not keep up with population growth. Such trends are already apparent today. In sub-Saharan Africa, for example, the rate of access to modern cooking has been decreasing year-on-year in recent years, and in general, access to electricity is prioritised in national agendas over modern cooking access.

The projections for energy access in the 66% 2°C Scenario are similar to those of the New Policies Scenario – while climate policies can have positive co-benefits for energy access, they are not enough in isolation. Dedicated policies beyond those that decrease GHG emissions will be needed to achieve improvements in modern energy access. Nevertheless, climate policies can complement the challenge of meeting energy access targets. The faster deployment of renewable and distributed technologies as a result of meeting climate objectives is expected to bring down costs of low-carbon technologies worldwide. This would allow a greater deployment of decentralised electricity access solutions in rural areas in particular, which currently account for 83% of the global population without access. Climate policies can also provide co-benefits for modern cooking access. One example is the displacement of LPG for water heating and cooking services in urban areas in developing countries through the use of electricity and renewables. This is a useful measure for reducing GHG emissions in urban areas, but would also help to restrain the tight LPG supply that can be observed in some rural areas (such as in India), where the amount of LPG available is insufficient to meet the needs of the poorest segments of the population. Although there is a risk that climate policies will increase the consumer price of LPG, targeted additional access policies can help to ensure that LPG remains available and affordable as a clean cooking option for those without access in rural areas. There may be further synergies between climate policies and measures to improve modern cooking access. Biomass consumption in the 66% 2°C Scenario would reach twice the level of today in 2050, which would increase competition for biomass and available land (see Box 2.1). Although traditional uses of biomass today are rarely ever in competition with modern uses of biomass, such pressure might increase in the future with the pursuit of climate goals and could act as a spur to incentivise a switch from the traditional use of biomass for cooking and a more efficient use of biomass in general.

Climate policies can be designed to complement energy access objectives. But achieving univeral access to modern energy by 2030 would generally have a negligable impact on global energy demand and GHG emissions. The IEA has been providing in-depth analysis related to access to modern energy services for almost two decades and consistently highlights that even achieving universal access to electricity and clean cooking by 2030 would add less than 1% to overall energy demand and energy-related CO_2 emissions in that year (IEA, 2013). This means that the additional contribution to climate change from achieving greater access to energy for the under-served is negligible. In some cases, it can even be positive. The IEA has estimated that, to replace kerosene lamps, providing electricity access to the 1.2 billion people (16% of the world's population) that still lack access to electricity could save an estimated 35 Mt of CO_2 per year, in addition to the multiple benefits that such a switch could provide (IEA, 2015). Another example is the traditional use of biomass for cooking. There is much uncertainty about the actual level of GHG emissions from traditional cookstoves using solid biomass, since their efficiency is widely variable. But, typically, their efficiency is low and the combustion process incomplete. Their displacement is a key priority for energy access, given their adverse impacts on human health. But this can reap climate benefits, too, as biomass is a renewable source only if harvested sustainably, while burning biomass in traditional stoves may actually emit more GHG emissions (i.e. including methane and nitrous oxides emissions) than even LPG stoves.

References

IEA (International Energy Agency) (forthcoming), *Energy Technology Perspectives 2017,* OECD/IEA, Paris.

- (2016a), *World Energy Outlook 2016,* OECD/IEA, Paris.

- (2016b), *Energy Technology Perspectives*, OECD/IEA, Paris.

- (2016c), *Energy and Air Pollution: World Energy Outlook Special Report,* OECD/IEA, Paris.

- (2016d), *Re-powering Markets*, OECD/IEA, Paris.

- (2016e), *20 Years of Carbon Capture and Storage*, OECD/IEA, Paris.

- (2016f), *Energy Efficiency Market Report*, OECD/IEA, Paris.

- (2015), *World Energy Outlook 2015,* OECD/IEA, Paris.

- (2013), *World Energy Outlook 2013,* OECD/IEA, Paris.

IMF (International Monetary Fund) (2016), *World Economic Outlook*, IMF, Washington, DC.

OECD (Organisation for Economic Co-operation and Development), (forthcoming), *Investing in Climate, Investing in Growth,* OECD, Paris.

Rose, S., et al. (2013), "Bioenergy in Energy Transformationand Climate Management", *Climatic Change,* 123 (3), pp. 477-493.

Sarkar, R. (2016), "The ZEV Imperative: Achieving >80% Decarbonization of Transportation", *FISITA World Automotive Summit*, p. 14, Palo Alto, California, www.fisita-summit.com/res/storage/R_Sarkar_ppt.pdf, accessed January 16, 2017.

UNDP (United Nations Population Division) (2015), *Word Population Prospects: The 2015 Revision*, United Nations, New York.

Chapter 3: Global Energy Transition Prospects and the Role of Renewables

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Key messages

The world has entered a period of energy transition. The global imperative to achieve sustainable growth and limit climate change, combined with a rapid decline in costs and rising investment into renewable energy, has put in motion a transition of the way that energy is produced, distributed and consumed. Innovation and the accelerated deployment of low cost renewable energy, energy efficiency, widespread electrification and the use of information and communications technologies are essential to accelerating this energy transition.

The importance of reducing energy-related CO_2 emissions and achieving the goal of limiting climate change is at the heart of this transition. The carbon-dioxide (CO_2) emission intensity of the global economy needs to be reduced by 85% over the next 35 years in order to limit global temperature increases to below 2^{o}C degrees compared to 1990 levels. This means reducing energy CO_2 emissions by 2.6% per year on average, or 0.6 Gt per year on absolute terms. To be in line with the aim of the Paris Agreement to reduce energy-related CO_2 emissions, the global energy transition (or decarbonisation) **must be accelerated over the next 35 years in order to prevent global temperatures from rising more than 2^o C.**

Governments have a critical role in accelerating the energy transition. Governments have the responsibility to enact an enabling policy framework that provides long-term certainty for the private sector and ensures a positive environment for the energy transition. Market signals must be put in place that create financial incentives for low-carbon solutions. The governments of the G20 countries play a key role in this regard given that they account for a large share of global greenhouse gas emissions.

A holistic approach to the energy transition should be at the heart of the G20 efforts. The transition is feasible and in line with the Paris Agreement and the UN Sustainable Development Goal as it encompasses all sectors of the energy system and would ensure an affordable, secure and sustainable supply of energy. The transition goes beyond the energy sector, and will have wide-ranging benefits for the economy and for the way societies operate.

Renewable energy and energy efficiency measures can potentially achieve 90% of required carbon reductions. We have a good understanding today of what the energy transition can look like from a technical, policy and business perspective. Accelerated deployment of renewable energy and energy efficiency measures are the key elements of the energy transition. By 2050, the accelerated deployment of renewables and energy efficiency can achieve around 90% of the emissions reductions, while the remainder would be achieved by fossil fuel switching and carbon capture and storage (CCS). In the decarbonisation case presented here, nuclear power stays at today's level until 2050, and CCS is exclusively deployed in the industry sector.

In this decarbonisation case, energy demand in 2050 would remain around today's level due to intensive energy efficiency improvements. Energy intensity improvements must double to 2.5% per year by 2030 and continue at that same level until 2050. **The share of renewable energy must meanwhile rise from around 15% of the primary energy supply in 2015 to around 65% in**

2050. Around half of the incremental energy intensity improvements could be attributed to renewable energy. This includes efficiency gains from renewable energy-based heating, cooling and transport and electrification coupled with renewable power. We have witnessed accelerated deployment of solar and wind power on a global scale in recent years, based on technology innovations and dramatic cost reductions. Electrification of end-use sectors will gather speed, for example in electric vehicles and heat pumps.

The energy supply mix would change substantially. Fossil fuels will continue to play a role in the energy transition. Total fossil fuel use in 2050 would be a third of today's level but the use of coal would decline the most, while oil demand would be at 45% of today's level – roughly equivalent to today's oil production volume of OPEC. The world will not run out of fossil fuels, but it will stop using the most challenging resources that have high production costs, such as oil sands and Arctic oil. While natural gas can be a "bridge" to greater use of renewable energy, its role will be a short-lived one unless it is coupled with high levels of CCS. There is a risk of path dependency and future stranded assets if natural gas deployment expands significantly without long-term emissions reductions goals in mind.

Such an energy transition is affordable – but it will require additional investments in low-carbon technologies compared to the Reference Case or business-as-usual. Further significant cost reductions will be major drivers for increased investments across the range of renewables and enabling technologies, but **cumulative additional investment would still need to amount to USD 29 trillion over the period 2015-2050 to meet decarbonisation targets.** This is in addition to the investments in the Reference Case of USD 116 trillion in the same period. Incremental system costs would amount to USD 1.8 trillion in 2050. However, reducing human health damages (a fundamental driver for energy policy in key G20 countries) and CO_2 emissions from fossil fuels would save between two- and six-times more than the costs of decarbonisation.

From a macroeconomic perspective, the energy transition can fuel economic growth, create new employment opportunities and enhance human health and welfare. GDP will be boosted around 0.8% in 2050 compared to the Reference Case. The cumulative gain through increased GDP from now till 2050 will amount to USD 19 trillion. Increased economic growth is driven by the investment stimulus and enhanced through pro-growth policies, in particular the use of carbon pricing and recycling of proceeds to lower income taxes. Important structural economic changes will take place. While fossil fuel industries will incur the largest reductions in sectoral output, those related to capital goods, services and bioenergy will experience the highest increases. The energy sector (including energy efficiency) will create around six million additional jobs in 2050 compared to the Reference Case. Job losses in fossil fuels would be completely offset by new jobs in renewables, with more jobs being created by energy efficiency activities. The overall GDP improvement will induce further job creation in other economic sectors.

Improvements in human welfare, including economic, social and environmental aspects, would generate benefits far beyond those captured by GDP. Around 20% of the decarbonisation options identified are economically viable without consideration of welfare benefits. Yet renewables improve welfare in ways that are not captured by GDP. The remaining 80% are economically viable if benefits such as reduced climate impacts, improved public health (a key consideration, given the millions of deaths every year due to air pollution), and improved comfort and performance are considered. However, today's markets are distorted - fossil fuel consumption is still subsidised in many countries and the true cost of burning fossil fuels, in the absence of a carbon price, is not accounted for. To unlock these benefits, the private sector needs clear and credible long-term policy frameworks that provide the right market incentives.

Early action is critical in order to limit the planet's temperature rise to 2^{o}C and to maximise the benefits of this energy transition, while reducing the risk of stranded assets. Taking action early is also critical for feasibly maintaining the option of limiting the global temperature rise to 1.5^{o}C. Delaying decarbonisation of the energy sector would cause the investments to rise and would strand an additional USD 10 trillion in assets. In addition, delaying action would require the use of costly technologies to remove carbon from the atmosphere (known as negative emission technologies, such as bioenergy with CCS) in order to stay below the 2^{o}C target. Also, further development of solutions will be needed for sectors where no significant or economically attractive solutions exist today. Early action is needed in deploying renewables, improving energy efficiency and establishing the enabling infrastructure and supporting technologies.

Sectoral approaches must be coupled with systems wide perspectives to address the main challenge of reducing the direct use of fossil fuels in end-use sectors. Deep emission cuts in the power sector are a key opportunity and should be implemented as a priority. The power sector is currently on track to achieving the necessary emissions reductions, but it must continue ongoing efforts and focus more on power systems integration as the share of variable renewable power rises. In addition, electricity accounts only for about one-fifth of final energy use today. The share of electricity in total final energy consumption needs to increase to 30% by 2050. This means that a broader coupling between the power sector and end-use sectors such as transport, buildings and industry is required. In transport, the number of electric vehicles needs to grow and new solutions will need to be developed for long-range haul trucks, airplanes and shipping. It is critical that new buildings are of the highest efficiency and that existing ones are retrofitted and refurbished at an accelerating rate. Buildings and city designs should facilitate renewable energy integration. There is an important role for governments to facilitate enabling infrastructure such as recharging stations, smart grids and sustainable biomass supply chains.

Carbon emissions from energy use need to fall to zero by 2060 and stay at this level thereafter to achieve targets by the end of the century. In order to limit the global temperature increase to below 2^{o}C with a 66% probability of meeting the target, a significant effort also is required to reduce industrial process and land use emissions to or below zero. Without such progress in non-energy sectors, the climate goal cannot be reached.

Increased investment in innovation needs to start now to allow sufficient time for developing the fundamental new solutions that are needed for multiple sectors and processes, many of which have long investment cycles. Technology transfer will also be part of this transition. For more than one-third of all current energy applications, economically viable technology solutions are limited today, mostly in end-use sectors (buildings, industry and transport). Solutions will also be required to overcome institutional barriers in these sectors, such as addressing carbon leakage in industry, and developing policies for bunker fuel use for aviation and shipping. Technology innovation efforts will need to be complemented by new market designs, new policies and by new financing and business models.

Introduction

This chapter presents the findings from IRENA's analysis that employs its REmap approach to analyse which technologies are required for an energy transition or a decarbonisation of the energy sector in line with the goals of the Paris Agreement and to assess the implications of a 2°C scenario, with a 66% probability of meeting that target. This work builds on the REmap technology options analysis for 2030 and expands the outlook to 2050. Moreover, energy efficiency and renewable energy technology options have been combined for the first time into a full-scale REmap case up to 2050. In the REmap case, while all types of low-carbon technologies are assessed in detail for a decarbonisation of the energy sector, the chapter pays particular attention to the role of renewable energy technologies in realising the transition. This is complemented by a cost-benefit analysis and an assessment of the REmap energy mix macroeconomic impacts, using a version of the E3ME econometric model that takes the REmap findings as the main input.

Box 3.1 • G20 Renewable energy toolkit and REmap

The REmap programme is part of the G20's toolkit of Voluntary Options for Renewable Energy Deployment (G20, 2015). In 2016, the G20 countries, under the Chinese presidency, agreed on a voluntary action plan for renewable energy. It builds on a toolkit with five pillars:

- Analysis of renewable technology costs, cost reduction potentials and best practice exchanges.
- Best practice exchanges on enabling policy framework design and power system integration of high shares of variable renewables.
- Development of a renewable energy specific risk mitigation facility.
- Assessment of country renewable energy technology potentials and development of roadmaps.
- Acceleration of modern bioenergy deployment.

The G20 accounts for 75% of the renewable energy potential worldwide (IRENA 2016a). This is the first time this important body has started an action agenda on renewable energy. Earlier REmap analysis for G20 has shown that use of renewable energy in the global energy mix can double by 2030, compared to the 2015 level (IRENA, 2016a). The results show that in each of the G20 countries, significant renewable energy opportunities remain beyond today's policy plans, and that the benefits exceed the cost. These options can double the global renewable energy share by 2030, a growth rate of more than one percentage point per year. (This does require using "modern" renewable energy sources, replacing any traditional uses of bioenergy, such as for cooking and water heating, that are inefficient or unsustainable.) The potential to accelerate renewable energy deployment varies by country. Some countries may get less than a 10% share of energy from renewable sources in 2030, while others can achieve more than a 90% share. The starting points vary, the state of the policy frameworks vary and the resource endowment and fuel pricing varies. But all countries can accelerate their renewable energy deployment significantly.

Definitions of the Reference Case and REmap

The analysis is based on a sector and technology bottom-up analysis for individual countries, whose output is fed into a global macro-econometric model that assesses the macroeconomic impacts of REmap compared to the Reference Case.

The analysis starts with the Reference Case, which is the most likely case based on current and planned policies and expected market developments for each country's energy sector. IRENA has collected data from the G20 countries about their national energy plans and goals for the period 2015 to 2050.

This Reference Case reflects the Nationally Determined Contribution (NDC) if it is already an integral part of the country's energy plan (which is the case for around 60% of the total global primary energy supply).[62] If there were any data gaps, such as missing years, in preparation of the Reference Case, they have been bridged using credible third-party scenarios (e.g. IEA). Important renewable energy deployments and energy efficiency improvements are already included in the Reference Case since each country has a goal to increase its current renewable energy capacity and improve the energy efficiency of its energy system.

The analysis then examines a low-carbon technology pathway that goes beyond the Reference Case for an energy transition. This is called the REmap case. Technologies covered under REmap include:

- Renewable energy technologies[63] for energy and as feedstock for production of chemicals and polymers (referred to as "RE" in the rest of this chapter).
- Energy efficiency measures ("EE") and widespread electrification that also improves efficiency[64] ("ELEC").
- Carbon capture and storage for industry ("CCS").
- Material efficiency technologies such as recycling ("OTHERS").

REmap explores the energy transition to decarbonise the energy system in line with the goal in the Paris Agreement of limiting global temperature rise to less than 2°C above pre-industrial levels with a 66% probability. Energy CO_2 emissions need to fall from 33 gigatonnes (Gt) in 2015 to below 10 Gt per year in 2050, then drop to zero by 2060 and stay at that level (emissions must drop below zero to limit the increase to 1.5°C). The 2°C target requires energy-related CO_2 emissions to drop to 20-22 Gt per year by 2030. Such a reduction translates to a decrease in the average CO_2 emissions per unit of gross domestic product (GDP) (or the carbon intensity of the global energy supply)[65] by more than 85% between 2015 and 2050 (IRENA, 2016c).

The analysis of the technology potential has been carried out at the sub-sector level for the world as a whole. For example, the analysis looked at iron-making processes in the steel industry.[66] Thirteen sector-specific background summaries as part of an innovation agenda have been prepared by IRENA (IRENA, 2017a).[67] The analysis also estimated the potential for additional

62 This chapter employs the physical energy content method to convert from final to primary energy.

63 All forms of renewable energy have been included, namely bioenergy, geothermal, hydropower, ocean, solar and wind energy.

64 Electrification is covered under energy efficiency as electricity-based technologies are generally much more efficient than those that rely on the combustion of fuels to deliver the same energy service.

65 In this study, carbon emission intensity is expressed in tonnes of CO_2 per USD GDP measured in purchasing power parity (PPP).

66 A detailed overview of the bottom-up methodology can be found online (IRENA, 2017b).

67 Industry: steel (referred to as "STEEL" in this chapter), cement ("CEM"), chemical and petrochemical ("CHEM"), aluminium ("ALUM") and pulp and paper ("PAPER"). Buildings: space heating ("SH"), water heating ("WH"), space cooling ("SC") and

renewable energy and energy efficiency in each G20 country beyond the Reference Case. Country results have been aggregated to assess the developments for the G20 as a whole, and they also have been scaled up to the world level based on global coverage factors by energy carrier and sector.

The energy demand of each end-use sector has been disaggregated to the main energy-consuming applications. Physical level activity (e.g. tonnes of steel production) has been combined with technology options. Each technology option has been characterised by its energy mix and cost. The growth rates of the various physical level activities were estimated for the period between 2015 and 2050. Estimates of the energy consumption for these activities under the Reference Case were also included. For REmap, the potential of increasing the use of low-carbon technologies for each application was estimated based on market growth rates, resource availability and other constraints.[68] Key energy and materials system interactions were taken into account.[69]

The assessment pays special attention to renewable energy-enabling technologies and sector-coupling solutions, such as electric vehicles, district heating and cooling, heat pumps and interconnectors that allow electricity to flow between networks.

The CO_2 emissions in both the Reference Case and REmap have been estimated by country and by sector. The system boundaries of the emission accounting have been provided later in the chapter where relevant. This allows the assessment of the changes in each sector's CO_2 emissions between 2015 and 2050 with the introduction of low-carbon technologies.

Five economic and human welfare indicators have been deployed to characterise the impacts of REmap. These include:

- The investment needed to achieve the REmap technology pathways.
- Macroeconomic impacts of those investments in renewable energy and energy efficiency. Those include impacts on GDP and employment, along with structural effects.
- Additional proxies of welfare, since GDP is a limited measure of human welfare. GDP does not capture important components, such as improved health because of reduced air pollution[70] and climate impacts avoided.
- The additional energy supply cost (i.e. system cost).
- An estimation of stranded assets, including both energy assets (in electricity generation and the upstream fossil fuel supply sector) and assets in the end-use sectors of buildings and industry.

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cooking ("COOK"). Transport: passenger cars ("CAR"), other road passenger ("ROAD_OTH"), other passenger transport ("PASS_OTH") and freight ("FRE"). Power ("POWER") and district heating and cooling ("DHC").

68 See (IRENA, 2017a) for details of this assessment.

69 For example, a switch to new iron-making processes reduces availability of blast furnace slag as a clinker substitute. Also biomass scarcity has been accounted for across all possible applications.

70 A detailed description of IRENA REmap costs and externality methodology can be found online (IRENA, 2016d; IRENA, 2014a).

Box 3.2 • Definition of the economic and human welfare indicators used

- Additional investment needs (in USD trillion): These needs are the sum of the differences between investment needs based on the technology mix in REmap and the Reference Case in 2015-50. Investment needs in 2015-50 are estimated by summing the investment in each year in that period. Investment in a given year is estimated as the product of the capital investment cost and the deployment of the technology in that year. These include investments for both energy generation capacity (e.g. power plants, heating equipment, etc.) and for infrastructure (e.g. transmission and distribution lines, energy storage, recharging infrastructure for electric vehicles, and hydrogen and CO_2 pipelines). Investment needs for a Delayed Policy Action scenario have not been estimated as that scenario is not considered as an option in this assessment. Investments related to delayed policy action could be significantly higher than the investment needs for the Reference Case or REmap given the effort that would be required to remain within the same carbon emission budget to realise the decarbonisation of the energy system.

- Macroeconomic impacts of those investments in renewable energy and energy efficiency: These impacts are measured in terms of GDP (total net output[71] produced by all economic sectors in a country in a given year), employment (in the renewable energy sector, in the overall energy sector and in the economy as a whole) and structural effects (i.e. differences in the contribution of different economic sectors to GDP).

- Changes in human welfare in economic, social and environmental terms: There is a broad literature on human welfare and sustainable development indicators, with significant work having been undertaken by institutions such as The World Bank, the Organisation of Economic Co-operation and Development (OECD) and the European Commission. This analysis does not intend to be as comprehensive, focusing only on two proxies to welfare: the reduced externalities from impacts of fossil fuel use on human health and from impacts of climate change (in USD trillion per year). They are calculated as the sum of the differences between the external costs from generation of energy-related to air pollutants and CO_2 emissions based on the energy mix in REmap and the Reference Case in 2050. No aggregation into a single welfare indicator has been done.

- Incremental system costs (expressed in USD trillion per year): These are the sum of the differences between the total capital and operating expenditures of all energy technologies based on their deployment in REmap and the Reference Case in 2050.

- Stranded assets (in USD trillion): The calculated stranded assets are the remaining book value[72] of assets substituted for before the end of their anticipated economic lifetimes and without recovery of any remaining value because of the need for a deep decarbonisation of the energy system in the 2015-2050 period.[73]

Table 3.1 shows the key assumptions used in this assessment for both the Reference Case and REmap. All assumptions have been set exogenously to the analysis.

No differentiation has been made in energy prices between the Reference Case and REmap. The energy prices provided in Table 3.1 are an average of both cases. Depending on region and demand/supply balance, prices would differ. For the macroeconomic analysis, lower future

71 Value of output minus the value of required inputs.

72 Book value is defined here as the cost of an asset, minus accumulated depreciation.

73 A detailed background paper of IRENA's stranded assets assessment can be found online (IRENA, 2017c).

energy prices are assumed in the REmap case, since they represent relevant expenditures and incomes for different economic agents. The prices used are in line with the New Policies Scenario and the 450 Scenario of the *World Energy Outlook 2016* (IEA, 2016).

Moreover, no carbon price has been assumed in this analysis. The approach taken to estimate the incremental system costs, and subsequently the cost of abatement of low-carbon technology options (in USD per tonne of CO_2), follows a government perspective where energy prices exclude all energy taxes and subsidies, and a standard 10% discount rate is applied. This shows the cost of the transition as governments would calculate it. For the macroeconomic analysis, on the contrary, a carbon price is used since it affects the energy costs that companies and households face, and the tax revenue that governments collect. The carbon prices assumed for the Reference and REmap cases are, respectively, based on the New Policies Scenario and the 450-Scenario of the *World Energy Outlook 2016*, differentiated by country and sector (IEA, 2016).

Since for some indicators (e.g. energy prices) there are differences between what were assumed in Chapters 2 and 3 of this study, a sensitivity analysis on the REmap analysis was carried out that uses similar assumptions to quantify the changes in the results. For instance, by making use of higher energy price assumptions, the sensitivity analysis also allows the assessment of the impact of introducing a carbon price to the energy system. The sensitivity analyses are presented at the end of this chapter.

Table 3.1 • Key assumptions

	Unit	2015	2050
Population	millions	7 350	9 700
GDP	%/yr in 2015-2050		2.8
Average energy prices			
Coal	USD/GJ	2.5	3
Crude oil	USD/barrel	50	80
Natural gas	USD/MBtu	7	11
Biomass feedstock	USD/GJ	-	8
Discount rates	%	-	10

Note: All economic data refer to real 2015 USD. GJ=gigajoules, MBtu= million British thermal units.

The aim of REmap is to communicate results to a diverse audience. This includes policy makers to technology developers, academia and the general public. Therefore, REmap employs a unique methodology to assess the potential of low-carbon technologies. The identification of the additional low-carbon technology potential is the most important step of the process. For this purpose, a spreadsheet-based simple accounting framework was developed. The aim is not to apply complex models or sophisticated tools to assess the potential, but to facilitate an open framework with countries to aggregate the national energy plans, and subsequently identify technology options. Deployment of technology options has been chosen independently. The choice of a technology analysis approach instead of a scenarios approach is also deliberate. IRENA's REmap is an exploratory study, and is not meant as a target-setting exercise. Instead, countries can make informed choices as to how to use the identified options. REmap was designed from the start to be practical and to co-operate directly with countries in order to analyse and discuss their specific cases in detail. Such an approach also creates an opportunity to discuss implementation of the options identified with the countries, and to improve the existing analysis continuously over the years. Thus, REmap is an evolving exercise.

Given its nature, the REmap approach also has a number of limitations. For instance, REmap uses a single time step for the years of 2030 and 2050. The time period between 2015 and 2030/50 is not assessed in detail. For example, the analysis does not take into account interactions, developments and dynamics across technologies or feedbacks in energy prices due to demand and supply changes (e.g. rebound effects). Moreover, inter-temporal dynamics and inertia that determine deployment, system constraints, path dependencies, and competition for resources, etc. also are not explicitly taken into account (Saygin et al., 2015).

An earlier study has compared the findings of REmap with the results of the IEA-ETSAP models at both national and global levels. The premise of this comparative analysis was that the sequence of technology options in REmap's cost-supply curves should be similar to the technology options selected by the ETSAP models as they increase the required share of renewables in their energy system. The comparison suggests that for a number of countries and regions, the results are directly comparable to the REmap country results (Kempener et al., 2015).

For the macroeconomic analysis, the REmap energy mixes are taken as an exogenous, fixed input. The energy mixes are fed into a fully-fledged post-Keynesian global macro-econometric model (E3ME) that takes into account the linkages between the energy system and the world's economies within a single and consistent quantitative framework.[74]

Energy transition to 2050: a key role for renewable energy

Energy CO_2 emissions fall by more than 60% by 2050 while GDP triples

Policy makers are looking for effective approaches to achieve decarbonisation. Renewable energy is a key solution. Reducing CO_2 emission levels by increasing the deployment of renewable energy is already affordable and would result in significant economic benefits. Many NDCs already anticipate deploying more renewables in order to reduce greenhouse gas (GHG) emissions. Those efforts need to be accelerated to reduce emissions quickly enough to limit global temperature increases.

Earlier analysis has indicated that renewable energy technologies, in combination with greater energy efficiency gains, can achieve most of the required emissions reductions by 2030 and 2050 (IRENA, 2016c). Some fossil fuel switching, CCS in industry and nuclear could close any remaining gap.

The Reference Case represents developments in energy-related CO_2 emissions based on policies in place and considers the latest energy policy of each G20 country as indicated in its national energy plan. For countries outside of the G20, the results have been scaled to the global level based on the findings from the G20 countries. In the Reference Case, GDP at purchasing power parity triples and primary energy demand grows by 50% between 2015 and 2050. Emissions will continue to grow, reaching 45.1 Gt by 2050 (+29%) (CO_2 emissions from fossil fuel combustion only grow to 40.2 Gt per year).

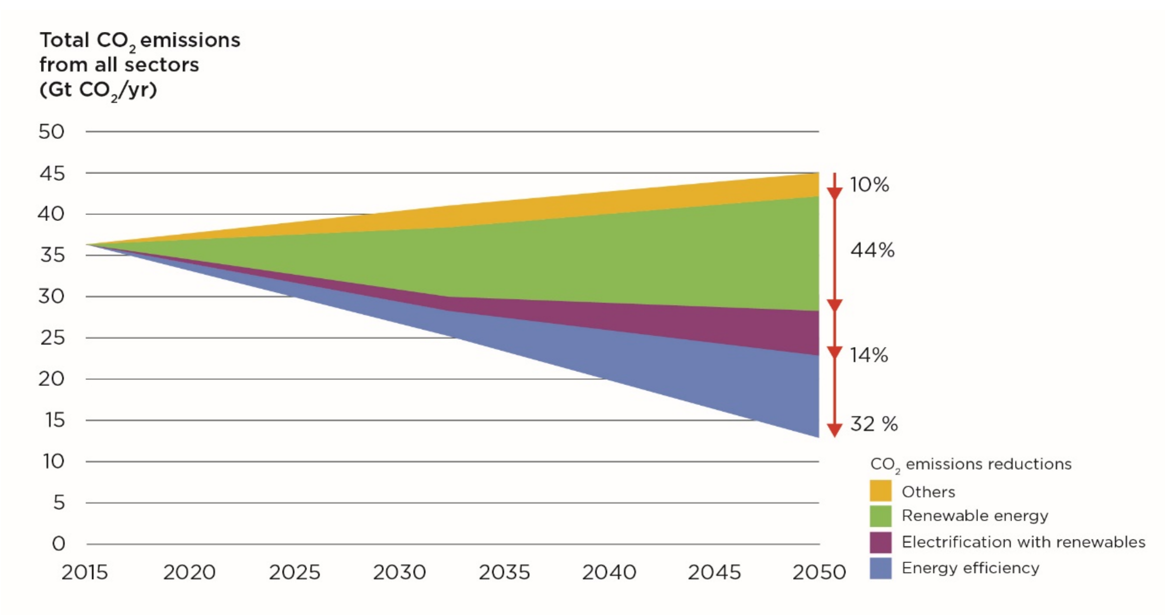
It should be noted that the energy plans for 40% of the world's total primary energy supply were not consistent with the corresponding NDCs. If all energy plans matched the NDCs, CO_2 emissions in the Reference Case would be about 3 Gt per year lower in 2030. Fully implementing the NDCs, therefore, is a welcome first step. However, they alone are not enough. If implemented in full, they will reduce emissions by 20% by 2030, far less than the 50% decline that is needed. Revising the NDCs in 2020 to make them more ambitious is a critical step, therefore, even more ambitious plans are needed for 2030 and beyond. Given the urgent need to reduce emissions and the long lead times for deploying low-carbon technologies, early action should be a key part of these plans.

74 See Annex B for details on the methodology.

Energy efficiency measures and renewable energy will deliver the lion's share of the emissions reductions needed to decarbonise the global energy system. Energy and materials efficiency improvements can reduce emissions by about 4 Gt by 2030, about 30% of the emissions reductions needed. Electrification cuts another 1.5 Gt, or 10% of what is needed. Renewable energy options that were identified based on the bottom-up analysis of the G20 countries can reduce emissions by another 10 Gt. As a result of these measures, 2030 emissions would fall to 25.5 Gt in 2030 (with the remaining fossil fuel combustion emitting about 22 Gt of CO_2 emissions per year).

This level is sufficient to put the world on a 2°C pathway in 2030. But to keep the world on this pathway, efforts need to be strengthened further between 2030 and 2050. This would require energy-related CO_2 emissions to drop to below 10 Gt by 2050, which would be 70% lower than 2015 levels and 31 Gt less than in the Reference Case. About half of these reductions would come from renewable energy technologies. Energy efficiency improvements and electrification would account for the bulk of the other half. The remaining 10% of reductions would come from additional measures in industry, notably CCS, material efficiency improvements and structural changes.

Figure 3.1 • Primary CO_2 emission reduction potential by technology in the Reference Case and REmap, 2015-2050



Notes: CO_2 emissions include energy-related emissions (fossil fuel, waste, gas flaring) and process emissions from industry. If only fossil fuel emissions were displayed in this figure, CO_2 emissions would start from 33 Gt in 2015 and would reach 40.5 Gt and 9.5 Gt per year in 2050 in the Reference Case and REmap, respectively.

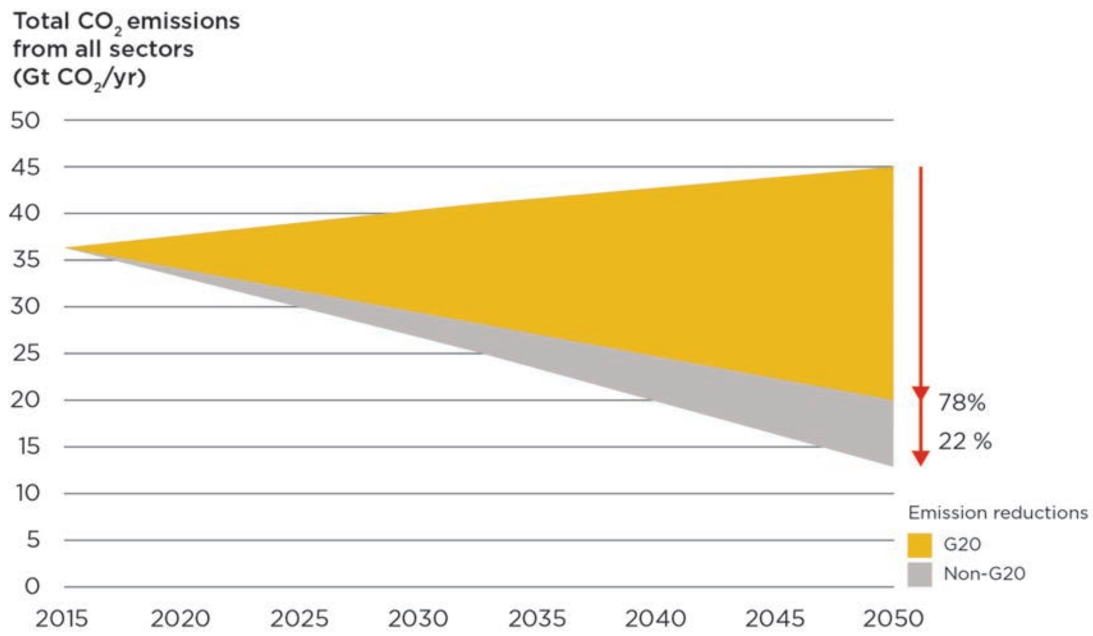
Key message • Renewables would account for half of total emissions reductions in 2050, with another 45% coming from increased energy efficiency and electrification.

G20 has a key role to play in the energy transition

Meeting the goals of the Paris Agreement requires the world to speed up decarbonisation of the enrgy sector. The UN Sustainable Development Goals (SDG) also call for an accelerated deployment of renewable energy. This means scaling up the deployment of mature renewable technologies such as solar photovoltaic (PV) and onshore wind. It also requires an accelerated rollout of emerging technologies.

This energy transition will not happen by itself. There is a critical role for governments to create an enabling policy frameworks that provide long-term assurance for the private sector and ensures a conducive environment for the energy transition. Market signals must be put in place that create monetary incentives for low-carbon solutions. The G20 will be responsible for making 80% of the global energy-related CO_2 emissions reductions needed to reach the 2050 goals (Figure 3.2). That requires a holistic approach at the heart of the G20 efforts.

Figure 3.2 • CO_2 emission reductions in the G20 and non-G20 groups, 2015-2050



Notes: CO_2 emissions include energy-related emissions (fossil fuel, waste, gas flaring) and process emissions from industry. If only fossil fuel emissions were displayed in this figure, CO_2 emissions would start from 33 Gt in 2015 and would reach 40.5 Gt and 9.5 Gt per year in 2050 in the Reference Case and REmap, respectively.

Key message • **CO_2 emissions will increase to 45.1 Gt by 2050 in the Reference Case but need to be reduced by more than 30 Gt. To reach the 2°C target, the vast majority of the needed emissions reductions must be made in G20 countries.**

Emissions from all sectors must be cut, with the greatest reductions coming from power generation and buildings

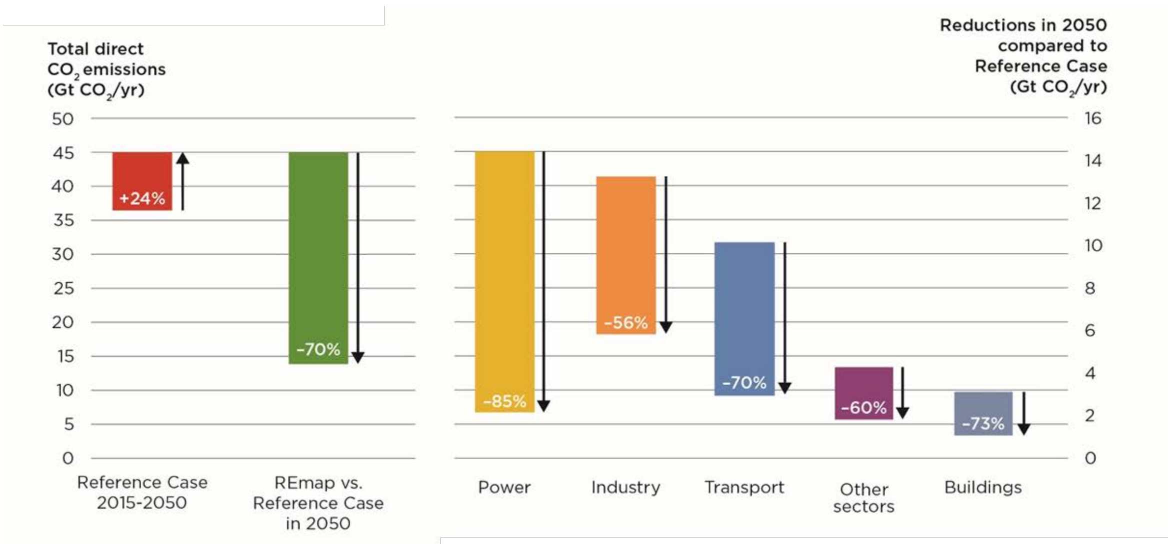
Achieving a global energy transition that limits global temperature change to less than 2°C is technically feasible. We also understand what this energy transition would look like from a technical, policy and business perspective. It would be achieved largely by the accelerated deployment of renewable energy and energy efficiency measures (Figure 3.1)

The largest CO_2-emitting sectors are electricity generation and industry. They are responsible for about 65% of all energy-related CO_2 emissions today. The remaining 35% comes from transport, buildings and district heating. Buildings have a low share, but this increases if indirect emissions related to electricity use are included. The sector breakdown of CO_2 emissions stays roughly constant between 2015 and 2050 under the Reference Case (Figure 3.3).

Under REmap, electricity generation sector emissions would fall to around 2 Gt per year by 2050, a decrease of 85% compared to the 2015 level. This is achieved by an aggressive deployment of renewable energy technologies, especially solar and wind. These renewable technologies would generate more than 80% of all electricity by 2050. Natural gas and nuclear would generate the remaining 20%. The decrease in power sector emissions is also an outcome of the demand-side measures in industry and buildings to reduce electricity use for heating and cooling.

In the REmap case, emissions in the building sector would decrease by about 70% by 2050. Transport and industry are the two most challenging sectors. Transport's emissions would be halved, while industry would become the largest remaining emitter.

Figure 3.3 • CO_2 emissions by sector in REmap relative to the Reference Case, 2015-2050

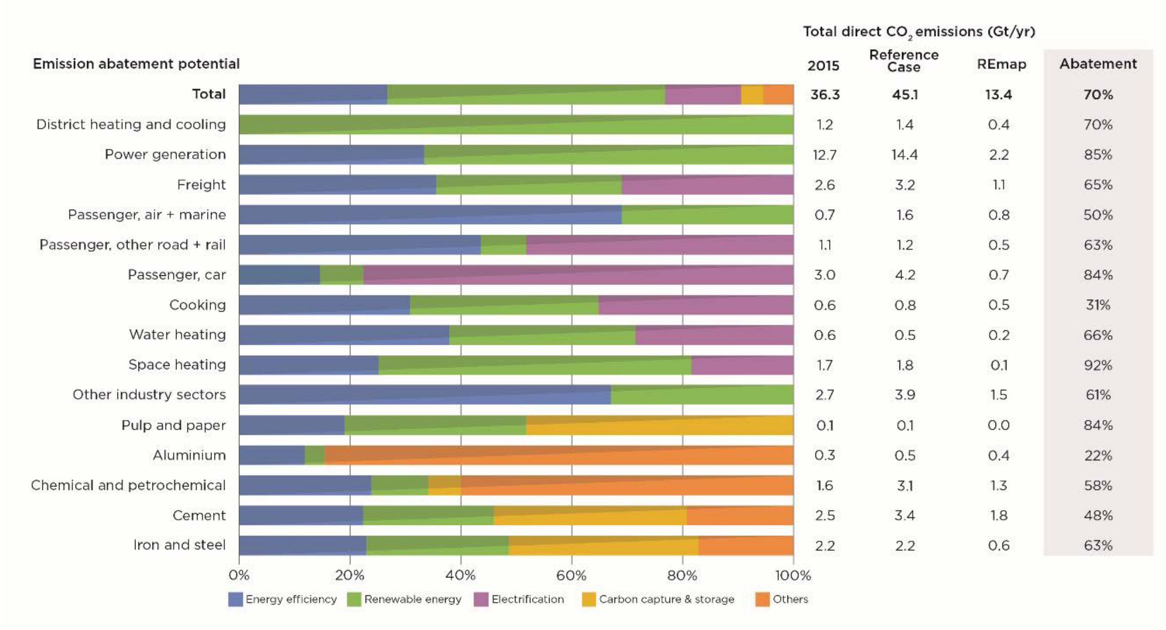


Notes: CO_2 emissions include energy-related emissions (fossil fuel, waste, gas flaring) and process emissions from industry. If only fossil fuel emissions were displayed in this figure, CO_2 emissions would start from 33 Gt in 2015 and would reach 40.5 Gt and 9.5 Gt per year in 2050in the Reference Case and REmap, respectively.

Key message • By 2050, total energy-related CO_2 emissions will need to decrease to below 10 Gt. CO_2 emissions from the power and buildings sectors will be almost eliminated. Industry and transport would be the main sources of emissions in 2050.

The breakdown of CO_2 emission reductions in the Reference Case and in REmap in 2050 are illustrated in Figure 3.4. To put this figure in perspective, it is necessary to understand the magnitude of emissions in each sector and the opportunities to reduce them. Developments in each sector are discussed in the following sections.

Figure 3.4 • CO_2 emissions reductions in REmap compared to Reference Case by technology, 2050



Notes: CO_2 emissions include energy-related emissions (fossil fuel, waste, gas flaring) and process emissions from industry. If only fossil fuel emissions were displayed in this figure, CO_2 emissions would start from 33 Gt in 2015 and would reach 40.5 Gt and 9.5 Gt per year in 2050 in the Reference Case and REmap, respectively.

Key message • While CCS and other low-carbon technologies will play the main role in industry, renewables and efficiency will be the most important for heating and cooling in buildings. The transport sector requires a mix of renewables and electrification.

Electricity generation

Electricity generation is the sector with the largest CO_2 emissions. Worldwide, generation is projected to increase to about 32 000 terawatt-hours (TWh) by 2030 and to around 43 000 TWh per year by 2050. Total electricity generation capacity would reach more than 12 000 gigawatts (GW) by 2050.

In the REmap case, total electricity generation remains just below the level in the Reference Case. That is because improved energy efficiency and demand-side measures would offset any increases in demand from increased electrification.

In the REmap case, renewable energy technologies would generate an increasing share of that electricity. The renewable share would rise from 23% of total electricity generation in 2015 to 59% by 2030 and 82% by 2050. That compares to a 31% share by 2030 in the Reference Case. This assessment is largely based on the country level scenario work carried out by the German Aerospace Centre (DLR) for the fifth energy revolution series (DLR-GPI, 2015).

Renewable sources like wind and solar that substitute for fossil fuels in electricity generation will achieve about a quarter of the more than 31 Gt CO_2 emissions reductions required in 2050 compared to the Reference Case. Additional emissions reductions will come from demand-side measures, such as energy efficiency improvements in appliances used in buildings, or using more efficient industrial motors and implementing better industrial energy management systems. Those reductions are included in the analysis for each end-use sector. If they were also accounted for under electricity generation, the sector would represent one-third of all the CO_2 emissions reductions needed in 2050. As a result of higher shares of renewable energy and more efficiency in end-use applications, overall CO_2 emissions from power generation would decline to

2 Gt per year by 2050 compared to 13 Gt in 2015. In this assessment, the deployment of CCS in the power sector has been excluded. This choice was made because of the additional costs CCS adds to electricity generation. With low energy prices, power plants combined with CCS may continue to be perceived as high-risk and not economically viable.

Industry

Industry is the second-largest CO_2 emitting sector, representing a third of all emissions worldwide. The industry sector as a whole accounts for the largest share 35% of the emission reductions in the REmap analysis. Within the sector, chemical, petrochemical and steel are among the largest energy consumers. However, less energy-intensive sectors, such as food and textile (covered under "other industry") will also have important roles in reducing industrial CO_2 emissions. Cement's share is large because of the process emissions that can be reduced by CCS.[75]

Cement production is the largest individual CO_2-emitting industry. Making cement requires the decomposition of limestone in a process called calcination, which produces large amounts of CO_2. As a result, the industry is responsible for 8% of all global CO_2 emissions. This is one of the few industries where CCS could play a role. In REmap, 35% of all emissions reductions in the entire industry sector come from using CCS in the cement industry. More emissions reductions – 20% of the total from the sector – would come from new cement types and substitutes for clinker.

The iron and steel industry is currently a large coal user and emits about half as much CO_2 as the cement industry. Since the 18th century, coal and coke have been used as chemical reducing agents in blast furnaces to make iron. That process could be replaced by hydrogen-based direct reduced iron or even electrolysis processes similar to the technologies being employed in aluminium making. In REmap, emissions from the industry would decline by 90% to 0.6 Gt in 2050, compared to the Reference Case. One-third of this reduction would be achieved with CCS, 25% would come from renewables (largely biomass) and 40% from energy and material efficiency measures.

Chemical and petrochemical industry emissions are similar in size to those from the iron and steel industry. The industry's total direct CO_2 emissions from production could be cut by 1.8 Gt of CO_2, from 3 Gt to 1.3 Gt, by 2050.[76] About 1.1 Gt of these reductions could come from material efficiency improvements and the remainder, or 0.7 Gt, from energy efficiency measures, renewable energy and CCS.

A unique feature of the chemical and petrochemical sub-sector is that most of the carbon is stored in chemicals and other products and, is released during waste incineration. These emissions do not fall within the modelling boundaries of the chemical and petrochemical industry as they are released in the waste sector. However, if one views these emissions together, more reductions could come from replacing oil and natural gas feedstocks with biomass feedstocks or recycled plastic. Biomass is already used in commercial facilities in Brazil to produce polyethylene-terephtalate (PET) bottles, for example. Avoiding carbon from fossil fuels in plastics and chemicals could cut waste management related emissions by an additional 1.8 Gt in this sub-sector. But bioplastics and recycled plastics are currently more expensive than conventional products. Clear economic incentives are therefore needed to reduce emissions from post-consumer incineration of packaging and other types of waste.

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75 Process emissions are not energy-related CO_2 emissions. These emissions are by-products of chemical reactions that take place in the production of materials. In this chapter, their assessment for certain industries was included as they represent a high share of that industry's total emissions (e.g. cement).

76 These emissions cover those that only come from the production of high value chemicals (ethylene, propylene, butadiene, aromatics), ammonia and methanol.

CCS is a key technology under REmap for the industry sector. However, its prospect is uncertain and realising its potential will depend on location, geology, water resources and other factors. The difficulties of deploying CCS thus pose a major challenge to the successful implementation of the Paris Agreement. In fact, using CCS in industry is even more challenging than in the power sector, because industry plants tend to be process specific, smaller and more scattered than power plants. The CCS process itself may also have to be redesigned for the industry sector. It also reduces plant efficiency, and results in residual emissions because the capture process also requires heat and electricity. These challenges will need to be quickly overcome if the technology is to play a role in industry.

Buildings

The building sector is growing quickly with today's 150 billion square metres (m^2) of residential and commercial floor area projected to increase to 270 billion m^2 by 2050. Most of the growth will be in urban areas. Today, half of the world's population lives in cities, a share that will rise further. Two billion more people will live in cities over the next two decades, which will require building the equivalent of 2 000 new cities of one million inhabitants. This is an unprecedented challenge.

Heating and cooling represents 80% of the building sector's total energy demand. Space heating alone accounts for the largest share of all thermal energy needed in a building, at about 60% of the total. The share for cooling is small today but demand for cooling is expected to increase to more than that of space heating by 2050.

It will be critical that new cities (and in fact, all new buildings in all locations) are built according to the highest energy efficiency standards to minimise energy demand. Using modern building shell insulation technology, heating and cooling demand can drop by one order of magnitude compared to conventional buildings. More attention will need to be paid to retrofit or replace existing inefficient buildings. In developed countries, accelerated renovation and refurbishment offers great potential to improve energy efficiency and reduce emissions.

There are also many renewable technology options for buildings. They include bioenergy, solar PV panels and solar water heaters, geothermal energy and electrification, as well as renewable energy-based district energy networks. Also, buildings design should facilitate renewable energy integration, along with approaches like floor heating or integrated building envelop systems that significantly increase the efficiency of energy use for heating and cooling. The optimal solutions vary by country and by case.

In buildings, appliances account for one-third of all the potential (to reduce indirect emissions related to electricity use), followed by space heating. For emissions reductions in heating, improvements in building shells, such as better insulation, account for 30% of the reduction potential. Electrification of heating and other functions represents another 20%, and the direct use of renewables accounts for 50% (including deployment for cooling). More efficient cooling systems and appliances can also save emissions from electricity generation, but these are not included in the building sector (because the emission reductions occur in the power sector).

Transport

The transport sector accounted for just above 20% of all energy-related CO_2 emissions in 2015, of which passenger cars and freight transport account for 80% and aviation for 10%. The aviation sector alone contributes about 2-3% of total global CO_2 emissions and as demand increases, particularly for long-distance passenger transport, aviation's emissions are projected to continue to increase in the coming years.

In the REmap analysis, the transport sector would contribute about 20% of the total emission reductions in 2050 compared to the Reference Case. Passenger vehicles have the largest contribution followed by freight. Passenger car emissions can be cut by improving fuel economy, switching to electric vehicles (EVs) or replacing oil with liquid or gaseous biofuels or renewables-based hydrogen. The analysis shows that such steps can cut transport emissions by 3.5 Gt CO_2 per year by 2050, which is an 85% reduction compared to the Reference Case.

In the REmap analysis, people travel increasingly by buses and other communal modes within cities and over long distances as well. They also ride two- and three-wheelers. Although the number of trips made by non-car forms of transit is 60% higher than the number of trips in passenger cars, the CO_2 emissions associated with these activities are lower than for cars, representing about 20% of the total.

Electrification is a key solution for the two- and three-wheelers as well as for reducing diesel use in railways. Bus transport can also be partly electrified. Where electrification is not possible, CO_2 emissions can be cut by using more biomethane and other advanced biofuels. Under REmap, biomass is estimated to supply a quarter of all energy for non-car passenger transport (excluding aviation and shipping), with electricity representing nearly 20% of the demand. As a result, non-car passenger transport emissions can be reduced by two-thirds.

Total aviation activity is expected to grow by 3% to 5% in the coming decades, higher than for any other transport mode. Biofuels represent the main alternative to fossil fuels in aviation.

Freight transport – mainly trucks, ships and trains – represents more than 40% of transport's total energy demand. The shipping industry is the backbone of global trade and a lifeline for island communities, transporting about 90% of the tonnage of all traded goods. The freight sector's energy demand is expected to increase in line with economic and population growth.

Under REmap, renewable energy can reduce freight transport's rapidly growing CO_2 emissions. For delivery trucks, electric drive is already an economic option. About 0.6 Gt of CO_2 emissions can be reduced by using biofuels (liquid and gaseous) in heavy duty trucks and ships and another 1.5 Gt of CO_2 emissions can be cut by efficiency measures and electrification across all modes of freight transport. By taking these steps, emissions from freight would decline by two-thirds by 2050.

In addition to these technological changes, the business models in transport will change over time. This is an outcome of a number of factors, such as changing demographics, lifestyles and socio-economic status of populations. As a result of these trends, new approaches, such as car sharing and car-pooling, are gaining popularity. While these trends are excluded from this assessment, they may have impacts on future transport energy demand, depending on the extent of their development.

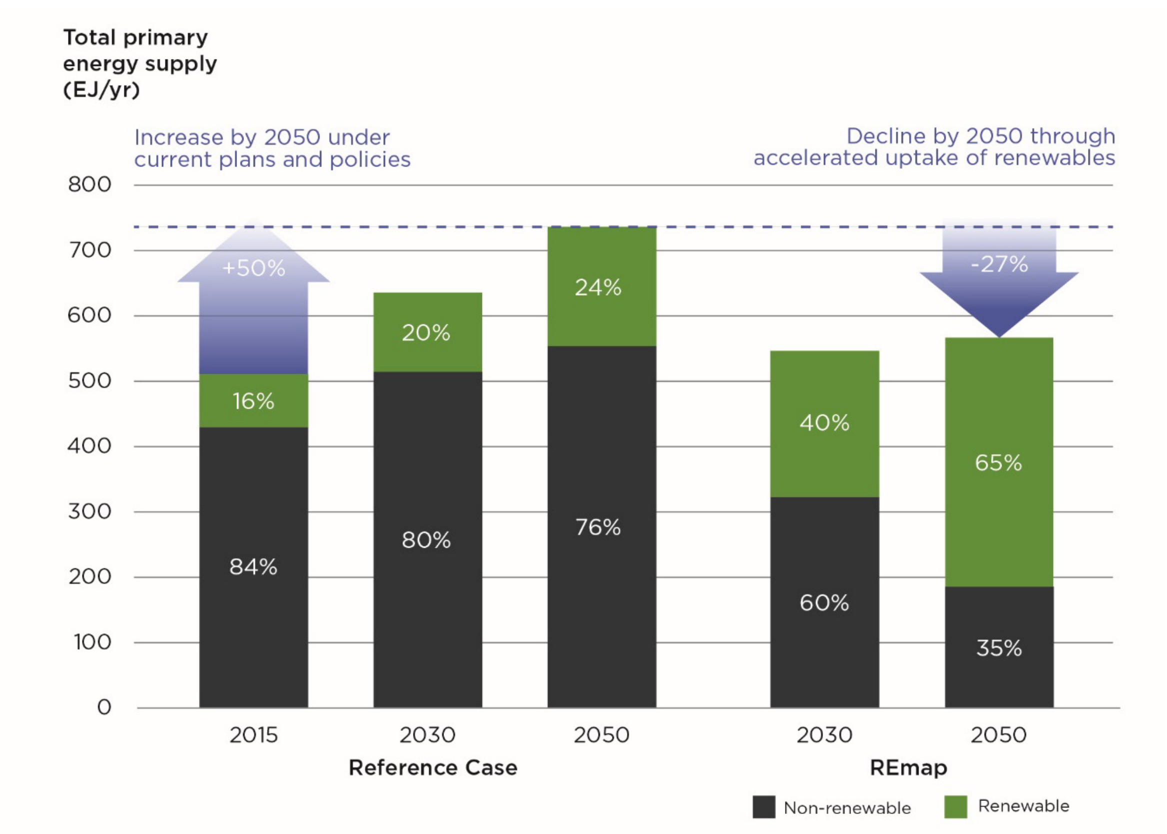
Renewables could feasibly account for two-thirds of the world's energy supply in 2050

The total energy demand in 2050 under REmap would be similar to today's level. But the supply mix would change substantially, compared to both today and to the Reference Case.

In the Reference Case, the total primary energy supply is estimated to grow by more than 50% between 2015 and 2050. This is equivalent to average annual growth of about 1.2% per year, roughly half of the rate seen in the past two decades. Despite this slowdown, the total primary energy supply would increase to about 835 exajoules (EJ) by 2050 in the Reference Case. Just under 80% of this total would still be supplied by fossil fuels in 2050, down slightly from today's level of 84%. Under today's national energy plans, renewable energy would bring little change in the supply mix over this time frame, since those plans mainly reflect market trends.

Under REmap, the total global primary energy supply in 2050 would reach 635 EJ per year in 2050, only marginally higher than today's level and 26% less than in the Reference Case. Total non-renewable energy use would be reduced by 67%. The share of renewable energy in the total primary energy supply grows to about 65% by 2050 (Figure 3.5). An overview of all renewable energy technologies deployed between 2015 and 2050 is provided in Table 3.3.

Figure 3.5 • Global total primary energy supply in the Reference Case and REmap, 2015-2050



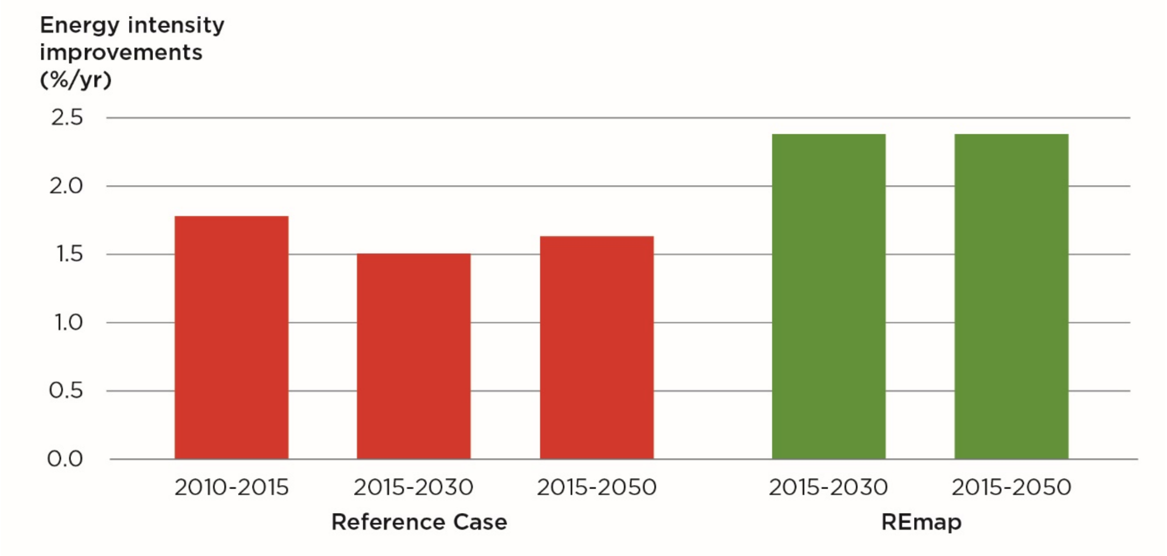
Notes: Data include the energy supply in electricity generation, district heating/cooling, industry, buildings and transport sectors. These sectors accounted for 85% of the global total primary energy supply (TPES) in 2015. Non-energy use of fuels for the production of chemicals and polymers is excluded.

Key message • Renewable energy would be the largest source of energy supply under REmap in 2050, representing two-thirds of the energy mix. This requires an increase in the renewables' share of about 1.2% per year, an eight-fold acceleration compared to recent years.

There is still an important role for fossil fuels in the energy transition. Total fossil fuel use in 2050 would be a third of today's level. Coal use would decline much faster, while oil demand in 2050 would be at 45% of today's level. For comparison, this is roughly today's oil production volume of OPEC. In the REmap case, the world will stop using the most challenging resources with high production costs, such as oil sands and Arctic oil. Even the role of natural gas as a "bridge" to renewables is a short one unless natural gas use is coupled with high levels of CCS. There is a risk of path dependency and future stranded assets (e.g. pipelines, liquefied natural gas [LNG] terminals) if natural gas deployment expands significantly without long-term emissions reductions goals in mind. Because of the need to reduce carbon emissions, most of today's fossil fuel reserves would remain unexploited.

Under REmap, total primary energy supply remains more or less flat between 2015 and 2050. Global GDP, however, triples over this period. As a result, energy intensity drops from about 5 gigajoules (GJ) per USD to 2.1 GJ per USD between 2015 and 2050.[77] This is equivalent to an energy intensity improvement rate of around 2.5% per year, representing nearly a doubling compared to the trends observed between 1990 and 2010. In 2015 the improvement rate was 1.8%, which is still much lower than what is required to reach the 2050 goal.

Figure 3.6 • Improvements in energy intensity in the Reference Case and REmap, 1990-2050

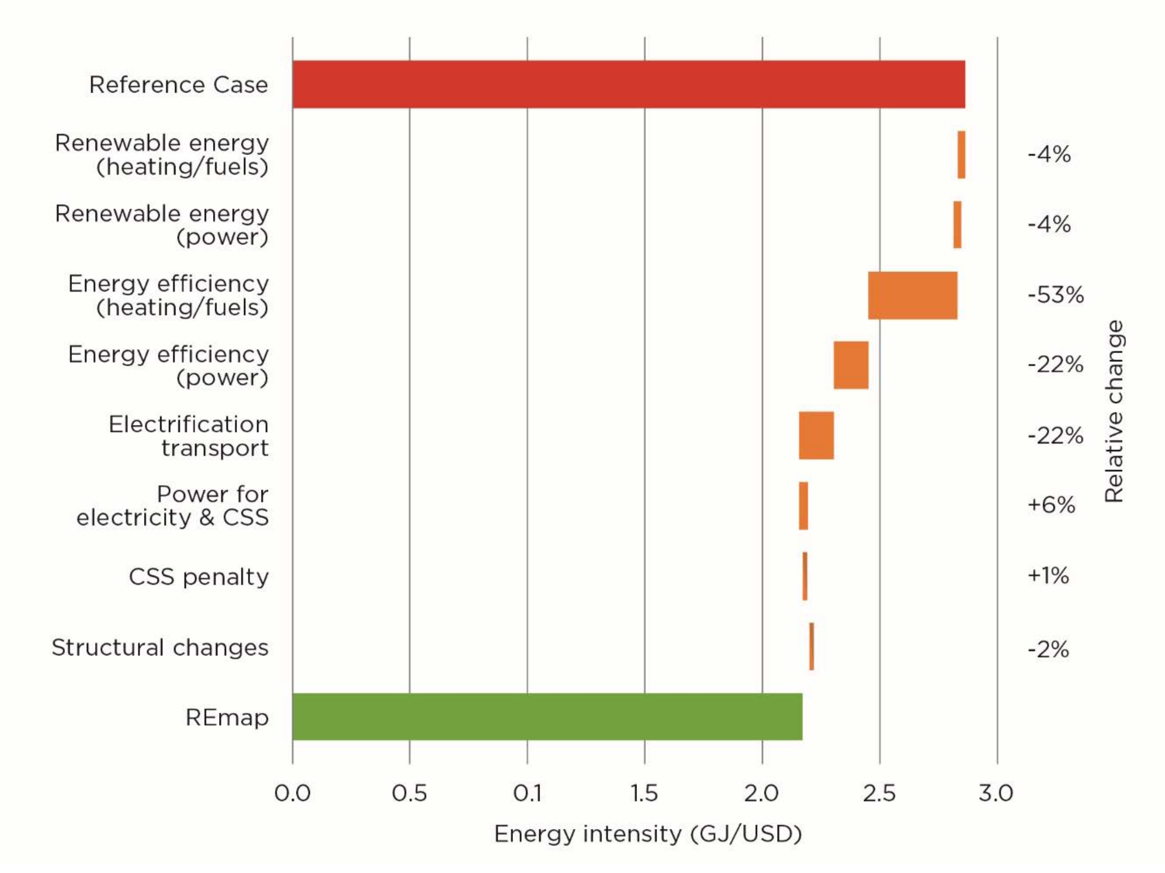


Key message • **Energy intensity improved at an annual rate of about 1.8% in recent years and is expected to be maintained in the Reference Case, while it would increase to around 2.5% per year in REmap.**

Figure 3.7 shows the factors that influence energy intensity to both decline and increase in 2050 in the REmap case compared to the Reference Case. About half of the decline (53%) is related to energy efficiency improvements in heating. This is followed by accelerated deployment of renewables that can result in a decline on a similar order of magnitude. This includes the net savings in primary energy use of 8% from accelerated deployment of renewable energy technologies. On the other hand, CCS in industry requires heat for solvent regeneration as well as for compression and pumping of CO_2. These processes increase the primary energy demand by 7% in total. The additional demand for energy offsets some of the decline in energy intensity improvements.

77 The reverse of this indicator yields energy productivity where output is divided by energy consumption.

Figure 3.7 • Energy intensity by factor in the Reference Case and REmap, 2050



Key message • Renewable energy and energy efficiency contribute equally to energy intensity improvements.

Box 3.3 • The prospect for technologies that remove CO_2 from the air

Limiting the global temperature increase to less than 2°C with a 66% probability requires emitting no more than an additional 575 - 1 125 Gt CO_2. This study assumes a carbon budget of 790 Gt CO_2. At the 2015 level of emissions, this budget would be depleted in just over 20 years. The budget would have to be one-half as large to limit the temperature increase to 1.5°C with a 50% probability.

Given the likelihood of exceeding these emissions budgets as projected in many scenario analyses, technologies that pull carbon from the air may be required to meet the goal of limiting global temperature increases. These "negative emission technologies" have two main advantages. They compensate for emissions that have already been released or could be emitted in the short-term. For example, in a scenario with delayed emissions reductions, it will be harder to reach 2°C without using negative emissions approaches. Negative emission technologies also offset emissions from sectors where abatement will be challenging, such as the manufacturing industry.

There are many negative emission technologies including:

- Direct air capture.
- Cloud treatment to increase alkalinity.
- Enhanced weathering of rock.
- Enhanced ocean productivity.

- Ocean and coastal ecosystem restoration.
- Afforestation and reforestation.
- Biomass combustion with CCS.
- Increased use of biomass-based construction materials.
- Biochar.
- Soil carbon sequestration.

(Carbon Brief, 2016)

BECCS and afforestation are probably the most well-known negative emissions technologies. Most studies that look into BECCS estimate a role in the order of 10 Gt CO_2 per year by 2050 (e.g. (Muratori et al., 2016)). If this level of BECCS were employed in REmap, net energy-related CO_2 emissions would reach zero by 2050. BECCS is in principle not too different than CCS and the implementation challenges are similar. BECCS would increase reliance on biomass, because the capture and storage processes require additional energy. With a post-combustion capture technology that requires about 3 GJ heat per tonne of captured CO_2, additional demand could easily increase to 30 EJ by 2050 if BECCS played a significant role. Depending on the biomass feedstock type and how the feedstocks would be sourced, there could also be additional impacts on land use. However, these impacts could be reduced by using second-generation bioenergy. Storing the captured CO_2 could also be a limitation. The estimated potential contribution of afforestation ranges between 2-4 Gt carbon-dioxide equivalent (CO_2-eq) per year, but afforestation also requires water and land. Direct air capture and enhanced weathering also require additional energy and there are logistical challenges associated with such technologies which may hamper feasibility (van Vuuren, 2017).

While negative emission technologies have not been considered in this study, they may have an important role in the future, even before 2050. The possibility of using negative emissions technologies in the future should not delay action now, because their prospects are uncertain.

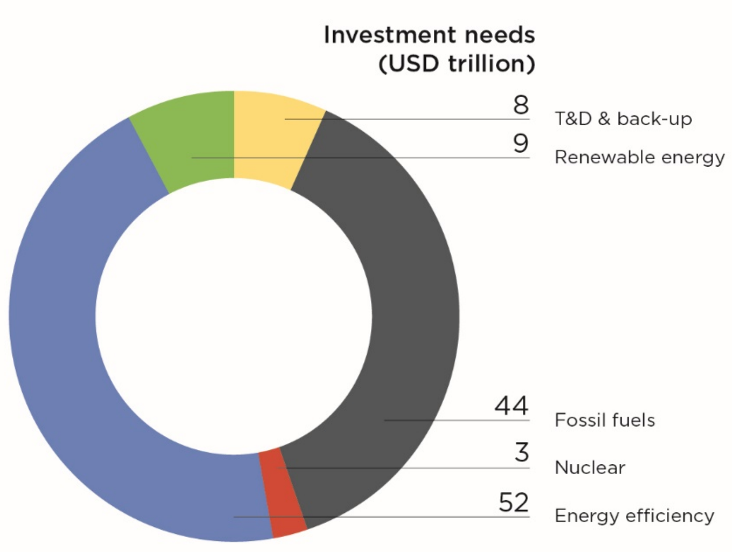
The investments needed for the energy transition are affordable

The REmap approach makes it possible to calculate the overall amount of additional investment needed to decarbonise the energy system, compared to the Reference Case. The analysis shows not just the market potential, but also where the investment challenges lie.

In the Reference Case, the total investments in the energy sector would add up to an estimated USD 116 trillion between 2015 and 2050, or USD 3.3 trillion per year on average. The largest share would be in energy efficiency improvements for heating/cooling in buildings and the second-largest share would be investments in fossil fuels, mainly related to supply.

Cumulative renewable energy investments in the Reference Case are estimated at USD 9 trillion, or USD 260 billion per year on average between 2015 and 2050. That represents a continuation of current investment levels for the next 35 years. Investment needs for the power sector would be USD 16 trillion, with about half for renewable energy investments.

Figure 3.8 • Total investment needs by area and value of stranded assets in the Reference Case, 2015-2050



Key message • The Reference Case foresees a cumulative investment need of USD 116 trillion for the energy sector between 2015 and 2050, equalling USD 3.3 trillion per year, or 1.7% of global GDP in 2050.

Making the transition to a decarbonised energy system would require a higher level of investment than in the Reference Case. The added investments, however, are affordable, in part because of expected further significant cost reductions in renewables and other enabling technologies. Depending on the technology, estimated cost reductions between 2015 and 2050 range from 10% (e.g. for energy efficiency) to 65% (e.g. solar PV).

Overall, the REmap case would require additional net investments of USD 29 trillion between 2015 and 2050. This has been estimated for each year between 2015 and 2050 by summing the product of capital costs and deployment potential of each additional low-carbon technology.

The additional investment needs can be split into five components:

- USD 23 trillion for energy efficiency (including electrification) – notably for building renovation.
- USD 16 trillion for renewable energy supply.
- USD 5 trillion for stranded assets that require early replacement (notably in buildings).
- USD 8 trillion for transmission and distribution, back-up and battery storage.
- USD 1 trillion for CCS, material efficiency improvements and nuclear.

These five components add up to additional investments of USD 54 trillion. However, there are also avoided investments on fossil fuels in both fossil fuel and nuclear electricity generation capacity as well as in the upstream sector.[78] Those avoided investments add up to USD 25 trillion. As a result, net additional investment needs are estimated at around USD 29 trillion between 2015 and 2050. This averages USD 0.83 trillion per year between 2015 and 2050, equivalent to 0.4% of global GDP in 2050, and compares with the average annual investments of USD 3.3 trillion per year in the Reference Case. To put these numbers in perspective, the total additional investments needed over 35 years are equivalent to about 10% of the total global GDP in 2050.

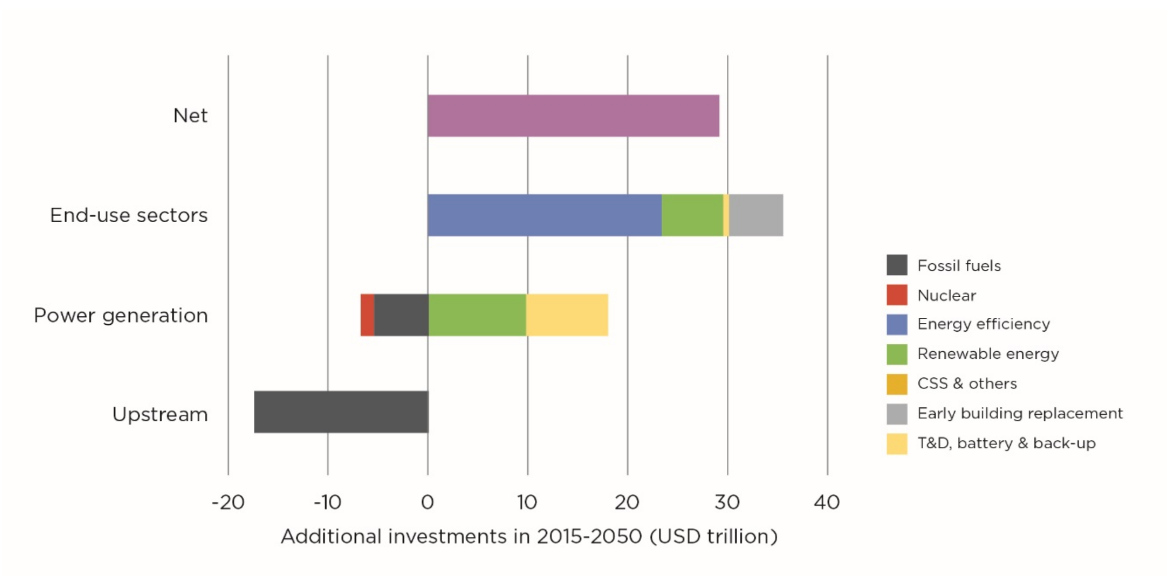
78 Upstream sector refers to the exploration and production step in the fossil fuel supply chain.

The total investment in the fuel supply would not need to rise over today's level to achieve climate targets. That is because the bulk of the additional investment needs will be in the end-use sectors (buildings, industry and transport), not in electricity generation. The reason is the good progress that has already been made building renewable energy capacity in the power sector, along with the progress expected in the coming decades as countries implement their national energy plans, as assumed by the Reference Case. More effort in all types of low-carbon technologies will be needed in the end-use sectors, notably energy efficiency in buildings. That effort requires high upfront investment costs, though the investments for energy efficiency measures estimated in this analysis can be interchanged with investments for other low-carbon technologies. For instance, rather than cutting emissions by improving energy efficiency, the same goal can be reached using heat supplied by decentralised renewables-based heating and/or district systems. However, it may be challenging to mobilise significantly more biofuels or install more solar water heaters over limited roof space. Either way the investments required to decarbonise buildings would be high.

Additional investment needs include USD 1.9 trillion for variable renewable technologies (VRE) in the transmission and distribution (T&D) of electricity. That is about half of the additional investment needs of T&D for the entire power system (including high-voltage direct current transmission lines and super grids). An additional investment of USD 0.8 trillion is needed for battery storage (excluding pumped hydro).

It is vitally important that the investments made in energy generation equipment and related infrastructure today and in the coming decades bring deep emission cuts by 2050. This is especially true for long-lived investments, such as in buildings, industrial production facilities, power plants, transport infrastructure, etc. Otherwise, the risks of continued carbon lock-in will be high.

Figure 3.9 • Additional investment needs by sector and technology in REmap relative to the Reference Case, 2015-2050



Notes: Electric vehicle charging infrastructure, hydrogen pipelines and refuelling stations are included. Electrification also includes additional costs for electricity generation growth.

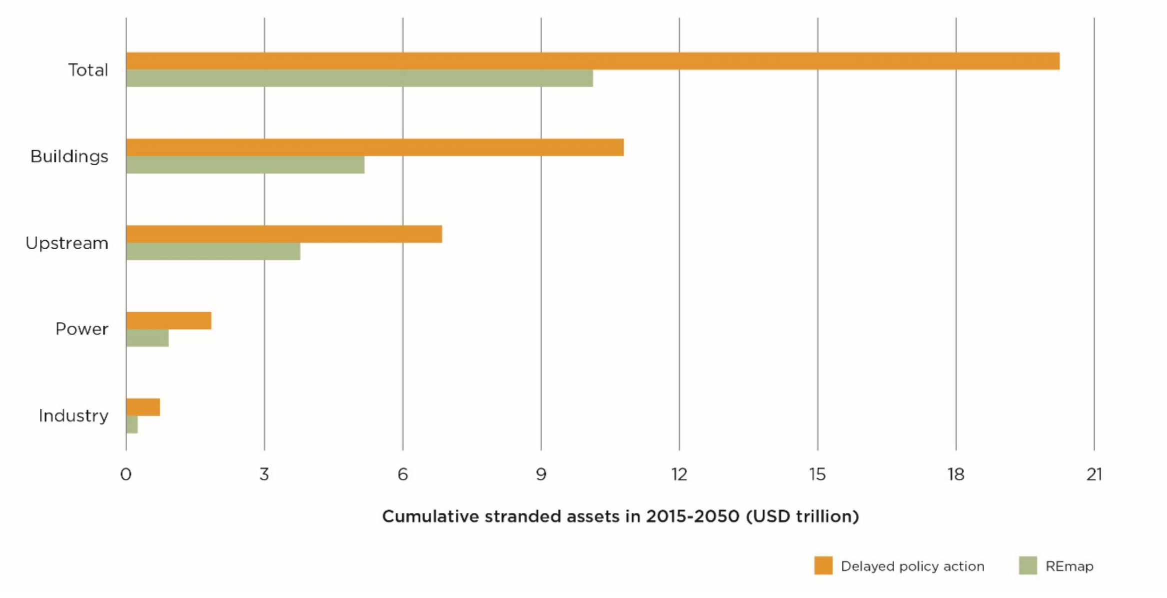
Key message • Meeting the 2°C target requires investing an additional USD 29 trillion between 2015 and 2050 compared to the Reference Case. The largest additional investment needs are in energy efficiency, followed by renewables. The total investment cost, however, is reduced by the avoided investments in the upstream sector and in fossil-fuelled power generation.

Early action is critical to minimise the risks of stranded assets and achieve climate targets

It is hard to over emphasize the importance of early action. Early action is needed not only in the deployment of renewables and other enabling infrastructure and supporting technologies, but also in the development of solutions for sectors where no significant or economically attractive solution exists today. If action is delayed, total investment costs will rise, the chances of stranded assets will increase and costly negative emission technologies will be needed to limit planetary warming. These latter technologies also bring their own risks as they have not been fully commercialised and therefore their feasibility and potential are uncertain (IPCC, 2014; Kartha and Dooley, 2016).

In the REmap case, a total value of USD 10 trillion is estimated for stranded assets for the 2015-50 period. To put this in context, USD 10 trillion is approximately 4% of global wealth in 2015 (estimated at USD 250 trillion at current exchange rates) (Credit Suisse, 2015). Figure 3.10 shows the potential for asset stranding in a Delayed Policy Action case, in which the accelerated renewables and energy efficiency deployment that begins immediately in the REmap case is delayed until 2030. Such delayed action would cause significant asset stranding. The total value of the stranded assets in the upstream energy, electricity generation, industry and buildings sectors would be USD 20 trillion.

Figure 3.10 • Stranded assets by sector in Remap and Delayed Action cases, 2015-2050



Key message • Delaying policy action will result in an additional USD 10 trillion in stranded assets.

The buildings sector would see the largest amount of asset stranding on a worldwide basis. About USD 12.5 trillion would be stranded in Delayed Policy Action case, more than double the amount in REmap.[79]

Buildings have a low stock turnover. This is especially true in Western Europe and the United States, where the growth in building stock is slow. In Germany, for example, more than 85% of

79 Here, Delayed Policy Action follows the same trend as the Reference Case until 2030, and then emissions start decline to ensure the carbon emission budget between 2015 and 2050 is not exceeded. This requires zero emissions in the end-use sectors by 2050.

the expected residential building stock in 2050 already exists today. As a result, it is difficult to avoid stranding building assets (i.e. buildings with inefficient building envelopes, equipment, etc.), even when all new buildings are constructed to the highest of standards in terms of energy efficiency and renewable energy use.

In REmap, total building stock grows from around 140 billion m^2 to 270 billion m^2 between 2015 and 2050. It is important to distinguish between the share of buildings that will be new and those that will need to be renovated. At a country level, an annual demolition rate that ranges from as low as 0.1% (e.g. European Union countries) to 1% (e.g. China, India, Indonesia) has been assumed. As a result, 184 billion m^2 of all building area in 2050 will be new. This represents about two-thirds of the total stock. In REmap, it is assumed that by 2020, all new buildings will be fossil fuel free. The remainder of the building stock would be from the existing building stock today. Without any additional effort for renovation, around 60% of this existing building stock in 2050 would continue to rely on fossil fuels. A share of this building stock needs to be deeply renovated in order to reduce the demand for fossil fuels in the sector enough to remain within the carbon budget. The construction value that is lost due to renovation of this building stock – or the stranded assets in buildings as defined in this assessment – is estimated to be USD 5 trillion in 2015-2050 under REmap. This includes a depreciation of the investment made before renovation. If depreciation is not included, the stranded asset value would be twice as high.

In this chapter, stranded assets and investment needs in buildings have been estimated separately. An example of stranded assets would be the additional costs of installing single-glazed windows, then replacing them with double-glazed windows, versus installing double-glazed windows in the first place. Similarly, stranded assets would occur through the ambitious deployment of energy efficiency technologies in both new and existing buildings. By comparison, investments refer to energy efficiency measures that either replace building equipment that has reached the end of its lifetime (e.g. efficient light bulbs) or that are implemented as an additional feature to buildings in order to reduce energy demand (e.g. wall insulation).

The second-largest group of stranded assets would be in upstream energy infrastructure, 75% of which would be in oil production. Large capital investments made in this upstream infrastructure from now until 2030 in the Delayed Policy Action case would result in USD 7 trillion worth of assets being stranded after 2030. The stranded assets in upstream oil would represent about 20-40% of the estimated valuation of today's oil upstream producers. In order to assess the upstream stranded assets, existing upstream assets first were valued based on current (estimated) valuation of fossil fuel producers, their share in global production, and the share of company valuation related to upstream operations (as per the share of the upstream sector in total operational income in recent years). In a subsequent step, the valuation was adjusted based on reduced net cash flows due to a reduced production outlook, in both the REmap and the Delayed Policy Action cases.

Electricity generation is the third-largest sector in terms of stranded assets. Under Delayed Policy Action, USD 1.9 trillion would be stranded. For example, the coal power plants now being built in the developing world would have to be stranded after 2030 to meet decarbonisation targets.

In addition, stranded assets in industry are estimated at USD 740 billion. Relatively lower capital expenditures for process heat equipment (compared to electricity generation) explain the lower amount compared to other sectors. The stranded assets in industry between 2015 and 2050 are equivalent to USD 21 billion per year, an amount that could be recouped through lower energy bills if industry achieved a 1.5% per year improvement in energy efficiency. Industry is therefore better placed than other sectors to anticipate and manage the effects of stranded assets.

Box 3.4 • Stranded assets definition

There are a number of definitions of stranded assets in the energy context. The term ”stranded costs” or ”stranded investment” is used by regulators to refer to “the decline in the value of electricity-generating assets due to restructuring of the industry” (Congressional Budget Office, 1998). This was a major topic for utility regulators as power markets were liberalised in the United States and United Kingdom in the 1990s. There is no universally settled view of what stranded assets are. IRENA’s analysis attempts to capture the breadth of views about the definition of stranded assets, and to include a number of issues related to climate and environmental change – from investment risk to the idea of a “just transition”.

Several organisations that work in the field of energy and climate have already examined what stranded assets could mean from their own perspective. The most commonly applied definitions are briefly discussed below:

- The IEA defines stranded assets as “those investments which have already been made but which, at some time prior to the end of their economic life (as assumed at the investment decision point), are no longer able to earn an economic return as a result of changes in the market and regulatory environment brought about by climate policy” (IEA, 2013a and IEA, 2013b). This is focused on asset stranding caused by climate policy in the power sector and is widely recognised in the literature.
- The Carbon Tracker Initiative also uses this definition of economic loss, but says stranded assets are a “result of changes in the market and regulatory environment associated with the transition to a low-carbon economy” (Carbon Tracker Initiative, n.d.).
- The Generation Foundation defines a stranded asset “as an asset which loses economic value well ahead of its anticipated useful life, whether that is a result of changes in legislation, regulation, market forces, disruptive innovation, societal norms, or environmental shocks” (Generation Foundation, 2013).
- The Smith School of Enterprise and the Environment at the University of Oxford employs a “meta” definition to encompass these (and other) definitions: “Stranded assets are assets that have suffered from unanticipated or premature write-downs, devaluations, or conversion to liabilities” (Caldecott et al., 2013).

For this analysis, IRENA defines stranded assets as the remaining book value[80] of assets substituted before the end of their anticipated technical lifetimes, and without recovery of any remaining value, to achieve 2050 decarbonisation targets. This definition emphasises that assets become stranded because of the requirement to reduce fossil fuel use to achieve a deeply decarbonised energy system by mid-century. It should be noted that the purpose of the IRENA analysis is not to propose a universal definition of stranded assets. While different approaches and definitions by sector and asset class are used for the purpose of this analysis, attention is paid to make sure these are sufficiently aligned with the overarching concept of stranded assets (which is fundamentally unanticipated or premature lost value). The purpose of the analysis is to point out the potential magnitude and guide investors towards this, not to claim high degrees of accuracy.

The clear majority of stranded oil assets would occur upstream, rather than in the power, buildings or industry sectors. Oil is primarily used in transport. The increasing use of ultra-low emission and electric vehicles, will cause oil demand and oil prices to drop, reducing the value of oil reserves. Compared to oil demand from transport, the demand for oil from electricity generation, heating in buildings and industry is minor.

80 Book value is defined here as the cost of an asset, minus accumulated depreciation.

Natural gas assets would be stranded across each of the four sectors. Gas T&D systems, including LNG terminals, would be affected because of their long life spans. Although gas has lower GHG emissions than oil and coal, it remains incompatible with required levels of decarbonisation. As a result, there would be significant stranding upstream and in gas-fired power generation.

Coal assets would also be stranded across each of the four sectors, but the power sector would be most affected. Coal-fired electricity generation is currently a major source of direct CO_2 emissions (producing about 25% of the global total). As a result, much of the policy effort has been focused on phasing out coal or limiting its growth. For example, the United Kingdom, France and Canada have recently announced plans to end the use of coal-fired power plants. Given the relatively modest value of stranded coal-fired power assets and the high level of emissions from coal plants, this approach is an economically viable way of achieving decarbonisation.

Box 3.5 • The significance of technology lock-in: power sector case

In calculating the value of stranded power plant assets it was assumed that the economic lifetime of a power plant equals its technical lifetime. If a plant is shut down before it reaches the end of its lifetime, the nominal value (capital expenditure minus accumulated depreciation) is assumed to be lost.

However, some might argue that often the economic lifetime of a plant differs from its technical lifetime. The economic life of a plant ends when marginal costs consistently exceed marginal revenues. This could happen due to market trends that cannot be perfectly foreseen at the start of operation (e.g. rising maintenance or input costs, or lower than anticipated power prices). In practice there also exists a grey zone of old plants that are mothballed or where operating hours are reduced significantly compared to new plants.

To account for the risk of reaching the end of an economic lifetime, companies might depreciate power plants over a shorter period than expected by their technical lifetime. The assumed lifetime has significant implications on the stranded asset calculations in this study. In this study the following technical lifetimes were assumed to be: coal, 50 years; natural gas, 30 years; oil, 50 years.

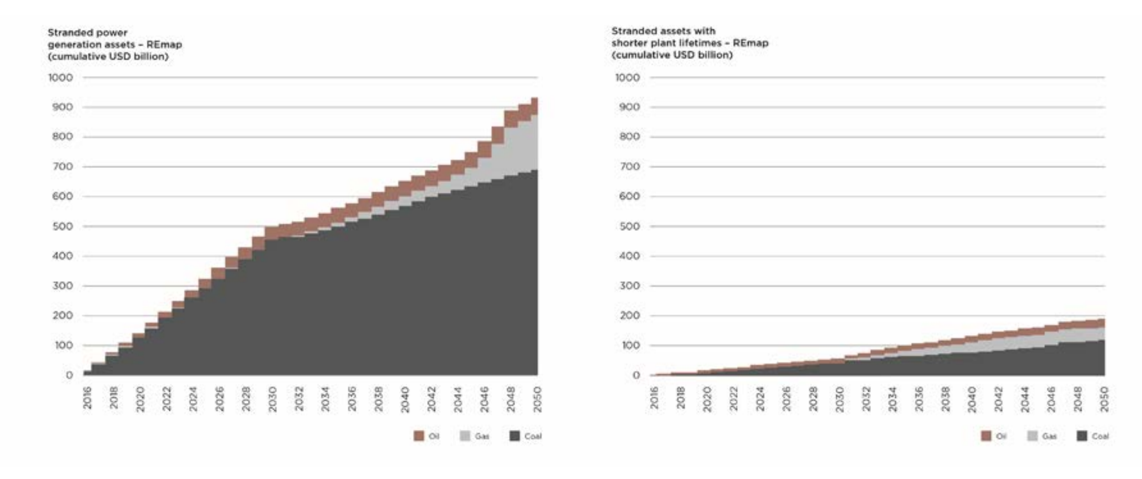
The resulting value of stranded assets in the REmap analysis is USD 940 billion (or about 3 800 GW) (Figure 3.11). If all companies used these lifetimes to depreciate power plants on their balance sheets, and no asset impairments occurred up to the point of stranding, then this is the value of asset impairments that could be expected up to 2050 because of decarbonisation.

However, given that some companies depreciate power plants over shorter periods of time, or have already witnessed asset impairment in recent years for a variety of reasons, the impact of stranded assets might be more limited. In some cases, the assets that get shut down are those that were already written off and have little value left on the balance sheet.

If one assumed technical lifetimes for coal and oil assets of 50 years and 30 years for gas, but only 25 years for the true economic lifetimes for coal and oil and 15 years for gas, then 2 250 GW of 3 800 GW of total stranded assets in the REmap analysis have economic value left at the point they are shut down. The remaining 1 550 GW (about 40% of the total) are plants that are stranded with no remaining economic value, but that still have remaining technical lifetime. With these assumptions, the value of stranded assets is USD 200 billion.

It is difficult to assess the assumptions that are made on balance sheets across countries and companies to value power plant assets. The shorter economic lifetimes as assumed above come with the risk of underestimating the magnitude of stranded assets. Electricité de France, for example, recently increased its depreciation period for nuclear plants from 50 to 60 years. In some countries, plants even run beyond their technical lifetime (recently a 100 year-old coal-fired power plant in Peru was decommissioned). It would be advisable for companies/countries to report more transparently about the reported book value of power plant assets and hence their exposure to the risk of stranded assets.

Figure 3.11 • Technology lock-in in power generation assets, 2015-2050



Key message • The power sector could see stranded assets in the range of between USD 200-940 billion by 2050, with most of it being coal-based generation assets.

Renewable energy's share of the global energy mix will need to double by 2030 and more than triple by 2050 from today's level

This analysis finds that supplying two-thirds of global 2050 primary energy with renewable sources is technically and economically feasible. We already have seen accelerated deployment of solar and wind power on a global scale in recent years, in part because of technology innovations and spectacular cost reductions. We also see increasing electrification of end-use sectors coupled with renewable power, for example in the areas of EVs and heat pumps.

This recent acceleration of renewable energy technology has occurred in spite of slow economic growth and low oil prices. It has been driven by the improving cost-competitiveness of solar PV and onshore wind power, as well as other factors such as air pollution policy and regulations.

IRENA's renewable energy statistics show that renewable energy added more capacity than fossil fuels and nuclear combined for the each of the last four years (IRENA, 2016e), and that the total renewable electricity generation capacity reached nearly 2 000 GW in 2015. Solar PV and onshore wind power continue to grow the fastest, while hydro still produces the lion's share of renewable power. For the past five years, the average annual increase in the share of electricity from renewable sources has been 0.7 percentage points. About 24% of all power worldwide was generated from renewable energy sources in 2016.

Yet, when including all non-electricity sectors, the growth in renewable energy amounts to only an annual average of 0.17 percentage points in terms its share of total energy consumption. This is due largely to the fact that consumption of electricity accounts only for one-fifth of total final energy use, and renewable energy use growth is slow in key building and transport sectors. As a result, the share of renewables was 24% in global total electricity generation in 2016, but only 19% in the total final energy mix.

In the Reference Case, current trends continue, yielding only minor changes in the energy mix. Of the total 520 EJ final energy demand in 2050, renewable energy covers only about a quarter of all demand, including the consumption of electricity and district heat sourced from renewables.

Today's renewables share is about 19% of total energy generated. That grows to 21% by 2030 when the national energy plans of all countries are included. That means that the renewable energy share continues to grow close to today's level of around 0.17 percentage points per year for the next 15 years until 2030. This rate drops to 0.05 percentage points in the 2030-2050 period and renewable energy covers only a quarter of the total final energy consumption in 2050. This result shows that existing policy plans for capacity additions and the importance given to renewable energy sources in country energy plans are still insufficient to make a significant change in the total mix.

Box 3.6 • The need for better statistics for solid bioenergy use

Different sources of energy statistics indicate that traditional uses of solid bioenergy for cooking and water heating in the residential sector account for a significant share of renewable energy worldwide, particularly in the non-OECD countries.[81]

Given the challenges involved in assessing how much bioenergy is used today in these parts of the world, it is worth pointing out the potential differences in the available data sets.

According to the energy statistics of the IEA, in 2014, 32.5 EJ of primary solid biofuels were used in the residential sector of the non-OECD countries. This bioenergy was in the form of firewood and charcoal. Data from the Food and Agriculture Organisation of the United Nations (FAO) statistical database (FAOSTAT) on firewood and charcoal production, adjusted for use in the residential sector, show a significantly lower figure of 13.6 EJ. The IEA estimate is more than two-times larger than the FAOSTAT estimate.

The large difference has important implications for policy making. Depending on which data source is used, the estimated current share of renewable energy in the global final energy consumption can range from 13% to 19%. Today, "modern" renewable energy, like solar PV and wind farms, has a 9% share. Using the lower solid biofuels estimate, modern renewables now have a share more than two-times greater than that of traditional uses of bioenergy. But with the higher estimate, the modern and traditional renewables have a more equal share.

Sustainable Energy for All (SEforALL) has set a voluntary target of doubling the share of renewable energy in the global energy mix by 2030 compared to today's level. Depending on which share is taken as a starting point, the doubling target can mean increasing the share of renewables to 26% or to 36% by 2030. Such wide ranges make policy making a challenging task. It also becomes impossible to understand how countries can contribute to such global goals.

Traditional uses of bioenergy also have impacts beyond energy. There are socio-economic impacts, and negative effects on human health and the environment. Without better data, policies to reduce these impacts will not be robust. These problems highlight the need to improve the statistical data on traditional uses of bioenergy and for better policy making.

While the share of oil use remains constant in the entire period in the Reference Case, the natural gas share increases at the expense of coal. The change in the share of electricity use is the largest among all other energy carriers.

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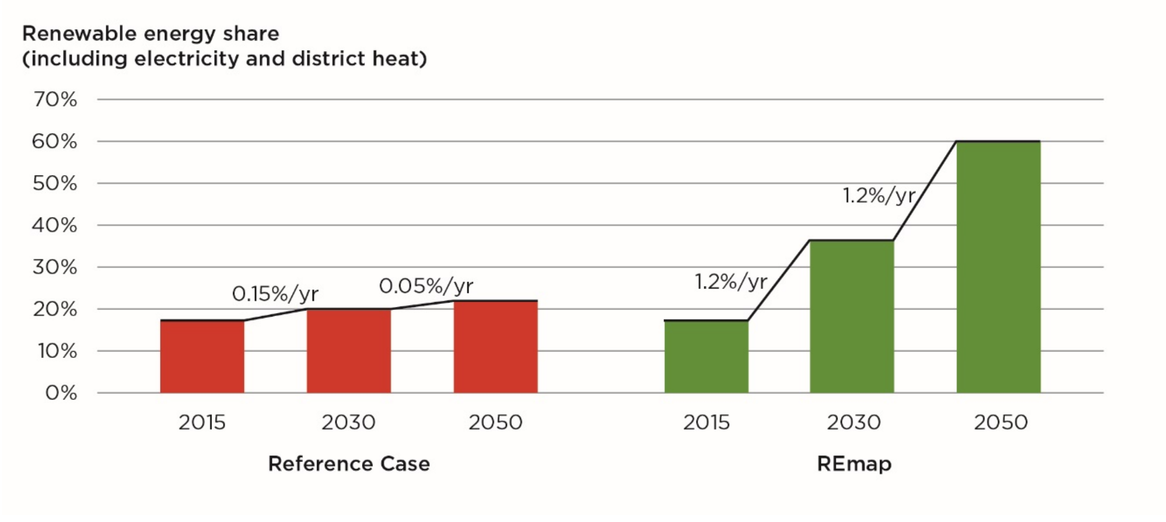
81 These are defined according to the IEA as wood, animal dung and agricultural residues that are burned in simple stoves at low rates of efficiency. Their use is most common outside OECD countries (IEA, 2012), and they are an important source of energy for many.

The use of ambitious energy efficiency technologies in REmap reduces the total final energy consumption in the 2015-2050 period compared to the Reference Case, with total energy consumption at about 380 EJ. The share of renewable energy increases to 60% by 2050 (Figure 3.12). This requires a growth in the renewable energy share of 1.2 percentage points per year, equivalent to a more than seven-fold increase over past rates. To achieve this rate, expanding the use of renewable energy technologies in all sectors will be required.

Figure 3.12 • Renewable energy share in global total final energy consumption, 2015-2050

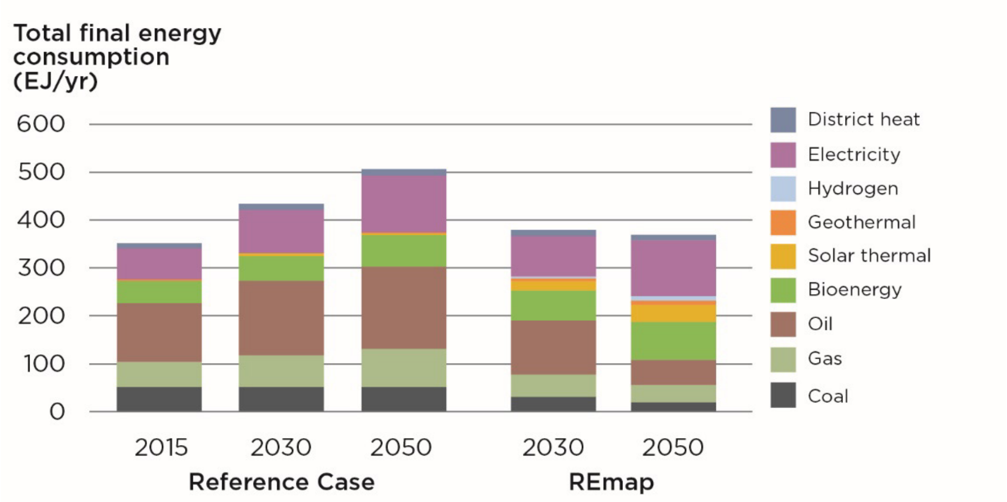


Note: TWh = terawatt-hours; CCS = carbon capture and storage.

Key message • Under REmap, the renewable share of total final energy consumption will rise from 19% to over 60% by 2050, a three-fold increase. The growth rate in terms of renewable share per year will need to increase seven-fold over past rates.

Figure 3.13 shows how total energy demand develops between 2015 and 2050 in both the Reference Case and in REmap. Under REmap, demand is flat in total final energy consumption (TFEC) terms. The share of fossil fuels in TFEC declines from 70% to 30%. Direct uses of renewable energy grow from 10% to 35%. Notably, the share of final bioenergy use in total final energy consumption rises from around 13% today to around 21% in 2050 (from about 50 EJ to 80 EJ). This can be divided into 7% transport biofuels and 14% solid and gaseous biofuels for power generation and heating. Solar water heater use grows for industry and buildings from negligible to about 35 EJ. Oil share decreases significantly, with transport relying more on biofuels and electricity. However, an amount of oil that is half of today's level would be used to meet the demand in non-road passenger transport and freight. Compared to the Reference Case, in final energy terms, there is a major change in oil and its products. In the Reference Case, oil use grows from 123 EJ to 170 EJ, while in REmap, oil demand drops to 55 EJ. Compared to current levels, coal use is more than halved and remains in use only for a few applications in the industry sector. Gas remains as an important fuel in this transition for supplying any heating in industry and buildings that remains unserved by renewables. Electricity's share increases significantly, rising from just below 20% in 2015 to more than 30% by 2050. Coupled with renewable energy supply, renewable power represents 40% of all final renewable energy use in 2050.

Figure 3.13 • Total final energy consumption by energy carrier, 2015-2050



Notes: Includes only buildings, industry and transport. Non-energy use of fuels for the production of chemicals and polymers is excluded.

Key message • Under REmap, renewables direct use and renewable electricity grow from 115 EJ in 2015 to 250 EJ in 2050, representing 65% of TFEC. Coal use dwindles.

Box 3.7 • China 2050 High Renewable Energy Penetration Scenario and roadmap

China has set ambitious emission reduction and non-fossil fuel energy targets for both 2020 and 2030. There is little doubt that these targets can be met on time, or earlier if China continues to cut back on coal consumption to reduce its air pollution problems. Despite these important mid-term targets, however, China needs to give more thought to a long-term strategy for reducing carbon emissions.

In the 2050 High Renewable Energy Penetration Scenario and Roadmap Study, the China National Renewable Energy Center (CNREC) presented enhanced low-carbon scenarios for achieving shares of renewables as high as 61% in total primary energy consumption and 86% in the power mix. In the scenarios, renewables would replace coal as the dominant energy fuel in the energy mix in 2050. According to the study, electricity demand will account for at least 60% of the TFEC, compared to the current 25%. That target requires that the road transport sector be substantially electrified, with 86% of vehicles being electric powered and 100% of trains being electrified by 2050. This would allow renewable electricity to play a major role.

In the scenario, CO_2 emissions would be reduced to 3.3 Gt by 2050 from the 2011 level of 7.3 Gt, largely by reducing coal's share of the total primary energy supply by a factor of five. This means a significant decline in coal use in the industry sector of China, where coal is exclusively used for steel (for about a quarter of all steel production, with the remainder produced from electric arc furnaces) and cement production industries.

Achieving this high-share renewable scenario will require strong political will, consistent policy support, effective institutional reforms in the energy sector (and in particular, in the power sector) and major technological breakthroughs in the next decade or so. Replacing coal with renewables in China is an extremely challenging and long-term task. Yet, as the Chinese proverb says, "the journey of a thousand miles starts with a single step". This study is indeed a step towards a low-carbon energy future for China.

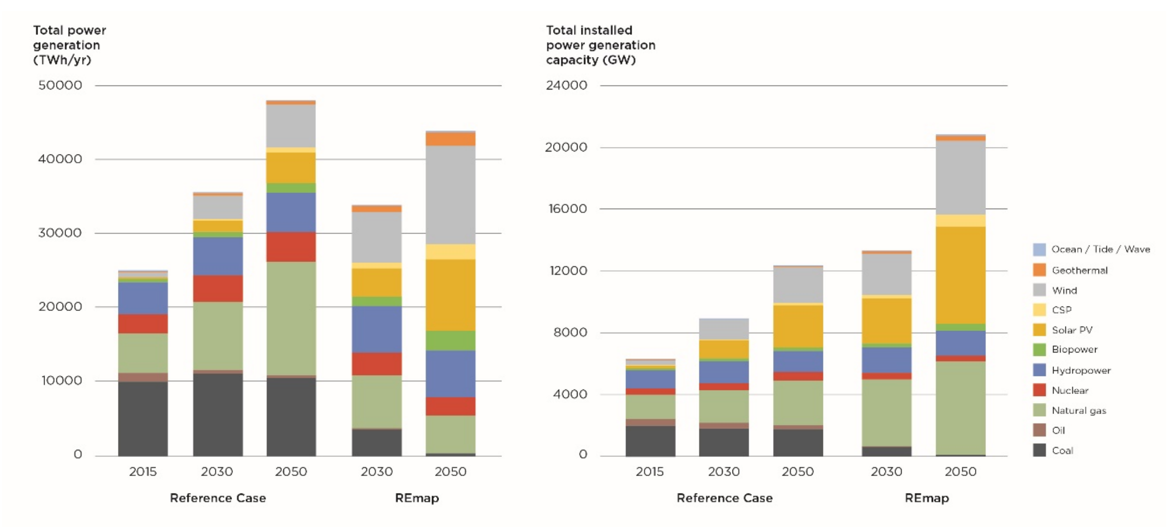
Source: (CNREC, 2016).

Renewables and natural gas will dominate the electricity generation mix

Because electricity generation contributes the single highest sectoral share of CO_2 emissions, decarbonising the sector by 2050 is a top priority. The sector is more on track than are end-use sectors in terms of deploying of renewable energy, but efforts to reduce the use of coal must be strengthened to continue on that path. This is particularly important given the increasing dependence of coal for electricity generation in Asia's fast growing economies. Phasing out coal without CCS in the electricity generation sector, especially in China, India and Indonesia, is a top priority, and no CCS deployment is foreseen in power generation until 2050 under REmap.

Renewable energy's share of electricity generation reaches 31% in the Reference Case in 2030, up from 23% in 2015. Under REmap, the renewable energy share reaches 82% by 2050, more than twice the level of the Reference Case, and nearly four-times higher than the level today. The transition thus requires current efforts to scale up significantly. Today the share of renewable energy in the sector increases by about 0.7 percentage points per year. Meeting the decarbonising goals will require this rate to more than triple to 2.4 percentage points per year until 2030, so that the share of renewables reaches 59% of energy generation. The increase must continue at a rate of at least one percentage point per year until 2050.

Figure 3.14 • Power generation capacity and total electricity generation by technology in the Reference Case and REmap, 2015-2050



Key message • The power sector will see the highest share of renewables. In REmap by 2050, a diverse mix of renewables will provide more than 80% of electricity, with wind and solar providing the largest shares. Coal and oil in power generation will be eliminated.

Total installed electricity generation capacity at the end of 2015 was about 6 200 GW (Figure 3.14). In the Reference Case, this increases by 180 GW per year to reach 12 400 GW by 2050. The largest additions are in solar PV and wind onshore and offshore power, representing 70-80% of the total. Total installed coal capacity remains same as today in the entire period to 2050. By comparison, gas capacity increases by 1 400 GW, from 1 500 GW to 2 900 GW, representing the largest share in total generation capacity by 2050.

In the REmap case, more renewable power capacity is added than in the Reference Case. Solar PV capacity climbs to 6 000 GW, while wind capacity reaches 4 800 GW. While oil-based capacity drops to zero, total installed nuclear capacity remains same as today. The remaining fossil and nuclear (though typically the least flexible of all options) capacity offer flexible generation, supplemented with a back-up natural gas capacity of around 5 000 GW worldwide by 2050.

A range of renewables, including biomass, concentrating solar power (CSP) and hydropower, also offer flexible generation. With these changes, total installed electricity generation capacity in REmap reaches more than 20 000 GW, a three-fold increase from today.

Renewable energy has the potential to meet more than half of all final energy demand in 2050

While the power sector holds great potential for renewables, electricity accounts only for around 20% of final energy use today. As a result, this analysis points to an essential role for renewable energy technology deployment in end-use sectors. Such a role is especially important because these sectors today account for approximately 80% of all global energy demand.

In the end-use sectors, IRENA's REmap shows that the renewable energy share can grow to 78% in buildings, 39% in industry and 50% in transport by 2050 (Table 3.2). The renewable energy share reaches 61% of TFEC, which includes the use of electricity and district heat sourced from renewables. If these uses are excluded (i.e. by considering the direct uses of energy only), the renewable energy share would reach an estimated 53%, thereby covering more than half of all energy demand by 2050.

Realising the renewable energy potential in the REmap case requires that the renewable energy share in TFEC increases to 36% by 2030 and to 60% by 2050. In 2030, consumption of renewable power would account for around 34% of the total final renewable energy use, with the remaining 65% being renewable energy used in heating and cooling, and the transport sector. Renewable power's share in the total final renewable energy use increases to 40% by 2050.

Table 3.2 • Global total and sector-specific renewable energy shares, 2015-2050

		2015	Reference Case		REmap	
			2030	2050	2030	2050
Industry	(excl. NEU, electricity & DHC)	9%	12%	15%	28%	44%
	(incl. electricity & DHC)	9%	13%	16%	23%	38%
	(incl. NEU, electricity & DHC)	10%	14%	17%	33%	46%
Buildings	(excl. electricity & DHC)	46%	42%	41%	59%	79%
	(incl. electricity & DHC)	37%	36%	38%	57%	78%
Transport	(excl. electricity & DHC)	3%	7%	10%	15%	44%
	(incl. electricity & DHC)	4%	7%	10%	17%	53%
Power generation		23%	31%	37%	59%	82%
District heating and cooling		7%	7%	15%	20%	30%
TFEC	(excl. NEU, electricity & DHC)	18%	18%	19%	32%	54%
	(incl. electricity & DHC)	19%	21%	23%	37%	61%
TFC	(incl. NEU, electricity & DHC)	18%	19%	22%	36%	56%
TPES		16%	20%	24%	40%	65%

Notes: NEU = non-energy use; DHC = district heating and cooling; TFEC = total final energy consumption; TFC = total final consumption; TPES = total primary energy supply.TFC includes the use of fuels for the production of chemicals and polymers.

In the Reference Case, total final renewable energy use would grow from around 65 EJ in 2015 to 88 EJ in 2030 and 125 EJ in 2050. In comparison, under REmap, the figure would reach 145 EJ in 2030 and 235 EJ in 2050 (Figure 3.15). Half of the total final renewable energy use in 2015 was accounted for by traditional uses of bioenergy, so modern renewable energy was about 32 EJ.

In REmap, the use of traditional bioenergy drops to almost zero, so the 145 EJ in 2030 (and 235 EJ in 2050) would come almost entirely from modern renewable energy. Overall, under REmap, modern renewable energy use is seven times higher than today by 2050.

Direct uses of renewable energy for transport, heating and cooling would account for less of the total final renewable energy use in 2030 compared to today, falling from a share of 80% in 2015 to 66%, because of greater efficiencies and the growing share of renewable electricity. The potential in end-use sectors remains equally high in 2050 as well. The share of end-use sectors in total final renewable energy use is high despite the significant decline in traditional uses of bioenergy.

Between today and 2050, the way heat is produced would also change. Solar water heaters would play a greater role under REmap for both industry and buildings, covering around 15% of all final renewable energy use. This is equivalent to 9% of all final energy use worldwide and would mean a huge market for solar heaters. In buildings, total installed solar water heating capacity under REmap reaches 5 540 million m^2 by 2030 and 11 700 million m^2. Industry use would be significantly higher than it is today, with capacities reaching 2 440 million m^2 by 2030 and 3 695 million m^2 by 2050.

The use of heat pumps would increase significantly in many developed markets. Heat pumps would replace fuels for heat generation with renewables-based electricity. In industry bioenergy for to generate process heat from combined heat and power plants would also grow.

In transport, which has the lowest renewable energy share among all sectors today, the share of liquid biofuels and biomethane in total renewable energy use would grow from 4% in 2015 to 12% in 2030 and 26% in 2050. In absolute terms, this represents four-fold growth, from 129 billion litres in 2015 to approximately 500 billion litres per year by 2030. After 2030, the amount would more than double, to 1 120 billion litres per year by 2050. Nearly half of this total amount would come from advanced liquid biofuels in 2050, which are made from a wider variety of feedstocks than are conventional biofuels, but which supply just 1% of biofuels today.

Daunting challenges remain in long-range freight transport, aviation and shipping. These uses account for about half of the global transport sector's total energy demand. The potential for electrification is limited. Biofuels are currently the main solution for these transportation modes. If the aviation sector switches from today's conventional petroleum-derived kerosene to advanced biofuels, it would consume about 40% of the total production of such fuels. But in general, bioenergy in transport will require a careful approach because growing its feedstocks may take land away from growing crops for food production. Possible hydrogen or breakthrough electricity storage solutions could reduce the need for biofuels.

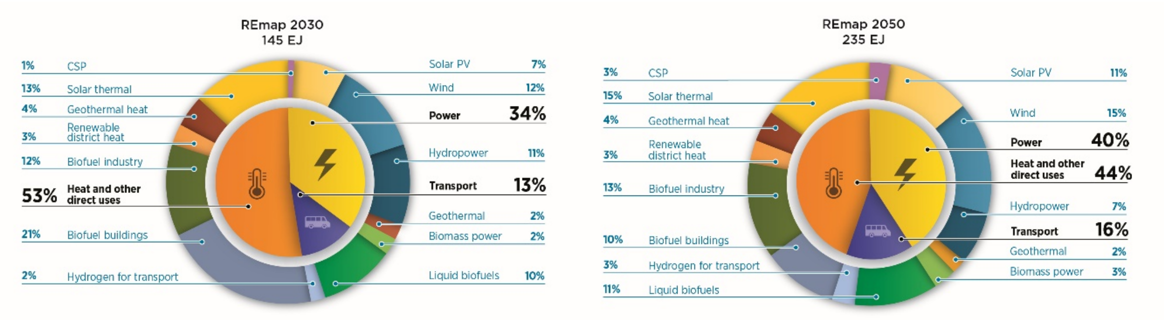
Transport has the lowest share of renewable energy today, but the sector is undergoing fundamental change. EVs are revolutionising the way we move. In combination with information and communication technologies (ICT), the whole transport concept is changing. As performance improves and battery costs fall, sales of EVs, electric buses and electric two- and three-wheelers are growing. In countries such as the Netherlands and Norway, 10-30% of all cars sold today are electric. Many other countries, such as China, are trying to boost the sales of EVs by setting targets or offering incentives. In REmap, the number of four-wheel EVs in use would reach 195 million by 2030 and 830 million in 2050. Carmakers already offer affordable models that can travel more than 380 km on a single charge, reducing drivers' anxiety about being stranded without power, thanks to improvements in battery engineering and recharging options.

The numbers of electric buses and electric two-wheelers are growing as well, especially in China. In the REmap analysis, 11 million electric buses and light-duty vehicles would be on the road in 2030 and 21 million by 2050.

Achieving these numbers will require at least 10% of the total passenger car vehicle stock in 2030 and more than one-third in 2050 to be battery-electric cars or plug-in hybrids. Yearly sales of these cars would need to average around 25 million. Still, total renewable energy use in transport would remain relatively small. To begin with, these vehicles are much more efficient than conventional vehicles, so small amounts of renewable electricity would go a long way. In addition, not all of the electricity cars use would come from renewables, and passenger vehicles account for only half of total transport energy use. As a result, the significant deployment of EVs would increase transport's renewable energy share by only eight percentage points under REmap in 2050, from 42% (including biofuels and hydrogen) to 50%. Electricity use share would climb from 0.6% in 2015 to 21% in 2050. Because of the greater efficiencies of using electricity, this increased share would keep transport's total energy demand relatively constant from 2015 to 2050 in the REmap analysis. In contrast, demand grows 60% over that time period in the Reference Case.

Hydrogen also plays a role in end-use sectors. Under REmap, renewables-based hydrogen use grows to 0.9 EJ by 2050 (1% of all industrial energy demand). Its main use would be to replace gas in the process of direct reduction of iron ore in iron making. It also would be used for the production of ammonia and methanol. In addition, there has been much discussion about possible other applications, such as in fuel cell-powered electric cars or other hydrogen-powered vehicles. The technology remains far from commercialisation, but some countries see a potential for hydrogen as a transport fuel. In the passenger car and freight segments, its use in 2050 would be just below 10% of all energy demand with a total consumption of about 7 EJ. More innovation is needed if hydrogen is to play larger roles and be used in more applications.

Figure 3.15 • Final renewable energy use by sector and technology in REmap, 2030 and 2050



Key message • Under REmap, final renewable energy use is four-times higher in 2050 than it is today. Power and heat consume about 40% and 44% of the total renewable energy, respectively, while transport uses about 16%.

Box 3.8 • Transforming the energy market through regional efforts and corporate sourcing of renewables

Recent years have seen the emergence of actors on a sub-national level committing to significantly scaling up their sourcing and use of renewable energy. Many cities, regional governments, communities and co-operatives have set a goal of getting 100% of their energy from renewables. Most of the time, the goal is to source 100% renewable power, but some projects are also looking to power transport, heating or cooling with renewable energy. The GO100% initiative tracks these projects. As of early 2017, it shows that 256 million people live in areas that have shifted, or are committed to shifting within the next few decades, to 100% renewable energy in at least one of these sectors. The initiative shows that there are currently 166 regions, cities or communities that have projects in place to go to 100% renewables (GO100%, 2017).

Companies are also increasingly seeking to achieve significantly higher levels of renewable power. The RE100 initiative brings together and tracks companies that have committed to sourcing 100% of their electricity from renewable energy. RE100's latest annual report lists 87 companies, including some of the world's leading companies, that have made such commitments (The Climate Group, 2017). These companies collectively consume 107 TWh, the same amount of power consumed in the Netherlands. The list is growing quickly. In the last two years, there has been an increase in interest from heavy industry in the RE100 initiative, as some of the world's largest car manufacturers and cement companies have become members. There are many more companies that also have similar aims but are not formally part of the initiative.

These corporate commitments have benefits that go beyond just the increase in renewable power capacity. The companies' efforts can spur innovation in energy service areas where new technologies are badly needed, such as in heavy industry and transport. The companies can also serve as test beds for innovative technologies and for energy service models that can pave the way for wider adoption of renewables on regional and national levels.

More focus is needed on power systems integration and sector coupling

The growth of solar PV and wind capacity is adding large amounts of variable renewable energy (VRE) to the electricity mix. Indeed, more and more countries already achieve VRE generation shares above 20%. Under REmap, the share of wind and solar increases to 31% by 2030 and to 52% by 2050. In terms of capacity, this changes the balance of dispatchable versus non-dispatchable capacity, with the non-dispatchable capacity rising to around half of the total. This growth, in turn, increases the challenges of integrating the variable power into the electricity system and will require the establishment of new business models.

The influence of VRE already becomes noticeable at shares of just 5-10%. The main technical challenges begin when variable renewables push demand for non-renewable generation below the minimal operating level of a country's dispatchable fleet. When renewable power is abundant, dispatchable power plants must produce less or switch off entirely. As a result, balancing supply and demand is difficult, and steps must be taken to ensure system flexibility. The options for meeting these challenges generally fall into four groups: strengthening the grid and interconnectors, or adding flexible generation, demand-side management and storage.

There are synergies between the end-use sectors and renewable electricity generation. If these synergies are utilised, they provide the means for demand-side management and storage, thereby increasing the flexibility of the power system. They also provide benefits for end-use sectors by increasing the share of renewable energy for heating, cooling and transport. For example, the power and road transport sectors can be coupled by recharging EVs at times of renewable power surpluses, a form of demand-side management. EVs can also provide a storage function, feeding power from plugged-in car batteries back into the grid when more electricity is needed in the system.

The power sector can also be coupled with heating and cooling. Heat pumps that operate on a flexible schedule can adjust their operation to account for peaks or dips in electricity supply in combination with cold or heat storage. For example, they can turn off temporarily when overall system demand jumps, thus reducing peak load. Smart thermal grids (district heating and cooling) offer even more flexibility by adding thermal storage. Surplus renewable electricity could also be used to make liquid fuels. In one plan being considered, abandoned oil and gas platforms in the North Sea off the coast of Europe would be refurbished into units that would convert electricity from offshore wind farms into hydrogen and synthetic gas.

Electricity storage is another key option for integrating higher shares of variable renewables. In the REmap analysis, electricity storage capacity reaches more than 1 000 GW by 2030, when the total installed solar and wind capacity will be 5 000 GW. This storage capacity is split into: 600 GW from electric vehicles, 325 GW from pumped hydro, 125 GW from stationary battery storage and 50 GW from second-hand car batteries.[82] Total storage capacity grows to nearly 3 000 GW by 2050, with EVs in operation accounting for majority of this total. REmap gives a large importance to natural gas back-up capacity as well. Total installed gas capacity for such purposes would reach 5 000 GW by 2050.

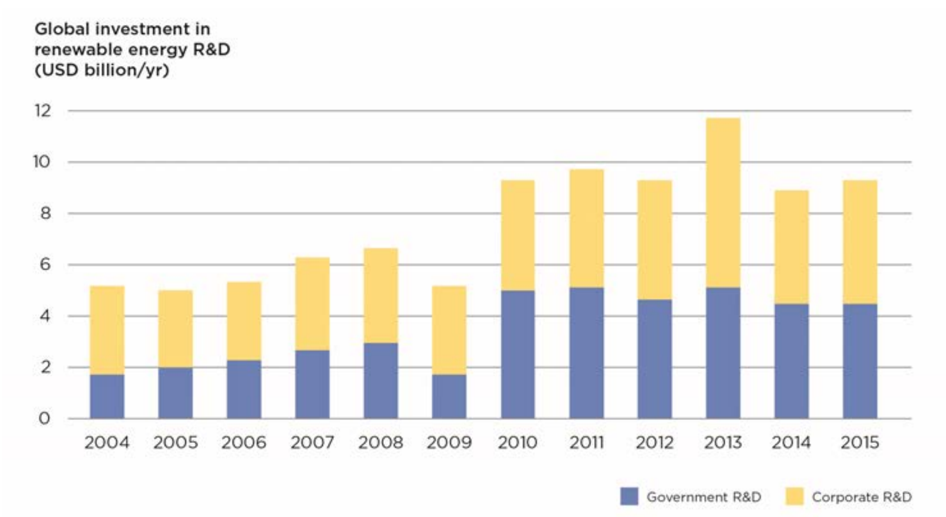
Box 3.9 • Energy innovation trends and initiatives

Innovation will continue to be crucial to decarbonising the energy sector. While technical solutions for the power sector already exist, continued innovation will enhance their performance, reduce their costs and help scale up the deployment of the best available technologies.

Non-power sectors have greater innovation challenges than the power sector does. For around one-third of all energy-related CO_2 emissions (primarily from the industry and transport sectors), no economically viable renewable energy supply alternatives exist today.

For example, renewables account for only 3% of the current energy demand for the transport sector. Promising developments in EVs may increase the share of renewables for passenger road transport. But the share of renewables in aviation and freight will not rise unless advanced liquid biofuels quickly become competitive with fossil fuels, which currently looks unlikely. In the industry sector, renewable options for high-temperature heat generation, which typically accounts for a large share of the energy demand in energy-intensive industries like iron, steel and chemicals, have not yet commercially emerged. Alternatives, such as electricity-based iron production (electro-winning), a process similar to that used for non-ferrous metal production, need to be further developed.

Figure 3.16 • R&D spending on renewable energy, 2004-2015



Source: (Frankfurt School-UNEP Centre/BNEF, 2016).

Key message • There is an urgent need to increase R&D investment. R&D for renewables is not currently growing and for end-use sectors R&D investment is miniscule.

82 Battery storage capacity from second-hand car batteries can be higher depending on their usability, which still needs to be determined.

Additional research and development (R&D) efforts in renewables will also further bring down the costs of zero-carbon technologies and decrease the overall costs of decarbonisation. Unfortunately, R&D investment in renewable energy technologies has not grown in the last seven years. Moreover, most R&D investments for renewables continued to be in power sector technologies (such as PV and wind) rather than in technologies for end-use sectors (such as biofuels and biomass), where they are urgently required.

In order to enable this energy transition, therefore, G20 countries should increase their R&D investments to find technology solutions for sectors where more innovation is required.

The magnitude of the challenge means that international collaboration is required. Innovations must be shared, materialised and widely replicated by others. There is a big opportunity for G20 countries to engage, co-ordinate efforts and demonstrate political leadership.

To meet this need for collaboration, several international initiatives aimed at nurturing R&D in clean energy technologies have been created. They include:

- The Mission Innovation initiative in which 22 countries and the European Union have committed to doubling their government R&D investments for clean energy over the next five years.
- IEA's Technology Collaboration Programmes (TCP) support R&D for the energy sector through a collaborative platform that brings experts together to exchange experiences and co-ordinate efforts. The 39 TCPs operating today involve about 6 000 experts from government, industry and research organisations in more than 50 countries.
- The Clean Energy Ministerial seeks the diffusion of clean energy technologies through initiatives focused on specific technologies, including mini-grids, smart grids, PV and wind grid integration, and super-efficient appliances.

Other areas of important innovation for the decarbonisation of the energy sector have often been overlooked. IRENA has several efforts aimed at identifying them including IRENA Innovation Week, which is held every other year. The most recent event, in 2016, focused on the power sector and highlighted the need for innovation in market design, business models, financial instruments and infrastructure. Similarly, the Ministerial Roundtable of the 7th session of the IRENA Assembly, which includes ministers as well as private sector leaders, emphasised that the transformation will not move forward without innovative policy and regulatory frameworks.

While the power sector has a long history of policy frameworks that encourage deployment of renewables, such frameworks are lacking in most countries for end-use sectors. In addition, there are difficult policy choices, including additional market regulations that will need to be made in these sectors to decarbonise their energy systems. Examples include limits on sales or higher taxes for inefficient cars, stricter energy efficiency regulations for existing buildings or requirements to demolish and replace old buildings, or structural changes and relocation of plants in industry. The G20 has the advantage of including developed as well as emerging economies, so it has a comprehensive picture of the different innovation needs and complementary innovative solutions for different constituencies.

As innovations emerge, continuing to share experiences and best practices is crucial. The G20 has a large opportunity to use all these initiatives to accelerate the decarbonisation of the energy sector.

Renewable energy use in G20 countries: contributions by each and all

All countries have opportunities to increase their amounts of renewable energy beyond the Reference Case. However, there are stark differences between countries and regions in their starting points of renewable energy use, renewable resource availability, access to financing, policy frameworks and many other factors. These differences explain why some countries can achieve a tripling or even a quadrupling of their renewable energy shares, while others are less likely to achieve significant growth.

Figure 3.17 shows the implications for individual countries of the global objective of doubling the share of renewables (to 36%) in the global energy mix by 2030 and increasing that to 60% by 2050. The starting points are the renewable energy shares in 2015. The global average renewable energy share was 19%. While Japan, the Russian Federation, Saudi Arabia, the United Kingdom and others are below 5%, some others, such as Brazil, India and Indonesia are above 20%.

In most countries, the Reference Case foresees modest increases in renewable energy shares based on the countries own long-term plans. For instance, Canada and the United States have rather conservative policy ambitions. In Mexico, the demand for all energy is growing as fast as the uptake of renewable energy technologies, so the renewable energy share remains the same for the entire period. In some countries, however, the renewable energy shares are forecast to decrease between 2015 and 2030. For India and Indonesia, this is explained by reductions in traditional bioenergy use, as more efficient cookstoves that use modern bioenergy or fuels like as liquified petroleum gas/kerosene come into use.

For all countries, REmap identifies additional potential for renewable energy technologies. For countries with high starting points or existing ambitious plans for growth, the additional potential in the REmap case over the Reference Case is rather limited. Many others do not have ambitious plans, however, REmap shows that they have significant extra potential. Canada, India, Turkey and the United States, for instance, all have high levels of renewable resources that remain untapped, both today and in the countries existing plans until 2030/50.

For some countries, the renewable energy potential may be greater than what was identified in REmap. But more work is needed by policy makers and other stakeholders to identify options, especially in countries where fossil fuels play a large role in the economy. The transition for these countries in adopting renewables might take more time.

REmap shows that the G20 as a whole could reach a 63% renewable energy share by 2050, equivalent to around 175 EJ final renewable energy use. This represents 70% of the total global final renewable energy use in 2050 (235 EJ). While each country has the potential for additional renewables beyond the Reference Case, the top-five G20 countries in terms of total renewable energy use – Brazil, China, India, Indonesia and the United States – account for half of the total global renewable energy use in 2050 and 70% of the G20. That means decisions in a few countries are critical for the success of a global renewable energy acceleration. But those countries alone will not be able to put the world on a pathway that limits global temperature increases to 2°C.

Figure 3.17 • Renewable energy share in TFEC in G20 countries in the Reference Case and REmap, 2015-2050

Key message • In the Reference Case, the renewable energy share in G20 countries would range from 5-40% by 2050. As REmap shows, achieving the 2°C target would require that shares increase to between 30-80% in all G20 countries.

Table 3.3 • Summary of Reference Case and REmap results

	Units	2015	Reference Case 2030	REmap 2030	Reference Case 2050	REmap 2050
Renewable energy in electricity generation						
Hydropower	GW	1 208	1 413	1 671	1 391	1 628
Pumped hydro	GW	155	300	325	300	325
Wind	GW	417	1 312	2 665	2 331	4 801
Onshore	GW	405	1 286	2 565	2 243	4 401
Offshore	GW	12	27	100	88	400
Solar PV	GW	219	1 220	2 921	2 703	6 348
CSP	GW	5	47	224	150	719
Biomass	GW	103	166	251	269	415
Geothermal	GW	12	36	126	63	283
Marine	GW	0.5	6	9	12	80
Battery storage	GWh	0.5	1 096	2 980	3 095	10 400
Electric vehicles	GWh	0.4	596	2 080	1 995	8 500
Two- and three-wheelers	GWh	0.1	500	900	1 100	1 900
Renewable energy use in transport						
Electric Vehicles	million vehicles	1.26	60	208	200	851
Passenger vehicles	million vehicles	1.24	59	197	198	830
Buses & Light-duty vehicles	million vehicles	0.02	0.64	11.0	1.5	21.9
2/3 wheelers	million vehicles	200	500	900	1 110	1 940
Bioliquids	billion litres	129	280	500	580	1 120
Ethanol	billion litres	94	195	255	320	635
Biodiesel	billion litres	25	55	135	155	310
Biojet	billion litres		29	111	105	175
Biomethane	billion m^3	0.4	1	24	3	200
Renewable energy use in industry						
Biomass heat (incl. CHP)	EJ/yr	8.0	12.8	16.8	19.6	31.2
Biomass feedstocks	EJ/yr	0.8	2.0	4.0	8.5	16.0
Solar thermal - concentrated	GWth	0.1	0.7	95	9	144
Solar thermal - flat plate, evacuated tube	million m2	1.0	17.1	2 440	221	3 695
Geothermal (direct heat)	EJ/yr	0.02	0.04	2.90	0.54	4.41
Heat Pumps	million units	0.2	2.5	34.2	5.6	79.5
Renewable energy use in buildings						
Biomass – traditional	EJ/yr	28.0	12	0	4	0
Biomass - advanced cooking	EJ/yr	2.5	3.1	13.9	5.6	8.3

Traditional cookstoves	million units	568	252	0	76	0
Modern cookstoves	million units	48	206	1 007	400	813
Biomass heat	EJ/yr	4	17	16.6	18.5	14.3
Solar Thermal	million m^2	622	1 364	5 542	1 962	11 695
Geothermal (direct heat)	EJ/yr	0.3	0.9	2.7	1.4	3.8
Heat Pumps	million units	4	23	102	47	232
Total final renewable energy use						
Total final renewable energy use	EJ/yr	64	88	145	120	235
Renewable energy share in TFEC	%	19	21	37	23	61

The economic case for the energy transition

Renewables offer a wide range of benefits, well beyond those related to energy security, climate and environment. There is growing evidence that they can support economic growth and improve human welfare. Renewables are key to achieving the United Nations' Sustainable Development Goal (SDG) of providing all people with affordable clean energy (Goal 7), while reinforcing other SDGs. They facilitate access to basic services, improve human health, enhance incomes and productivity, and promote gender equality and educational opportunity. Renewables also create new jobs and spawn new local industries, and can contribute to sustainable urban development (IRENA, 2017d). This section discusses the benefits of the REmap energy transition in detail.

Mitigating climate change through renewable energy deployment would yield macroeconomic benefits

The world is faced with an urgent need to decarbonise. At the same time, many major advanced and developing countries are suffering from sluggish economic growth and high unemployment. The traditional view has been that there is a trade-off between economic growth and decarbonisation. Much of the climate change mitigation literature, notably the model comparison exercises compiled in the IPCC's Fifth Assessment Report, has estimated negative economic impacts of decarbonisation (Clarke et al., 2014). However, the literature is now several years old, and its authors admit the significant uncertainties around their estimations, acknowledging the possibility of positive economic impacts, especially if the technologies required for decarbonisation (e.g. renewables) improve in cost and performance (Box 3.10).

Box 3.10 • Existing literature acknowledges the possibility of positive economic impacts

Forecasting the economic impacts of global decarbonisation is a daunting task. The IPCC itself, being the most scientifically sound reference on the topic, admits the uncertainties. The Fifth Assessment Report forecasts negative economic impacts, but allows for positive ones, if certain circumstances take place - circumstances either already existing, or likely to come about.

The role of technology: the past ten years have been a period of outstanding technological advances and cost decreases for renewable energy technology, which the IPCC Fifth Assessment Report was not able to capture. Citing IPCC: "Because technology will underpin the transition to a low-carbon economy, the availability, cost, and performance of technologies will exert an influence on economic costs" (Clarke et al., 2014). The Fifth Assessment Report was published in 2014, with most model comparisons being done between 2009 and 2014, with model runs done using data that could be even older.

Modelling approach: most of the underlying models are based on neo-classical economics (i.e. computable general equilibrium (CGE) techniques) which assume that markets are perfect, agents fully rational and the economy works at full capacity. This is largely questionable, as postulated by post-Keynesian economics. The IPCC's Fifth Assessment Report admits the large uncertainty around assuming perfect markets. Citing IPCC: "The aggregate economic costs reported (…) assumed (…) in many cases an idealized implementation environment with perfectly functioning economic markets devoid of market failures (…) The reality that assumptions of idealized implementation and idealized implementation environment will not be met in practice means that real-world aggregate mitigation costs could be very different from those reported here" (Clarke et al., 2014). In fact, recent research is trying to relax some of these strict assumptions in several CGE models (e.g. by including unemployment or explicitly representing money supply). Also interestingly, several recent CGE-based analyses are showing positive impacts of more ambitious decarbonisation or renewable energy deployment, such as in the case of Brazil or China (CNREC, 2016; Dai and Liu, 2016; Wills and Grottera, 2015).

The role of the "double-dividend": the IPCC states that climate policy does not happen in an idealised, perfect market environment, and if there are synergies between climate and other policies, economic impacts could be more positive. This is for instance the case of climate and fiscal policy. A "double-dividend effect" could take place if carbon price revenues are used to reduce distortive taxes (such as those on labour). This is very much in line with the literature on "green tax reform", with the findings of OECD's G20 report in the case of "pro-growth policies" being implemented (OECD, forthcoming), and with the environmental taxation initiatives advocated by institutions (e.g. the OECD, the European Commission, the International Monetary Fund (IMF) or the European Environment Agency). Citing the IPCC, "literature has also looked into the use of carbon revenues to reduce pre-existing taxes (generally known as the "double-dividend" literature). This literature indicates that total mitigation costs can be reduced through such recycling of revenues. (…) Climate policies will interact with pre-existing policy structures as well as with other market failures (…) and these interactions can either increase or decrease policy costs. A number of authors have argued that costs could be much lower or even negative [i.e. positive economic impacts] compared to those produced by studies assuming idealized policy and implementation environments" (Clarke et al., 2014).

Rapid technological advancements in renewables are indeed taking place, and in many circumstances renewables are becoming the cheapest source of energy, a trend which is likely to continue in the future (IRENA, 2016f). Such changes can be a driver for the economic impacts of decarbonisation to become positive.

These, among other factors, are beginning to force a rethinking of the traditional view of the trade-off between economic growth and decarbonisation. There is growing evidence that mitigating climate change through renewable energy could actually bring positive economic impacts, stimulating growth and employment worldwide. Some of this evidence is for G20 members: the United States (ICF Resources LLC, 2015; Synapse Energy Economics et al., 2015), China (CNREC, 2016; Dai and Liu, 2016), Japan (Pollitt et al., 2014), Germany (Blazejczak et al., 2011; Lehr et al., 2012), France (Callonnec et al., 2016) or Brazil (Wills and Grottera, 2015). [83]

Overall, a policy intervention that reduces greenhouse gas emissions while simultaneously boosting economic output is particularly compelling, and there is growing evidence that this could be the case. This section explains the impact of the REmap energy transition on GDP at an aggregate level, and then describes the changes in economic structure and the effects on

83 These positive results for Brazil and China are obtained with neo-classical CGE models.

employment. The analysis in this section has been carried out using the global post-Keynesian macro-econometric model E3ME.[84]

Decarbonising the energy sector can yield global GDP growth

Achieving the energy transition in the G20 as outlined by REmap would increase global GDP[85] by 1.1% in 2030 and by 0.8% in 2050[86] compared to the Reference Case (Figure 3.18). The additional economic activity generated between now and 2050[87] would be an estimated USD 19 trillion,[88] which is similar to the total value of all the companies traded on the New York Stock Exchange, the largest stock exchange in the world.[89] In 2050 alone, the additional output would be USD 1.6 trillion, similar to the combined GDP of Indonesia and Turkey today (IRENA, forthcoming a).

The main driver of the global economic surge is the investment boost from the high capital requirements of renewables and energy efficiency. Upfront investment is, for both, a larger share of total lifetime cost than it is for fossil fuel-based technologies.

The additional investment in the REmap case, compared to the Reference Case, is about USD 0.83 trillion per year globally (on average between now and 2050). Of that, 40% is in renewables supply and 60% is in energy efficiency and the electrification of end uses. These investments more than offset the reduced investment in conventional energy sectors, increasing overall investment in the energy sector (as seen in Figure 3.9). These investments take place mainly in the power sector and in the end-use sectors where energy efficiency measures are implemented (e.g. residential or transport sectors), and lead to higher economic activity across the economy (even after accounting for a partial competition for capital across the economy (Box 3.11).[90] It should be noted that there are uncertainties around the estimates of investments required, especially in the case of energy efficiency. Given the key role that these investments play in driving GDP growth, the current economic situation of low interest rates and low growth present an ideal opportunity for such an intervention, as also pointed out in (OECD, forthcoming).

An additional driver increasing GDP is the growth in household expenditure. Such expenditure is caused by a larger real disposable income due to: reduced income taxes as a result of the increased government revenue from carbon pricing (i.e. the double-dividend effect of a green tax reform[91]); and reduced expenditures on energy that can be allocated to other expense categories

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84 For further details, see Annex B.

85 While the GDP measure fails to capture the broader improvements in human well-being (*e.g.* including social and environmental aspects), it would still increase in the energy transition. Estimates of the welfare and broader sustainable development implications of renewable energy deployment are the focus of current and recent IRENA work (IRENA, 2017d, 2016g, 2016h, forthcoming a)

86 Estimates of the impact of renewable deployment on the GDP for the G20 countries alone are slightly higher. As of today, the G20 represents 86% of global GDP, and by 2050 under the Reference Case it would account for 82%.

87 Discounted at a *social* discount rate of 3%.

88 All monetary figures are expressed in constant 2015 prices.

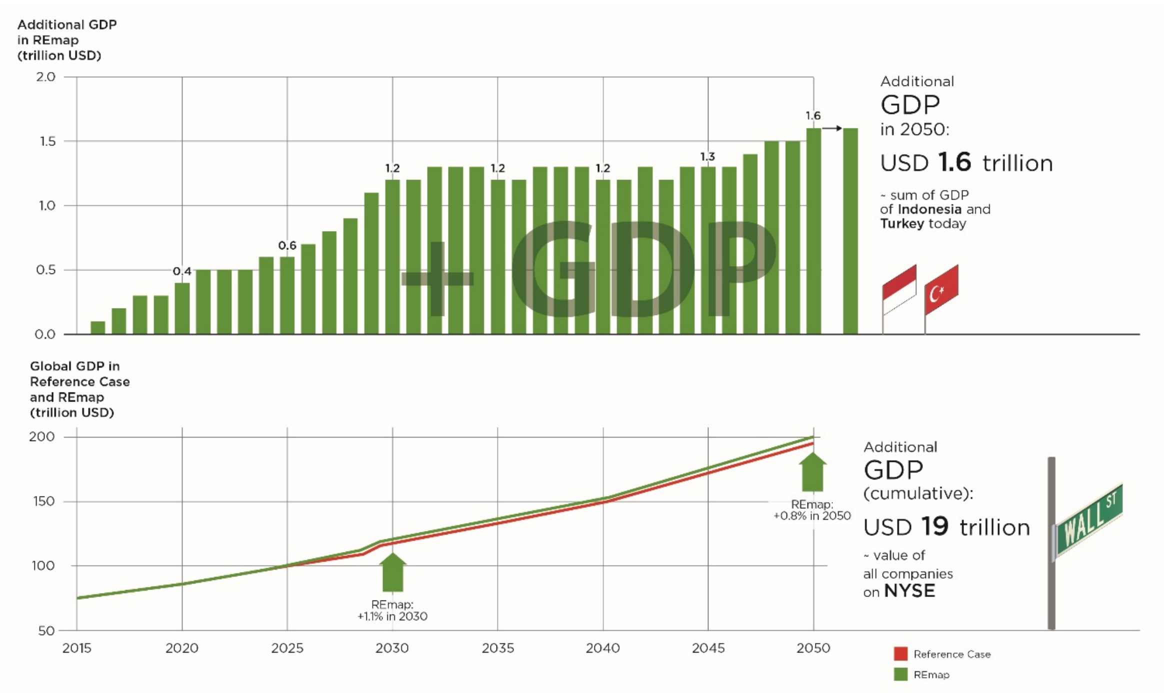
89 Total market capitalisation of all listed companies (NYSE Market Data, 2017). Since the market capitalisation of a company could be interpreted as the discounted value of all future cash flows expected by the market, it is a meaningful comparison for a discounted cumulative additional GDP, even if the discount rates used are arguably different (private versus social).

90 The only investments that are assumed to be financed by debt are those in the power sector. Such debt is assumed to be private and not public, a key difference from the OECD G20 report (OECD, forthcoming). As such, the decarbonisation does not directly increase public debt.

91 The present macroeconomic analysis assumes carbon prices in line with IEA's *World Energy Outlook 2016*, New Policies Scenario and 450 Scenario respectively for the Reference and REmap cases (in terms of value, geographical and sectoral application). The analysis also assumes that carbon pricing is revenue-neutral for the government, by reducing income tax (i.e. "revenue recycling" through reduced income taxes). Such reform is a sort of "green tax reform", and is widely considered by the literature to yield positive GDP impacts, a finding also consistent with the upcoming OECD G20 report (OECD, forthcoming).

(electricity prices fall in many countries where renewables are more cost-competitive,[92] and prices of fossil fuels drop).

Figure 3.18 • Global GDP impacts of the REmap energy transition: additional and absolute GDP values, 2015- 2050



Notes: The top graph illustrates the additional real global GDP in each year (USD 2015 trillion, undiscounted) and is equivalent to the area between the two GDP lines in the bottom graph. The figure of the additional cumulated GDP sums these yearly figures, discounted at a social discount rate of 3%. The bottom graph represents the global GDP in real terms (2015 USD) in each of the two cases. All GDP figures are expressed in market exchange rates.

Key message • Decarbonising the energy sector in line with REmap increases global GDP by around 0.8% by 2050 compared to the Reference Case. In cumulative terms this constitutes almost USD 19 trillion in increased economic activity between today and 2050.

Overall, this analysis suggests that it is possible to carry out a fundamental transition in the energy sector without slowing GDP growth. In fact, the rates of GDP growth may increase. However, important changes in the sectoral contributions to GDP can be expected.

Box 3.11 • GDP impacts in case of full capital crowding out and the double-dividend effect

The investments required in the decarbonisation case (as outlined by REmap) could displace (i.e. "crowd out"[93]) capital available to other productive sectors, having a possibly depressing effect on the economy. There is no clear evidence in the economic literature for whether this happens in reality, with different schools of thought (mainly post-Keynesian versus neo-classical) following very different assumptions. This analysis follows a post-Keynesian approach, which is different than the mostly neo-classical approaches used in the existing literature on the economic impacts of climate

92 The analysis considers the cost of integration of renewables as a mark-up in the price of electricity for each country. The mark-up increases with the share of variable renewables in the country.

93 In the economic literature, the expression "crowding out of capital" is used with two different meanings. In some cases it means that public investment can hinder private investment. In some other cases, it means that investment (either public or private) in a sector reduces capital availability for investment in other sectors. In this report, the second meaning is adopted.

change mitigation, but is still grounded on solid empirical evidence (Anger and Barker, 2015; Arestis and Sawyer, 2011).

One of the main differences between the schools of thought is that pure post-Keynesian approaches assume no crowding out of capital. For the purpose of this analysis, the central scenario assumes a partial crowding out. Furthermore, a sensitivity analysis is carried out under full and null crowding out conditions (see the sensitivity analysis section below). In the full crowding out case (the closest to a neo-classical approach, such as the one used in OECD, forthcoming), GDP impacts are reduced, but remain positive, because the secondary driver increasing GDP (increased expenditure) is not significantly affected.

The main reason for the increased expenditure is the double-dividend effect of recycling the proceeds from carbon pricing to reduce income taxes. The positive economic effect of such recycling method is in line with the: i.) literature on "green tax reform"; ii.) narrative included in the IPCC's Fifth Assessment Report (when it refers to the synergies between climate and other policies); iii.) findings on "pro-growth policies" in OECD's G20 report; and iv.) the environmental taxation initiatives proposed by relevant international institutions such as the OECD, the European Commission, the IMF and the European Environment Agency.

Decarbonisation will bring about a shift in the composition of the economy

The transition towards a decarbonised energy sector will bring structural changes in the economy. Some sectors and industries will see reduced activity, while others will thrive. In a decarbonisation case where investment in capital-intensive renewables and energy efficiency is significantly scaled up, sectors related to capital goods and services would receive a boost, while those related to fossil fuels would see reductions in output. This dynamic is reflected in the GDP impacts experienced by different countries depending on the relative importance of various sectors. Accordingly, countries relying on fossil fuels for a large share of their GDP could face declines in economic activity. This has important strategic, policy and political economy implications for countries and for the global decarbonisation of the energy sector (OECD, forthcoming). Continued policy interventions, including towards economic diversification, could help mitigate the negative economic impacts in fossil fuel exporting countries (OECD, forthcoming). The structural effects of the REmap energy transition are represented in Figure 3.19 in terms of changes in output per sector compared to the Reference Case.

The main negative impacts of decarbonisation would occur in the fossil fuel industry and in utilities. As the demand for fossil fuels falls, related activities, including exploration, production, refining and distribution, would experience slowdowns. Prices would drop as well, combining with lower demand to reduce overall sectoral output. The coal industry would be hit the hardest, with output falling by about 20% in 2030 and close to 30% in 2050 in comparison with the Reference Case. The oil and gas industries would experience smaller reductions due to a lower substitution effect (the carbon content of their products is relatively lower and their products are harder to substitute). The production of the oil and gas sector in real terms would fall by 10% and 20% in 2030 and 2050, respectively, compared to the Reference Case.

Utilities also would experience a slowdown. Despite increased electrification in the economy (the share of electricity in global final energy consumption goes from 24% in the Reference Case to 29% in REmap by 2050), energy efficiency measures would limit final consumption enough to reduce overall power generation by around 10% compared to the Reference Case. As a result, output from the power sector falls by 4% by 2030 and 7% by 2050.[94]

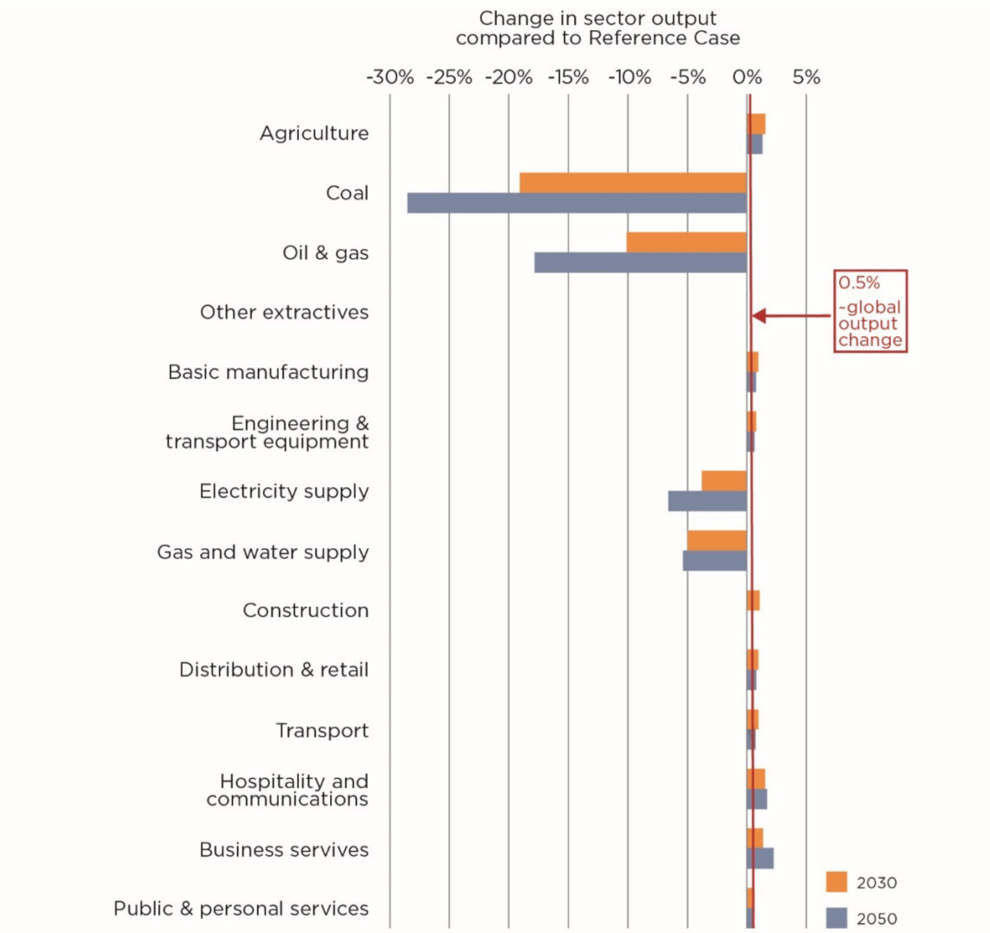
Within the power sector, however, there are some important differences across technologies that are not evident in the macroeconomic analysis because of methodological limitations.[95] Some power technologies, such as coal power generation, will decrease their output, while others, such as renewables, and other activities such as T&D, smart grids or demand response, will increase. Some light is shed on these aspects in the jobs analysis in the next section, where estimates have been made for employment by technology.[96] Beyond the power sector, other utilities would also experience reductions. Gas and water supply activities decrease by 5% (mainly because of the reduction in gas demand).

94 While generation (in TWh) falls around 10%, sectoral output (in USD) falls around 4-7%. These figures are not directly comparable, since there are significant price effects playing a role. For instance, generation may be falling more (in TWh terms) in a country with cheaper electricity overall, so the effect on global output would be smaller. The difference between generation and output changes does not relate to the different electricity prices between scenarios, as the measure of output is in real terms, so such price effects are stripped out of the calculation.

95 The macroeconomic representation does not include a measure of output for each power generation technology, only showing the sector as a whole. This is a consequence of the available data and the definitions used in national economic accounts. Some academic literature has attempted to split the power sector into different technologies and a similar bottom-up approximation based on employment factors has been used for the jobs analysis in the next section.

96 Indeed, structural impacts can be analysed from the point of view of sectoral output (measured in USD terms) but also from the employment perspective. As such, the employment analysis by technology in the section below can be used as a proxy for structural impacts and changes in output across power generation technologies.

Figure 3.19 • Structural changes of the REmap energy transition, 2030 and 2050



Notes: The vertical red line indicates the global output change (2030 and 2050 average), for comparison with output change per sector. Output and GDP differ since the latter discounts intermediate inputs. Importantly, it should be noted that representing output changes in percentage terms has the drawback of making the impacts in large sectors seem relatively smaller than they are in absolute USD terms.

Key message • Fossil fuel industries see the largest reductions in sectoral output, while the highest increases are in sectors related to capital goods, services and bioenergy.

The activities that stand to gain the most from the energy transition are those that benefit from the capital-intensive nature of renewables and energy efficiency, and from the overall economic improvement (as seen above through GDP increases).

The additional investments in renewables and energy efficiency more than offset the reduced investments both in fossil fuels upstream and in conventional power plants. As a result, the activities supplying capital goods and services increase their overall output. In particular, activities related to construction, engineering and manufacturing of goods required for the transition (such as renewable energy equipment or EVs) will increase their output by around 1%. At the next level of the supply chain, activities providing goods for the construction, engineering and manufacturing sectors would increase their economic output by around 0.5%. Examples include basic metals and non-metallic mineral products (e.g. cement). Going further upstream in the supply chains, activities extracting and delivering raw materials would see an increase, although this is a relatively small sector and the changes in output would be so limited that they do not show up in the analysis.

Output also increases in many areas of the services sector. While some services are part of the supply chains for renewables and energy efficiency activities (e.g. planning or transport), most of the impacts are the result of induced economy-wide effects due to the overall GDP increase. For example, higher household income increases demand for food, education and health services. Distribution and retail, hospitality, ICT and business services would increase their output between 1% and 2%.

In addition, output from the agricultural sector also would increase, mainly due to the rise in bioenergy feedstock production.

Overall, the decarbonisation of the energy sector would bring about a major economic transformation. Sectors related to sustainable energy, including those in the supply chain for the required investment goods and services, increase their participation in the economy. These transformations, and the economy-wide structural changes that will take place, imply a transfer of labour from activities related to fossil fuels to those related to renewable energy or energy efficiency. The next section describes the likely impacts on jobs in the energy sector and across the wider global economy.

The energy transition will increase employment across the energy sector and in the economy as a whole

The energy transition will increase employment levels. This is a key finding, given the fundamental role of jobs in social and economic development, which goes well beyond wage generation (World Bank, 2012).

Global jobs in the overall energy sector

The decarbonisation of the energy sector will bring higher employment levels in energy, since the number of new jobs created in renewables and energy efficiency more than offsets job losses in fossil fuels (Figure 3.20). Global energy sector employment today stands at around 40 million jobs (direct and indirect).[97] Of these, IRENA estimates 9.4 million jobs to be in renewables,[98] a number that has been growing consistently in recent years (IRENA, 2016i).

In the Reference Case, global renewable energy jobs (direct and indirect) would reach 15 million by 2030 and 17 million by 2050. In comparison, in the REmap case, the number of jobs would increase to 24 million by 2030 and 26 million by 2050. Although employment in renewables is higher in the REmap case, these estimates suggest a possible plateau, as increases in renewable energy jobs are limited by a combination of energy efficiency improvements (which reduce total energy demand) and growing labour productivity. In addition, bioenergy, one of the most labour-intensive renewables, would reach a supply limit.[99]

Overall, the increased employment from renewables alone would offset job losses in the fossil fuel sectors (which would be around 7 million in 2030 and 8 million in 2050). Furthermore, when jobs related to the increased rates of energy efficiency are considered (9 million in 2030 and around 5 million in 2050), the overall energy sector (including efficiency) employs significantly more people in the REmap case (Figure 3.20).

However, many individual workers in the fossil fuel sectors may suffer if they cannot easily transfer to renewable and energy efficiency jobs. As a result, the transition requires a consistent

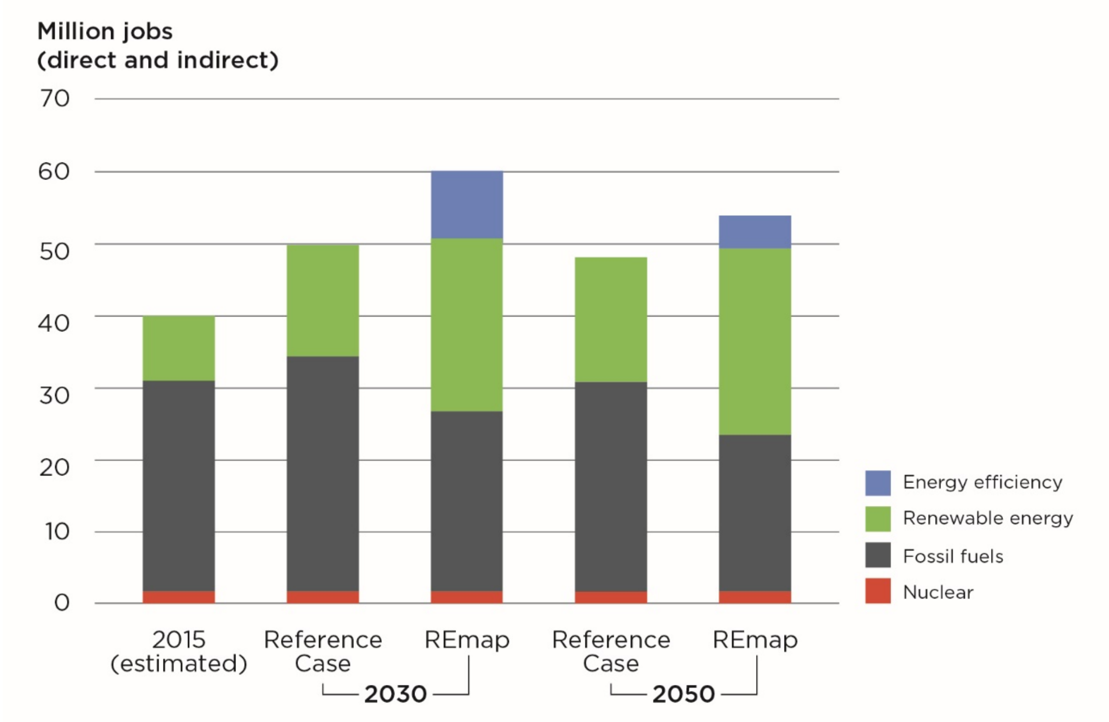
97 All jobs figures include direct and indirect jobs. The 2015 values for fossil and nuclear energy employment are IRENA estimates based on the literature.

98 Including large hydropower.

99 Total primary supply of bioenergy feedstock reaches a maximum of around 150 EJ/year in REmap.

and comprehensive mix of policies, including retraining programmes. For instance, significant job losses will happen in the coal sector. But some coal workers are already shifting to the decarbonised energy sector, taking jobs as solar PV technicians, for example, or as construction workers employed in energy efficiency retrofits (Galgóczi, 2014; Renner, 2016).

Figure 3.20 • Employment in the overall energy sector, 2015, 2030 and 2050[100]



Note: Due to methodological limitations, energy efficiency jobs are only computed for the REmap case based on the additional investments needed in energy efficiency (in REmap vs Reference Case).

Key message • New jobs in renewables and energy efficiency more than offset job losses in fossil fuel sectors.

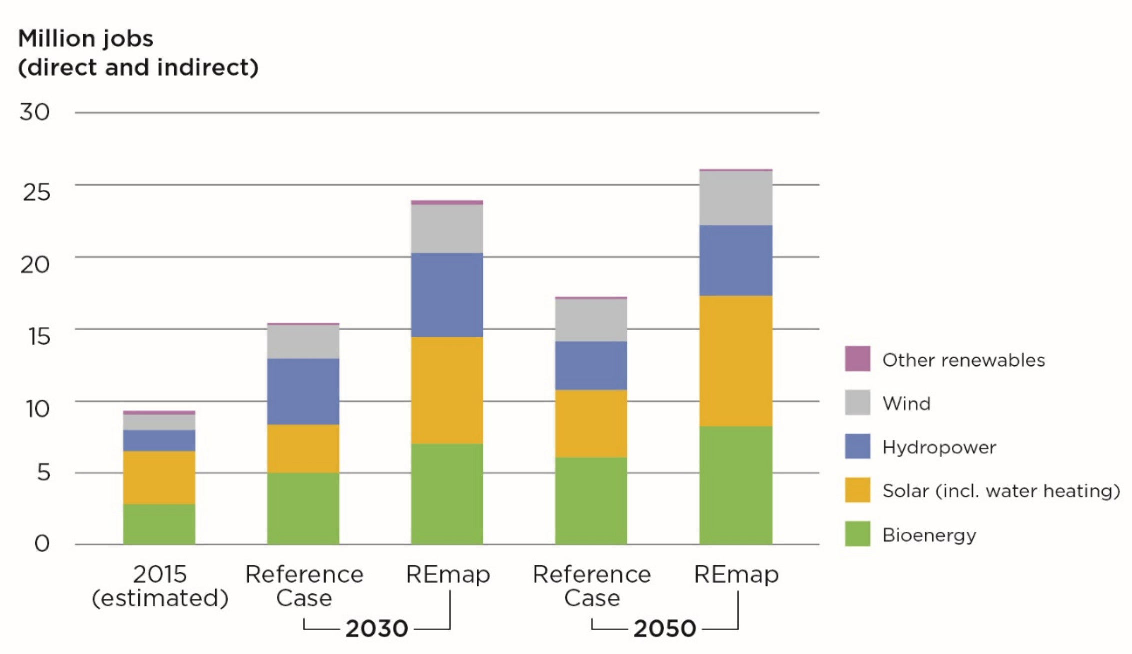
Renewable energy jobs by technology and country

Most of the renewable energy employment in the REmap case would be in solar (7 million jobs by 2030 and 9 million jobs by 2050), bioenergy (7 and 8 million, respectively), hydropower (6 and 5 million, respectively) and wind (3 and 4 million, respectively).[101] The ranking of technologies remains unchanged from that of today (Figure 3.21). Compared to current levels, global employment increases in all renewable technologies.

100 The level of employment in energy efficiency is not reported for the reference case as no figure is available from current data (energy efficiency is not defined as a separate sector). The results therefore only show the net additions for the REmap case. This limitation does not affect the conclusions, which compare the REmap and reference cases.

101 Solar jobs include all electric and thermal applications. Bioenergy jobs include feedstock and power generation. Hydropower includes large and small hydropower. It should be noted that there are significant data gaps that affect the analysis presented here, due in part to the existing informality in some of the labour markets considered.

Figure 3.21 • Renewable energy employment by technology, 2015, 2030 and 2050

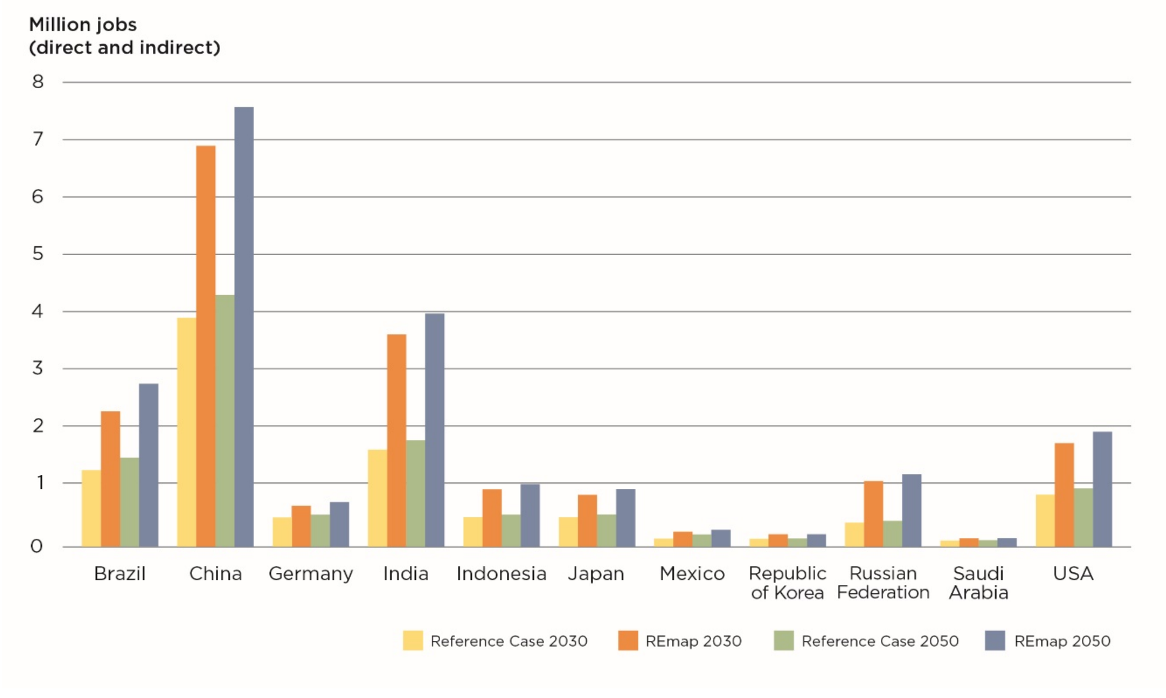


Key message • Renewable energy jobs can reach around 25 million by 2050, with solar and bioenergy being the main employers.

The largest employment in absolute terms will be in the G20 countries (Figure 3.22). Employment in renewables will be dominated by China, India, Brazil and the United States. Large domestic deployment and equipment manufacturing will make China the global leader in terms of renewable energy employment, with seven million jobs by 2030 and close to eight million by 2050. The number of renewable energy jobs in India is expected to grow significantly as the country's already significant ambitions are further scaled up. Meeting India's 2022 target of 100 GW of solar is, alone, expected to create 1.1 million jobs (CEEW and NRDC, 2016) , and there could be about four million jobs in renewables in India by 2050. Brazil also ranks in the top- five employers with close to 2.5 million by 2050, due to its bioenergy sector (consisting mainly of feedstock harvesting and processing). In the United States, a strengthening of policies to encourage emissions reductions could yield two million renewable energy jobs by 2050.

It is also important to note that key fossil fuel-exporting countries like the Russian Federation and Saudi Arabia also gain substantial numbers of jobs in renewables. In Saudi Arabia, many of the jobs are related to the construction and installation of solar energy, while in the Russian Federation there are large numbers of jobs in bioenergy feedstock production (both for domestic use and exports).

Figure 3.22 • Renewable energy jobs in the highest employing countries, 2030 and 2050



Key message • The largest renewable energy employers are all G20 countries.

Employment impacts in the whole economy

Looking beyond the energy sector and its supply chains, economy-wide (i.e. net) employment is higher in the REmap case than in the Reference Case, due to increased rates of overall economic growth (GDP is higher in the REmap case by 1.1% in 2030 and by 0.8% in 2050). In addition to direct and indirect job creation in sectors like construction and manufacturing, a significant induced job creation takes place in sectors related to services, because of the increase in economic activity described above. Global economy-wide employment increases by around 0.1% by 2030 and 2050. Many of the new jobs are created in labour-intensive sectors like construction and hospitality.

Reaping the benefits depends on implementing coherent energy and economic policies

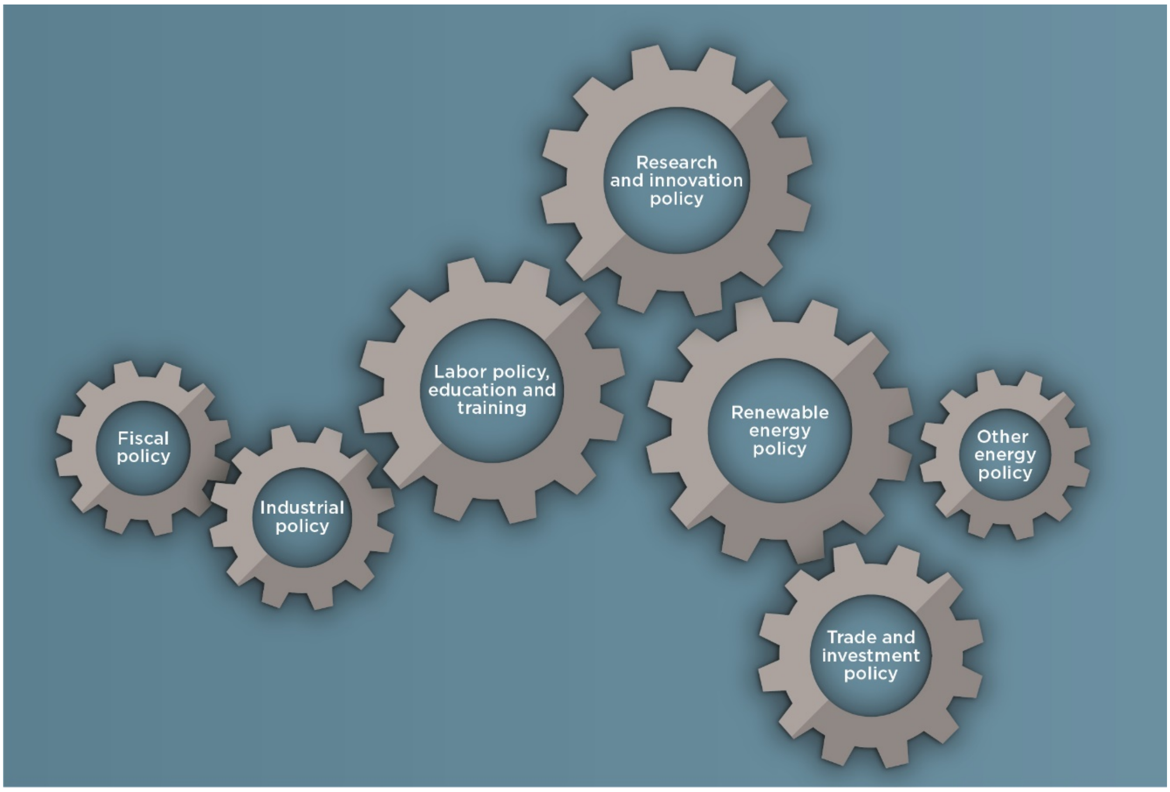
The analysis in this section shows that the energy transition can fuel economic growth and create new employment opportunities. Thanks to the growing business case for renewable energy, climate change mitigation and economic growth are no longer an "either-or" choice. This is a significant conclusion in the current context of sluggish economic growth.

Job creation in renewables and energy efficiency, for instance, would more than offset job losses in fossil fuel sectors. Millions of new jobs will exist in activities related to deployment and maintenance of renewables, construction, implementation of energy efficiency measures, manufacturing of required equipment and bioenergy supply. Many of these labour requirements could be met with workers from fossil fuel industries, as in many cases the skills are complementary. Active labour and retraining policies will need to underpin such shifts. This highlights the importance of looking beyond energy policy.

Macroeconomic benefits will only be realised if countries implement a coherent mix of economic policies to complement the energy policies underpinning decarbonisation (Figure 3.23).

Therefore, policy makers should place renewable energy policy in the broader context of the energy sector while also considering a range of cross-cutting policies beyond energy, such as industrial, fiscal, trade and labour policies (IRENA, 2016h, 2013, forthcoming b; IRENA and CEM, 2014).

Figure 3.23 • A broad and coherent mix of policies



Key message • A broad and coherent mix of policies is needed to reap the positive macroeconomic impacts of the energy transition.

Policies will remain central for decarbonisation, beginning with renewable energy deployment

Within the realm of energy policy, renewable energy policy is a key pillar of decarbonisation. Supportive policies can attract investments, increase deployment and drive cost reductions. Since the early 2000s, a wide variety of measures have been used to promote deployment, starting with national-level frameworks that are translated into specific measures such as regulatory instruments and fiscal incentives. The measures also enable favourable conditions for sector development related to grid access and financial mechanisms (Figure 3.24). By the end of 2015, 146 countries had implemented renewable energy support policies, which cover electricity generation, heating and cooling, and transport. In fact, 114 countries had implemented power policies, 66 countries transport policies, and 21 countries heating and cooling policies (REN21, 2016).

In the power sector, the appropriate policies must be tailored to country priorities and conditions, including the maturity of the country's power markets, the level of development of the renewable energy sector and whether demand is rising, stable or falling. Based on these factors, renewable energy policies should consistently provide transparent, predictable and stable market environments, while allowing enough flexibility to adjust to market changes

(IRENA, 2014b). Among a wide range of instruments, recent trends have seen the gradual evolution of renewable power policies from tariff-based mechanisms to hybrid instruments such as auctions, which are gaining importance as they allow renewable energy to be deployed in an efficient, well-planned and flexible manner (IRENA, 2015).

Figure 3.24 • Overview of the types of renewable energy policies and measures adopted

NATIONAL POLICY	REGULATORY INSTRUMENTS	FISCAL INCENTIVES	GRID ACCESS	ACCESS TO FINANCE	SOCIO-ECONOMIC BENEFITS
• Renewable energy target • Renewable energy law/ strategy • Technology-specific law/ programme	• Feed-in tariff • Feed-in premium • Auction • Quota • Certificate system • Net metering • Mandate (e.g., blending mandate) • Registry	• VAT/ fuel tax/ income tax exemption • Import/ export fiscal benefit • National exemption of local taxes • Carbon tax • Accelerated depreciation • Other fiscal benefits	• Transmission discount/ exemption • Priority/ dedicated transmission • Grid access • Preferential dispatch • Other grid benefits	• Currency hedging • Dedicated fund • Eligible fund • Guarantees • Pre-investment support • Direct funding	• Renewable energy in rural access/ cook stove programmes • Local content requirements • Special environmental regulations • Food and water nexus policy • Social requirements

Up to now, renewable electricity support policies have concentrated primarily on deployment measures to create markets. Falling costs and growing deployment have now brought new challenges to making renewables an even greater component of the power sector. The integration of growing shares of variable renewable generation, in particular, is crucial to a cost-effective energy sector transition. In response, countries are increasingly shifting their policy focus towards the deeper integration of renewables across the broader energy sector.

Policies also need to focus on heating and cooling for buildings and industry, and on the potential of renewables to fuel transport. Renewables-based thermal applications, combined with continued advances in energy efficiency, will play a critical role in the future energy system. More focus should be placed on policies for thermal renewables, which clearly lag behind those for power applications. Renewable heat sources are location-specific and vary in quality and quantity. In addition, each sector has specific characteristics. As such, thermal renewable energy policies will need to be tailored at country- and sector-specific levels. The potential synergies between renewables and energy efficiency require more holistic approaches to energy policy than current ones.

Renewables can contribute to the transport sector in three ways: liquid biofuels used in blends with conventional fuels; gaseous biofuels used in flexi-fuel vehicles; and renewable electricity to power electric and hybrid vehicles. Liquid biofuels currently represent the larger share of renewable energy use in the transport sector. Their use has historically been driven by blending mandates that support biofuels markets. However, investment in new production capacity has declined in recent years, due in large part to lower oil prices. Looking forward, EVs will play a key role in decarbonisation. They introduce high shares of renewables in transport and also facilitate the integration of renewables in power markets. Policies will need to support investments in the required infrastructure, and to provide economic signals that encourage charging at times that take advantage of the profile of variable renewable generation.

A system-level approach to policymaking is needed to accelerate the transition

Not only must renewable energy policy shift from an exclusive focus on deployment to ensuring deeper integration, it must also provide incentives to enhance system flexibility. For example, there is a need for policies that advance demand-side management and storage, as well as electric mobility and industry load shifting. The related changes in market design should be geared towards providing adequate, reliable and affordable electricity services, while sharing system benefits and costs in an equitable manner. Given the larger share of distributed energy sources, the positions of established players and new stakeholders will also need to be balanced. Efforts towards the smooth integration of renewables will also benefit from the coupling of the power sector with heating and cooling, and transport, together with energy efficiency improvements.

Implementing a system-level approach will rely on strong institutional capabilities, central to supporting the energy transition. The pace of the transition will be strongly influenced by the abilities of institutions and individuals, in the energy sector and beyond, to take decisions that are informed, sound and consistent with long-term decarbonisation goals. For instance, energy efficiency improvements require the right decisions to be made by a myriad of actors who face very different, and sometimes conflicting, interests. In many countries, institutional capacities remain weak, affecting awareness, policy design and implementation processes. Where such capacities exist, they are commonly restricted by a lack of resources.

To strengthen and empower institutions, it is crucial to identify, assess and address existing barriers to their operation and development. Cross-sectoral needs assessments should guide the elaboration of national capacity-building programmes for the energy sector. Such initiatives should focus on establishing appropriate steering processes, institutionalising inter-sectoral coordination mechanisms, and creating or strengthening specialised renewable energy and energy efficiency institutions. The transition to a decarbonised energy system also requires strategies that achieve better synergies between different stakeholders in the sector. Targeted capacity-building activities should be provided to stakeholders, including ministries in charge of energy, renewable energy funds or facilities, regulatory authorities, and electricity production, distribution and transmission companies.

The energy transition requires the implementation of appropriate economic policies

Reaping the full benefits of the energy transition requires aligning energy policies with a broader set of economic policies. These include policies related to labour and training, domestic value creation and industry development (IRENA, 2013; IRENA and CEM, 2014).

Labour and training policies will be key enablers

Jobs will be created in all segments of the value chain (construction, installation, feedstock supply, manufacturing and operation and maintenance) and will form a global workforce with an array of skills. Construction and installation of renewable energy plants will be the largest segment by employment numbers followed by feedstock supply (bioenergy), manufacturing and operations, and maintenance. As in any industry, skills required for these jobs will vary by technology, geography and segment of the value chain. Figure 3.25 illustrates an example of labour needs for a solar PV project (IRENA, forthcoming b).

Job creation in renewables and energy efficiency will offset jobs losses in fossil fuel sectors only if a skilled and versatile workforce can easily transfer from fossil fuel sectors to renewable and energy efficiency jobs. Such a transfer could help overcome the skills gap that is already being seen in the renewable energy sector in some countries, posing a key barrier for the development of the industry.

Forward-looking policies have a major role to play in anticipating skills gaps and labour shortages in a timely manner. These policies should consider two aspects. First, shortages of necessary skills in the renewable energy sector could slow down the pace of deployment. Second, education and training policies should facilitate the retraining of workers from other industries in renewable energy technologies. Furthermore, energy sector strategy should take into account the evolution of skill needs in the future in the context of rapid technology changes, in particular to build, manage and operate smart power systems (IRENA, 2013).

Figure 3.25 • Workforce requirements for a 50 MW solar PV plant

	Project planning	Manufacturing and procurement	Transport	Installation and grid connection	Operation and maintenance	Decommissioning
Workforce for 50 MW	2 100 person-days	21 500 person-days	3 500 person-days per 1000 miles	39 400 person-days	20 500 person-days per year	5 200 person-days

In addition to renewable energy technology-specific skills, training programmes should provide skills that increase workers' employment flexibility. In many countries, the majority of renewable energy jobs will be in installing, operating and maintaining renewable energy production facilities, rather than in manufacturing equipment. Therefore, workers need transferable skills that allow them to be employed flexibly in line with the evolution of technologies and the automation of production. Therefore, it will be crucial to align education and training policies with the respective support policies to allow adequate planning for the long-term energy transition.

Domestic value can be created through industrial policies

The activity increase in sectors related to needed technologies (e.g. renewables and EVs) and other capital goods required for the transition (e.g. metals and cement) will create new markets and trade flows. There will be opportunities for all parts of the economy to take part, including current fossil fuel exporters, who can embrace the energy transition as a contribution to economic diversification. Countries will have the opportunity to localise different segments of the renewable energy value chain, depending on the state and competitiveness of local complementary industries, as well as on the projected long-term demand for goods and services (for which a stable enabling framework is key). Some segments, such as construction materials and services, are more easily localised than others, such as manufacturing of advanced components.

Countries may need active industrial policies to ensure that suitable capacity is in place, a key strategic consideration for the energy transition. Supplier development programmes, industrial upgrades, cluster cultivation, quality standards and specifications, and training could contribute to enhanced industrial competitiveness and production quality. Nascent industries can be further supported through measures that create demand for local goods and services. However, these measures need to be planned with a target deadline and designed in a way that ensures technology transfer and leverages existing industrial capabilities. Policy makers should keep in mind that these measures could increase the cost of supply and potentially deter some suppliers.

Scaling up investment towards decarbonisation

Targeted use of public funds to cover early-stage financing and to provide guarantees for some of the investment risks associated with capital costs of renewable energy and energy efficiency can have a significant impact on the sector's attractiveness to private investors.

To scale up investments, limited public funds need to be used in a way that maximises the mobilisation of private finance, including from large-scale institutional investors. This entails a shift from traditional public financial instruments (e.g. grants and loans) towards risk mitigation instruments such as guarantees that cover political, currency and power off-take risks. New capital-market instruments, such as green bonds and yieldcos, are increasing available finance by offering new groups of investors access to renewable energy investment opportunities (IRENA, 2016j).

Human welfare benefits offset increased energy system costs

The transition in the energy system provides a unique opportunity to meet decarbonisation goals while also fuelling economic growth, increasing incomes and creating jobs. Looking forward, system-level, adaptable frameworks that take into account the multiple impacts of renewable energy and energy efficiency can tip the balance in favour of low-carbon investments.

Accelerating the decarbonisation of the energy system requires continued focus on the mix of policies covering energy, economic investment and technology frameworks that are driving the transition. Accelerating the transition requires strategies that consider the synergies between renewables and energy efficiency, and promotes deployment across end-use sectors.

Improved human welfare thanks to reduced pollution

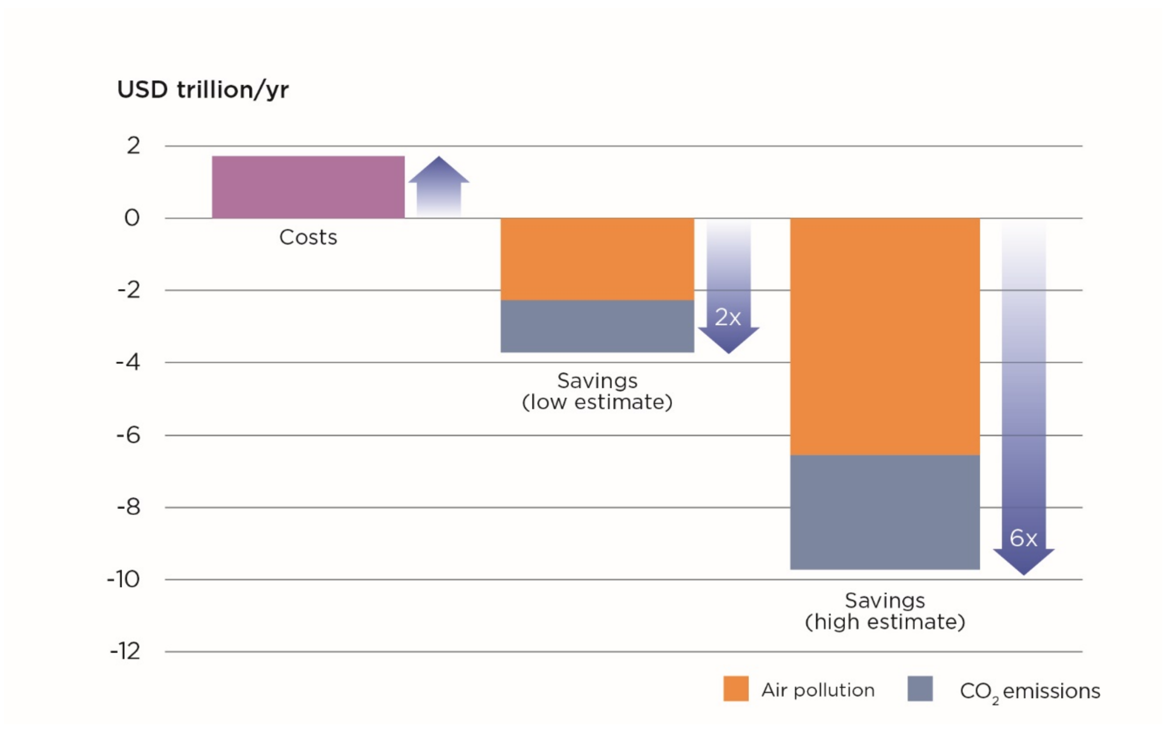
IRENA analysis shows that in the case of renewables, a quadrupling of the share of modern renewable energy from 9% to 36% between 2015 and 2030 can create benefits in terms of reduced climate change damage and reduced health impacts from local air pollution that exceed the cost by a factor four to fifteen. Reductions in outdoor and indoor air pollution each contribute 40% to these benefits while 20% is related to avoided CO_2 emissions (IRENA, 2016c). Indeed, the goal of reducing air pollution is currently a fundamental driver of energy policy in a number of G20 countries.

In the context of this study, IRENA has expanded its externality analysis to cover the period until the end of 2050. Comparing costs and reduced externalities for 2050 shows the scale of the savings from increased share of renewables and higher shares of energy efficiency combined with other low-carbon technologies. These technologies would also provide reductions in externalities related to the impact of non-renewable energy use on human health and climate change. When these reduced externalities are considered, total benefits would be between two and six-times greater than the incremental system costs of decarbonisation, which are estimated to be USD 1.8 trillion per year worldwide in 2050 (Figure 3.26). In absolute terms, reduced externalities can bring benefits of up to USD 10 trillion annually by 2050. Outdoor air pollution is a major externality, and it accounts for about two-thirds of this total. CO_2 reductions are also important, but their relative importance depends on the assumed social costs of carbon (here, between USD 50 and USD 110 per tonne CO_2 in 2050).

However, there remain uncertainties in valuing externalities. While developing policies to internalise external costs, it will also be important to enhance the understanding of these uncertain external costs. The analysis in this report merely refers to the impact of renewable energy technologies (pathways with more efficient non-renewable energy uses, for example, have not been considered).

On a sector level, the effect of implementing decarbonisation varies, but in all sectors there are incremental system costs. The largest savings from reduced externalities are found in the power sector, mainly due to the drop in the use of coal. Transport would see the second-highest reduction in externalities, largely because of the higher assessment of air pollution costs stemming from the combustion of fuels in urban environments. In buildings there are some savings from CO_2-related externalities, but overall there is a slight increase in air pollution related externalities as the share of bioenergy for heating increases as gas use decreases. In total, if quantifying the cost and reduced externalities together, all sectors except buildings result in moderate to significant savings when the energy system is decarbonised.

Figure 3.26 • Costs and reduced externalities of decarbonisation, 2050



Key message • Benefits from reduced externalities exceed the costs of decarbonisation by a factor between two and six in 2050. Health benefits from reduced air pollution health alone exceed the costs.

The costs of decarbonisation are small compared to improved human welfare through reduced externalities

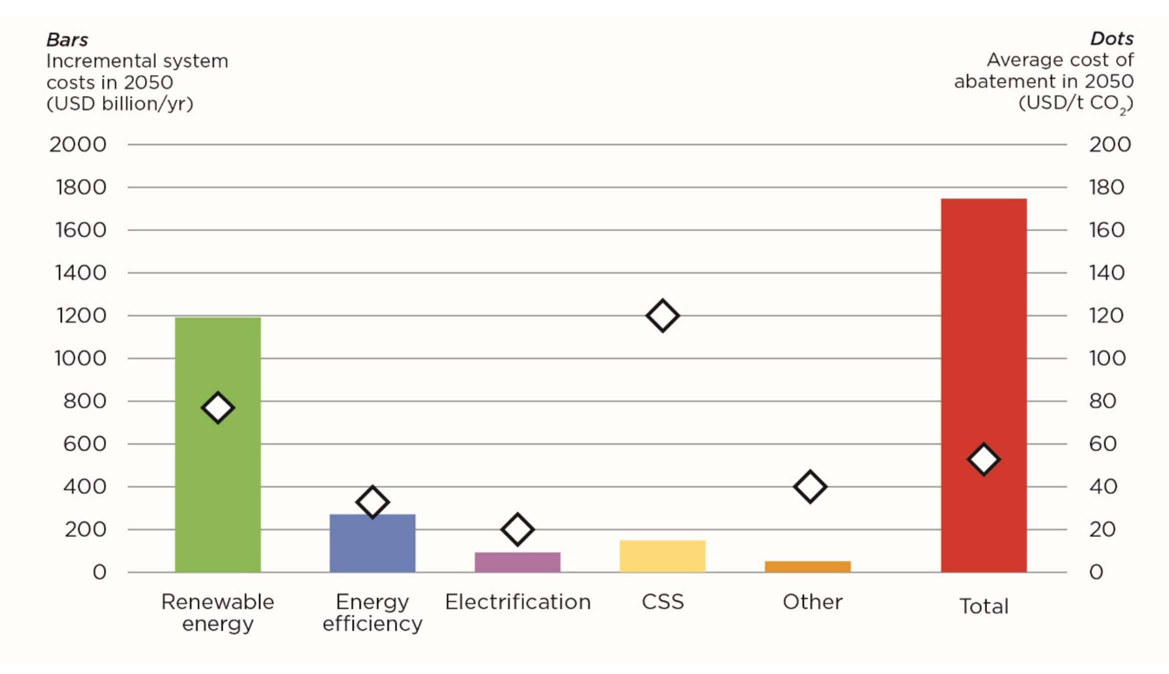
A dramatic reduction in carbon emissions is not possible without significant additional spending. As noted above, additional investments needs on average amount to USD 0.83 per year between 2015 and 2050.

When these investments are annualised, and any additional operation & maintenance costs of individual low-carbon technologies are included, the portfolio of technologies identified in REmap requires incremental system costs on top of the Reference Case that amount to USD 1.8 trillion per year by 2050 globally. This assumes a crude oil price of USD 80 per barrel, and a discount rate of 10%. In the REmap analysis, CO_2 emissions are reduced by about 31.5 Gt per year in 2050 compared to the Reference Case. This translates to a cost of USD 60 per tonne of CO_2 emissions eliminated.

Despite significant technological learning that has reduced, and will continue to reduce, renewable energy capital costs, some of the technologies will still be more expensive than their non-renewable counterparts even by 2050. The incremental system costs of renewable energy technologies are calculated to be USD 1.8 trillion per year in 2050. This includes about USD 500 billion per year in incremental system costs related to the costs of integrating variable renewable energy to the power system. It also includes the costs of grid integration measures such as energy storage, flexibility from dispatchable power, national T&D grids and interconnectors, as well as curtailment. However, as Box 3.12 explains, new technologies could unleash new business opportunities and actually bring savings. For instance, if there were no costs associated with integrating variable renewables to the power system, implementing the electricity generation mix under REmap would result in savings of up to USD 300 billion per year in 2050. This is explained by the much lower variable costs (i.e. avoided spending on fossil fuels) of generating electricity with solar, wind and other renewables compared to non-renewable technologies. Electrification in transport and heating/cooling also has incremental system costs, as does CCS.

It is necessary to put these costs in the context of the total CO_2 emissions that would be avoided in 2050. This is indicated with the dots in Figure 3.27 that show the average cost of abatement for each technology. The most expensive technology is CCS for industry, where the abatement cost is USD 120 per tonne of CO_2. Energy efficiency measures, by comparison, have much lower costs: around USD 35 per tonne of CO_2. Abatement costs of electrification (excluding any investments associated with charging infrastructure) and renewable energy are estimated at USD 22 and USD 75 per tonne of CO_2.

Figure 3.27 • Incremental system costs and the average cost of abatement by technology, 2050



Key message • When abatement cost is viewed in terms of cost per tonne of CO_2, energy efficiency is the most economically viable, followed by renewable energy. The bulk of the system costs lie in renewables and end-use sector electrification technologies.

Box 3.12 • System integration costs of variable renewable power

When assessing the cost of a power system that has integrated variable renewables, the comparison is often made to the costs of a legacy top-down power system, characterised by few large dispatchable thermal generators, synchronously connected to the grid and often centralised. In this power system, vertically integrated utilities with generation, transmission, distribution and sales are the norm.

In contrast, variable renewables are more distributed, usually located where the resources are best. They are typically non-synchronous (i.e. connected to the power system through powered electronics), non-dispatchable, connected to the distribution system rather than to the transmission system, and owned by a variety of entities. This type of power system thus has fundamentally different characteristics. There are reductions in system inertia and in the ability to provide fault-clearing short circuit current. The system requires a faster rate of change of frequency (RoCoF) and an increase in reserve allocation to compensate for generation forecast errors, among other things.

Given the relative novelty of the technologies and the processes to deliver such power system services, the changes associated with variable renewables can be considered sources of additional or incremental cost, when compared to the extension of conventional technology to maintain traditional operational parameters.

However, it is very likely that innovation in technology and institutional design will reduce the additional or incremental cost of a system that can reliability operate in a new, more dynamic and decentralised environment, by reducing both the amount of services required and the cost of providing them.

For example, the increasing use of ICT will enable a faster market that is more responsive to the balancing needs of a power system, with less inertia and faster rates of change. Key technologies and upgrades in this space include improvements in grid monitoring speed and the establishment of standard communication protocols over Power Line Communication. These advances will make it possible to create an “internet of energy”, in which aggregators will be able to compete in providing services to the grid through efficient use of distributed resources such as rooftop PV, distributed and fast-responding electricity and thermal storage, EVs, demand response and other sources that have not yet been invented.

Such developments will significantly reduce the additional costs that are typically associated with the deployment of variable renewables. In theory, new business opportunities unleashed by new market designs and ICT may mean that deploying VRE will no longer be seen as a cost at all.

On the institutional side, as markets move towards joint procurement of energy and services closer and closer to real time, the forecast errors of VRE generation and the associated costs for operational reserves decrease. As variable renewables, demand response and energy storage are allowed to compete in providing services to the grid, the need to commit additional generation units just to ensure that sufficient reserves are available to compensate for (reduced) forecast errors is reduced, as such services will be provided by an optimised mix of “always committed” sources.

The potential for – and uncertainty around – the developments above make it very difficult to estimate a realistic 2050 figure for the incremental cost of global power systems that have successfully integrated variable renewables. The size of that potential, however, suggests that most estimates using the paradigm of the “old grid” are likely to be lower than predicted when compared to real future costs. Examples around the world demonstrate that markets with large shares of variable renewables incurred significantly less integration costs than expected, as a result of technology cost declines and the ability of markets to exploit low cost flexibility options.

The abatement costs of individual technologies can be ranked to show their contributions to the 31.2 Gt of CO_2 emissions avoided in 2050 in the REmap analysis, compared to the Reference Case. The marginal abatement cost curve shown in Figure 3.28 ranks the abatement costs and the relative contributions of each technology at a global level.[102]

The costs of emissions mitigation rise exponentially with the emissions reduction percentage. The total costs are largely determined by the tail end, i.e. the last few percentages of emissions reduction. At this moment, these costs are highly uncertain. Figure 3.28 starts with technologies on the far left that result in savings and ends on the far right with technologies that cost more than the fossil fuel equivalent they substitute for. Costs of technologies range from as low as USD -200 to as high as USD 1 000 per tonne of CO_2. The average cost of abatement is USD 60 per tonne of CO_2 (and USD 40/t CO_2 excluding grid integration costs).

Technologies that bring savings are mostly energy efficiency measures. Those measures include early replacement of condensing gas boilers for water/space heating, smart home systems, efficient industrial motor systems, heat pumps, some insulating measures and renewable electricity generation technologies (excluding the grid integration costs). These technologies represent about 20% of the mix.

Other technologies cost more. When these technologies are ranked, the curve follows a flat line until it reaches about USD 250 per tonne of CO_2.

Many of the industry technologies come with additional costs, such as CCS, biomass-based plastics and some biomass use process heating. In transport, advanced biofuels have high costs compared to their petroleum equivalents at the crude oil prices assumed in this analysis. In buildings, triple-glazed windows and some insulation measures for walls and doors come with additional costs.

Technologies with much higher costs also include those related to demolishing buildings before the end of their normal life spans and replacing them with new buildings, as indicated earlier in the stranded asset discussion. However, such new and efficient buildings offer benefits, such as better comfort and well-being, which have not been included in the estimates shown in Figure 3.28. If these were to be quantified, the costs of abatement would be significantly lower.

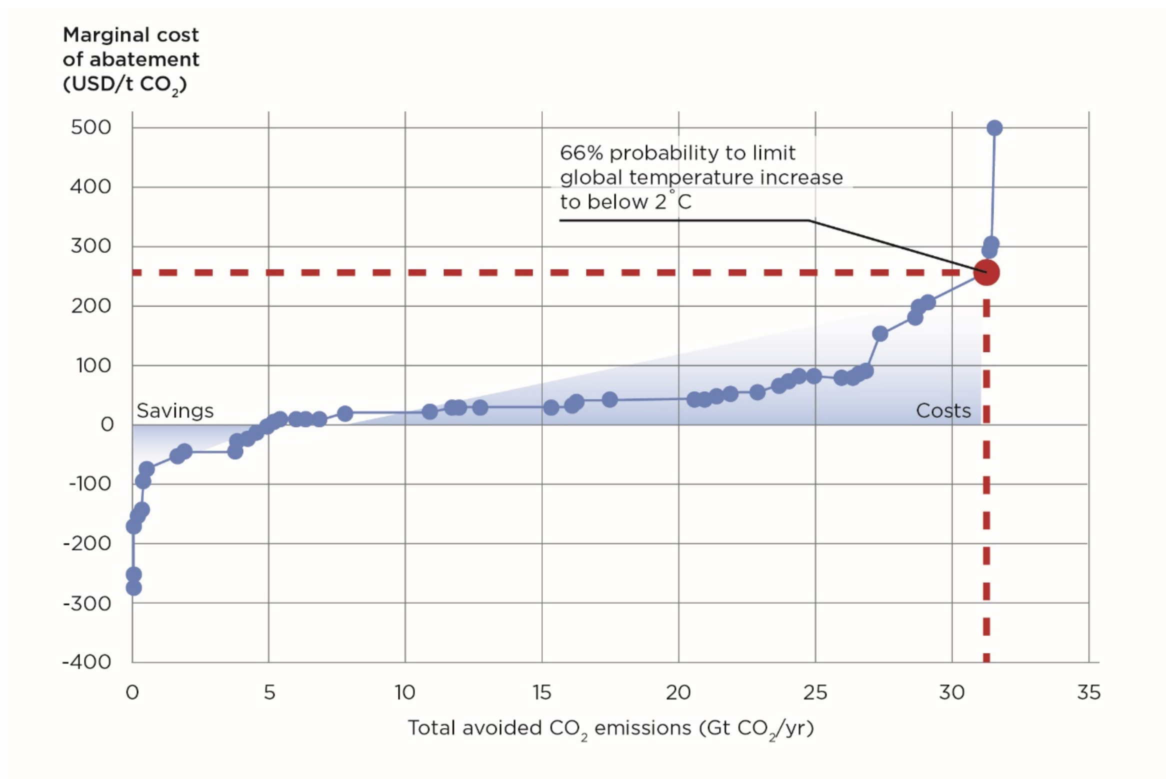
The cost-supply curve provides important information about which technologies would require policy support to improve their economic viability. These technologies fall under the area shaded as “costs” in Figure 3.28 and they result in a total incremental system cost of USD 2.1 trillion per year in 2050. To improve the economic viability of these technologies, different measures need to be implemented. One of them is providing subsidies. Some improvements will also happen by learning investments and some will require corrections to the market. One instrument to correct for market distortions is a carbon price. Carbon prices are today typically used in the power generation or the industry sectors. For instance, if one assumes a carbon price of USD 60 per tonne of CO_2 in 2050, all low-carbon technologies for power generation covered in this assessment reach cost-competitiveness. Technologies that remain more expensive are typically located in end-use sectors.

If the same carbon price were applied for technologies identified for the industry sector, only about half of them would be cost-competitive. Likewise in buildings and transport, many renewable energy technologies remain costly by 2050. In transport for instance, national emission policies and regulations are aimed at the local level (e.g. tighter emissions regulations for internal combustion vehicles that encourage deployment of EVs) can improve the cost-competitiveness of some costly technologies. Market instruments, such as correcting for harmful

102 Each dot on the figure refers to a low-carbon technology (e.g. biomass-based boilers to generate industrial process heat).

effects of fossil fuels from air pollution externalities that are not priced, are also important (similar to a carbon price). Subsidies may be necessary for some building sector technologies, as their upfront costs to households are significant. The various required subsidies in different sectors would add up to about USD 500 billion per year.

Figure 3.28 • Marginal abatement cost curve for low-carbon technologies beyond the Reference Case, 2050



Notes: Each dor on the figure refers to a low-carbon technology (e.g. biomass-based biolers to generate industrial process heat). Prices: Crude oil USD 80/bbl; coal USD 50/tonne; natural gas USD 11/MBtu. Discount rate: 10%. Grid integration costs of renewable energy are excluded from the figure.

Key message • One-fifth of the carbon emissions reductions can be achieved without any additional costs. Average cost of abatement is USD 60/t CO_2, with the marginal cost to reach the 2° C target estimated to be USD 250/t CO_2. Costs rise steeply beyond 32 Gt per year in avoided emissions of CO_2 compared to the Reference Case.

The marginal abatement cost-supply curve presented in Figure 3.28 represents just one possible mix of technologies. There are many other possible models and scenarios. So it would be beneficial to compare the technology and cost findings with the outcomes of other studies. Alternative portfolios also can be generated based on different views of the parameters that constitute a decarbonisation of the global energy sector.

With any given mix of technologies, such as that shown in Figure 3.28, decision makers will be tempted to pick low cost options, from the left end of the curve, and to skip high-cost options on the right side. But the figure gives a global perspective, and not all options are available everywhere. To the right of the cost curve, some technology options have higher costs. This does not, however, mean that the potential for low cost technologies has been exhausted, or that only technologies with high costs remain for implementation. Therefore, the cost curve should not be misinterpreted as a series of steps from left to right, in order of costs that can be chosen in isolation; rather, there are interactions, and all of these options need to be exercised together to achieve this level of costs and the indicated renewable energy shares. For instance, some options produce savings or improvements in efficiency that help reduce the costs of more expensive options.

While this cost-supply curve is static, the energy system in general (for instance, the process of meeting electricity or heat demand) is dynamic. For example, there are institutional barriers or transaction costs along with technology costs. Incorporating these could change the ranking of technologies. The position of individual technologies on the cost curve can also change, depending on taxes, subsidies and external effects. Macroeconomic effects can change the ranking as well. The focus on the cheapest individual options will not result in the least expensive overall transition. Instead, a holistic approach is required. Only when all of these options are pursued simultaneously can the energy sector be decarbonised.

Key sensitivities and robustness of the findings

This analysis outlines a path for limiting global temperature change by 2100 to 2^{o}C with a 66% probability of meeting the target. But there is still a one-out-of-three chance that temperatures will rise more than 2^{o}C even with this ambitious emissions reduction path. As a result, there is no room for complacency. Policy makers would be well advised to aim for even more ambitious reductions, especially given the limited success of efforts in the last three decades.

The pathway presented in this analysis is consistent with a temperature limit of 2^{o}C (with 66% chance) if:

- Energy-related CO_2 emissions follow the designated path until 2050 and then drop to zero by 2060, and remain at zero thereafter.
- Process-related CO_2 emissions (that today amount to 2 Gt per year) drop and cumulative process emissions from 2015-2100 remain below 60 Gt. This implies a very significant effort to reduce process emissions from cement production, where no immediate solution is available.
- Land use, land-use change and forestry (LULUCF) net emissions for the period 2015-2100 amount to zero. Today these areas are major sources of GHG emissions. These emissions need to drop over time and turn negative in the second-half of the century. That means massive reforestation, restoration of peat bogs and other restoration measures.
- Reduction of energy-related CO_2 emissions must be supplemented with a substantial reduction of all other forms of anthropogenic GHG emissions.
- Modern energy access puts emphasis on renewable energy solutions.

Although the LULUCF and most other non-CO_2 GHG of emissions are outside the scope of traditional energy policy, they will still need be considered in the context of decarbonising the energy sector. For example, land-use changes will be needed to increase the capacity for wind and solar PV. Moreover, many of these measures aimed at reducing emissions, such as reforestation, can take decades to show an effect – and they may turn out to be ineffective. If that is true, the emissions that might have been allowed because of the expectation of future reductions from these measures could not be reversed. As a result, there is a risk that the ambitious energy transition outlined in this analysis will not limit climate change to 2^{o}C, even if it is implemented successfully.

In addition, this chapter proposes only one pathway to decarbonise the energy sector. There are uncertainties around realising this foreseen potential, and alternative pathways should be sought. Therefore as a last step, this study conducted a sensitivity analysis for some of the technology and the key economic parameters (see Table 3.4).

Incremental system costs are sensitive to energy prices, discount rates and the capital costs of technologies. Fossil fuel prices are the most important, followed by finance costs and technology costs. These finance parameters are more or less equally important in terms of CO_2 emissions: a change of +/- 30% from the default value will result in a change of +/- 10% in avoided CO_2 emissions.

If a crude oil price of USD 60 per barrel instead of USD 80 is assumed, CO_2 emissions would be 4 Gt per year *higher* in 2050. As a result, realising the 2°C target will require additional carbon pricing. Lower prices for natural gas and coal would have comparable effects. Similarly, higher discount rates or a slower decline than anticipated in the capital costs of clean energy technologies would make it much harder to meet the target.

The analysis is much less sensitive when it comes to the assumptions on energy efficiency and bioenergy. If improvements in energy intensity are lower than expected or the biomass supply is smaller by 2050, the changes in results are negligible. The reason is that other low-carbon technologies with similar or slightly higher costs of abatement can fill any gaps to meet the same emissions budget.

Table 3.4 • Ranges used for sensitivity analysis of the key parameters and findings

			Analysed impacts					
	Nominal value	Sensitivity (nominal value)	Incremental system costs in 2050 (USD billion/yr)			Avoided CO_2 emissions in 2050 (Gt CO_2/yr)		
			Default	High	Low	Default	High	Low
Fossil fuel prices*	See table 3.1	105-55 USD/barrel (80)	1.8	-0.3	3.8	31.2	33.5	28.3
Cost of finance*	See table 3.1	7-13% (10%)	1.8	2.6	1.0	31.2	29.2	32.9
Renewable energy technology costs*	See: (IRENA, 2016f)	+/- 30%	1.8	3.1	0.4	31.2	28.0	33.4
			Incremental system costs in 2050 (USD billion/yr)			Additional investments in 2015-2050 (USD trillion)		
			Default	High	Low	Default	High	Low
Energy intensity improvement rates**	2.60%	2%	1.8	-	2.0	39	-	41.5
Biomass supply potential**	150 EJ	100 EJ	1.8	-	1.8	39	-	39.5

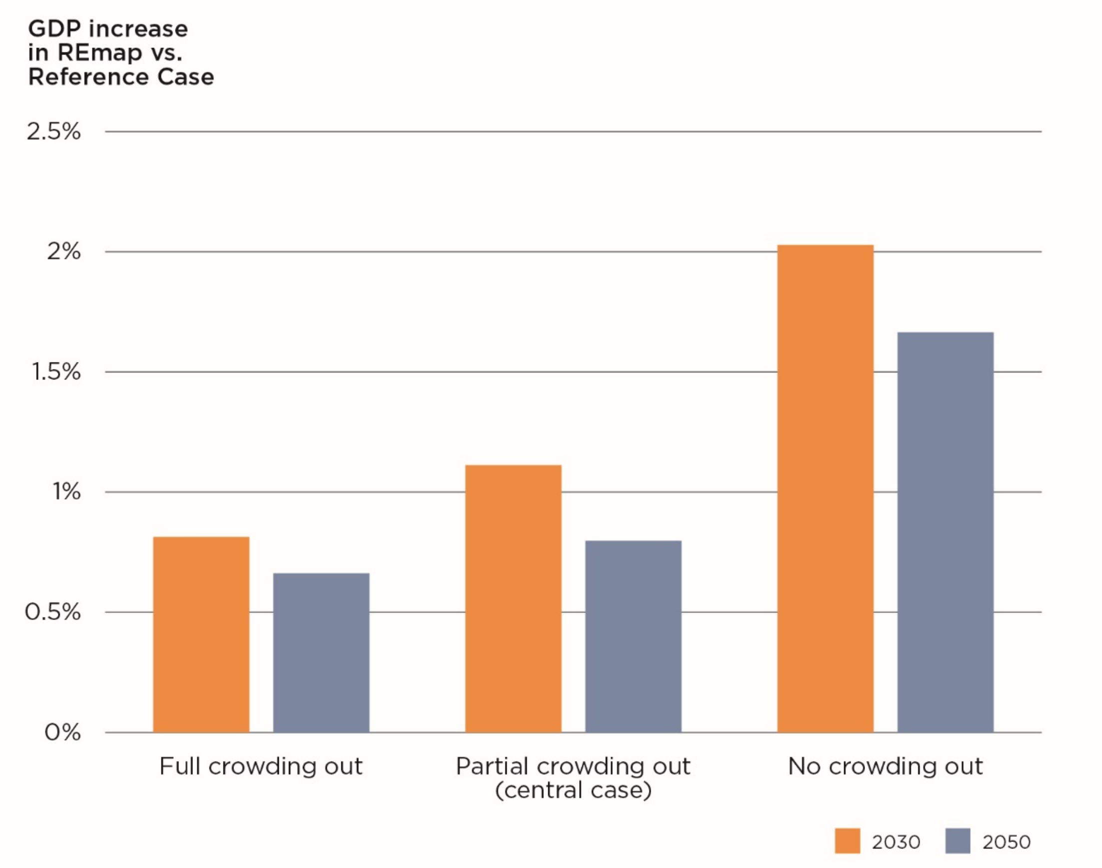
Notes : *Impacts on incremental system costs in 2050 and CO_2 emissions reductions were estimated, assuming USD 250/t CO_2 as cut-off criteria for abatement costs.
**Impacts on incremental system costs in 2050 and additional investment needs in 2015-2050 are measured, assuming the deployment of low-carbon technology options other than the tested technology to fulfil the same carbon budget.

A sensitivity analysis has also been done in the macroeconomic analysis on the critical issue of crowding out of capital. The investment requirements for a capital-intensive decarbonisation based on renewables and energy efficiency could displace (i.e. "crowd out") capital that would normally be available to other productive sectors, having a depressing effect on the economy. If that occurs, the overall GDP increase driven by decarbonisation could be significantly reduced or even turned negative (IRENA, 2016h). This is the case, for instance, if the displaced investments have a larger multiplier effect in the economy than the ones driven by decarbonisation (e.g.

because the needed goods are produced domestically instead of imported), or if they reduce potential GDP growth (e.g. a reduction in productive capacity like railways or factories).

To take this effect into account, our analysis assumes partial crowding out of capital in the central case presented above, while a sensitivity analysis consisting of two additional model runs has been done with full and null crowding out. The results are shown in Figure 3.29 and highlight the same policy conclusion as IRENA's analysis in 2016. The energy transition raises GDP significantly compared to the Reference Case as long as the required investments do not fully compete with investments elsewhere in the economy. If there is such competition, the increase in GDP is smaller, but still positive. In other words, in the worst-case scenario, GDP impacts are small, and if finance is available, GDP impacts are more positive.

Figure 3.29 • Global GDP impacts in different capital crowding out cases



Notes: Partial crowding out is modelled by forcing savings to be at least 50% of investment. Full crowding out imposes savings to be equal to investment. Null crowding out does not impose any relation between savings and investment.

Key message • In the worst-case scenario (full crowding out of capital), GDP impacts are small; otherwise (if dedicated finance is available), GDP impacts are more positive.

The question of whether capital crowding out occurs in reality is a difficult one to address, and it is not something that can easily be tested. Different schools of economic thought suggest different outcomes and all macroeconomic modelling exercises must make assumptions about the degree of crowding out. It is important for the reader to be aware of this issue when interpreting results - this is an important difference between this analysis and the one carried out in the forthcoming OECD G20 report (OECD, forthcoming).

The modelling assumptions relate to the balance between investment and savings in the economy.[103] The difference between the schools of thought is how this balance (which is an accounting identity) is maintained. In strict neo-classical economics, the approach is relatively basic: if investment is to increase (at least at the global level), then there must be an increase in savings to fund it. More savings mean lower expenditures on current consumption, and therefore lower GDP. In contrast, post-Keynesian economics includes the banking system as an intermediary. So when a bank advances a loan, it creates both a liability to the company getting the loan and an asset on its own balance sheet. The balance between investments and savings is thus maintained, but the resulting increase in money supply allows for additional investment without forcing higher volumes of saving elsewhere in the economy.

103 In economic terminology, both terms are different, which can be confusing to a lay reader who is used to thinking in terms of personal finance, wherein putting money in a bank account can be considered an investment, while in economic terminology it is a saving.

References

Anger, A. and T. Barker (2015), "The Effects of the Financial System and Financial Crises on Global Growth and the Environment", *Finance and the Macroeconomics of Environmental Policies*, Springer, pp. 153–193.

Arestis, P. and M. Sawyer (2011), "Economic Theory and Policies: New Directions after Neoliberalism", *New Economics as Mainstream Economics*, Springer, pp. 1–38.

Blazejczak, J. et al. (2011), "Economic Effects of Renewable Energy Expansion: A Model-based Analysis for Germany", Discussion Papers, German Institute for Economic Research, DIW Berlin.

Caldecott, B., Howarth, N. and P. McSharry (2013), *Stranded Assets in Agriculture: Protecting Value from Environment-Related Risks*, Smith School of Enterprise and the Environment, University of Oxford, Oxford.

Callonnec, G. et al. (2016), *Mix Électrique 100% Renouvelable à 2050: Évaluation Macroéconomique - Impacts et Enjeux Économiques de la Transition Énergétique* (A 100% Renewable Mix by 2050 : Macro-economic assessment - Economic Impacts and Stakes of the Energy Transition), Agence de l'Environnement et de la Maîtrise de l'Énergie, Paris.

Carbon Brief, (2016), "Explainer: 10 Ways 'negative Emissions' Could Slow Climate Change." Carbon Brief. https://www.carbonbrief.org/explainer-10-ways-negative-emissions-could-slow-climate-change.

Carbon Tracker Initiative, n.d., "Carbon Tracker Initiative's Definition of Stranded Assets" www.carbontracker.org/resources/ accessed 23 August 2016.

CEEW and NRDC (Council on Energy, Environment and Water and Natural Resources Defense Council), 2016, "Filling the Skill Gap in India's Clean Energy Market-Solar Energy Focus", *CEEW-NRDC Policy Brief*, CEEW and NRDC, Delhi.

Clarke, L. et al. (2014), "Assessing Transformation Pathways", *Climate Change 2014: Mitigation of Climate Change, Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, United Kingdom and New York.

CNREC (China National Renewable Energy Centre) (2016), China Renewable Energy Outlook 2016, CNREC, Beijing.

Congressional Budget Office (US), (1998), "Electric Utilities: Deregulation and Stranded Costs", *Congressional Budget Office Paper*, CBO, Washington, DC.

Credit Suisse, (2015), Global Wealth Report 2015, Credit Suisse AG Research Institute, Zurich.

Dai, H., and J. Liu (2016), CREAM-CGE Updates 2016-3-5 and email communications in September 2016.

DLR-GPI (2015), "Energy [r]evolution - A Sustainable World Energy Outlook 2015", Greenpeace International, Global Wind Energy Council and Solar Power Europe, Amsterdam and Brussels.

European Commission (2016), "Impact Assessment Accompanying the Document Proposal for a Directive of the European Parliament and of the Council on the Promotion of the Use of Energy from Renewable Sources (recast)", COM(2016) 767 final; SWD(2016) 419 final, European Commission, Brussels.

- (2014), Impact Assessment accompanying the Communication "A Policy Framework for Climate and Energy in the Period from 2020 up to 2030", COM(2014) 15 final, European Commission, Brussels.

Frankfurt School-UNEP Centre/BNEF (2016), *Global Trends in Renewable Energy Investment 2016*, Frankfurt School of Finance and Management gGmbH, Frankfurt.

G20 (2015), *G20 Toolkit of Voluntary Options for Renewable Energy Deployment*, G20, Antalya.

Galgóczi, B. (2014), “The Long and Winding Road from Black to Green: Decades of Structural Change in the Ruhr Region”, *International Journal of. Labour Research*, Vol. 6.

Generation Foundation (2013), “Stranded Carbon Assets: Why and How Carbon Risks Should Be Incorporated in Investment Analysis”, Generation Foundation, London and New York.

GO100% (2017), “GO 100% Map”, http://www.go100percent.org/cms/index.php?id=4.

ICF Resources LLC (2015), *Economic Analysis of US Decarbonization Pathways: Summary and Findings*, ICF Resources LLC, Fairfax, VA.

IEA (International Energy Agency) (2013), *Redrawing the Energy Climate Map: World Energy Outlook Special Report*, OECD/IEA, Paris, www.worldenergyoutlook.org/media/weowebsite/2013/energyclimatemap

- (2012), *Technology Roadmap: Bioenergy for Heat and Power*, OECD/IEA, Paris.

IPCC (Intergovernmental Panel on Climate Change) (2014), *Climate Change 2014: Synthesis Report, Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, IPCC, Geneva.

IRENA (International Renewable Energy Agency) (2017a), *Bottom-Up Assessment Methodology of IRENA’s Decarbonisation Scenarios*, IRENA, Abu Dhabi.

- (2017b), *A Proposal for an Innovation Agenda for the G20: Sector Analysis of Low-Carbon Technology Options*, IRENA, Abu Dhabi.

- (2017c), *Stranded Assets and Renewables: Accelerated Renewable Energy Uptake and What It Means for Asset Stranding in Energy, Industry and Property*, IRENA, Abu Dhabi.

- (2017d), *Rethinking Energy 2017: Accelerating the Global Energy Transformation*, IRENA, Abu Dhabi.

- (2016a), *G20 Toolkit for Renewable Energy Deployment: Country Options for Sustainable Growth based on REmap*, IRENA, Abu Dhabi.

- (2016b), *REsource Renewable Energy Statistics*, IRENA Data Statistics,

www.resourceirena.org/gateway/dashboard.

- (2016c), *REmap: Roadmap for A Renewable Energy Future: 2016 Edition*, IRENA, Abu Dhabi.

- (2016d), *The True Cost of Fossil Fuels: Externality Cost Assessment Methodology*, IRENA, Abu Dhabi.

- (2016e), *Renewable Energy Capacity Statistics 2016*, IRENA, Abu Dhabi.

- (2016f), *The Power to Change: Solar and Wind Cost Reduction Potential to 2025*, IRENA, Abu Dhabi.

- (2016g), *Renewable Energy Benefits: Decentralised Solutions in the Agri-food Chain*, IRENA, Abu Dhabi.

- (2016h), *Renewable Energy Benefits: Measuring the Economics*, IRENA, Abu Dhabi.

- (2016i), *Renewable Energy and Jobs: Annual Review 2016*, IRENA, Abu Dhabi.

- (2016j), *Unlocking Renewable Energy Investment: The Role of Risk Mitigation and Structured Finance*, IRENA, Abu Dhabi.

- (2015), *Renewable Energy Auctions: A Guide to Design*, IRENA, Abu Dhabi.

- (2014a), *A Renewable Energy Roadmap (REmap 2030): Cost Methodology*, IRENA, Abu Dhabi.

- (2014b), Adapting Renewable Energy Policies to Dynamic Market Conditions, IRENA, Abu Dhabi.

- (2013), *Renewable Energy and Jobs*, IRENA, Abu Dhabi.

- (forthcoming a), *Renewable Energy Benefits: Measuring the Economics*, *Second Edition*, IRENA, Abu Dhabi.

- (forthcoming b), *Renewable Energy Benefits: Leveraging Local Industries*, IRENA, Abu Dhabi.

IRENA and CEM (International Renewable Energy Agency and Clean Energy Ministerial) (2014), *The Socio-economic Benefits of Large-scale Solar and Wind: an EconValue Report*, IRENA, Abu Dhabi.

Kartha, S. and K. Dooley (2016), *The Risks of Relying on Tomorrow's "Negative Emissions" to Guide Today's Mitigation Action*, Stockholm Environment Institute, Working Paper No. 2016–8, Somerville, MA.

Kempener, R. et al. (2015), "A Global Renewable Energy Roadmap: Comparing Energy Systems Models with IRENA's REmap 2030 Project", *Informing Energy and Climate Policies Using Energy Systems Models*, Giannakidis, G. et al. (eds.), Springer International Publishing, pp. 43–67.

Lehr, U., Lutz, C. and D. Edler (2012), "Green Jobs? Economic Impacts of Renewable Energy in Germany", Energy Policy, Vol. 47., pp. 358-364.

Muratori, M. et al. (2016), "Global Economic Consequences of Deploying Bioenergy with Carbon Capture and Storage", *Environmental Research Letters*, Vol. 11, pp. 1–9.

NYSE Market Data (2017), "NYSE Group Shares Outstanding and Market Capitalization of Companies Listed, 2016", New York Stock Exchange, New York, NY.

OECD (Organisation for Economic Co-operation and Development) (forthcoming), *Growth, Investment and the Low-Carbon Transition*, OECD, Paris.

Pollitt, H. et al. (2014), "An Economic and Environmental Assessment of Future Electricity Generation MixesiIn Japan – An Assessment Using the E3MG Macro-Econometric Model", *Energy Policy*, Vol. 67, pp. 243–254.

REN21 (Renewable Energy Network for the 21st Century) (2016), *Renewables 2016 - Global Status Report*, REN21 Secretariat, Paris.

Renner, M. (2016), "Can Coal Miners Become Solar Technicians?", Worldwatch Institute blog.

Saygin, D. et al. (2015), "The Implications for Renewable Energy Innovation of Doubling the Share of Renewables in the Global Energy Mix between 2010 and 2030", Energies, Vol. 8, pp. 5828–5865.

Synapse Energy Economics, Labor Network for Sustainability and 350.org (2015), *The Clean Energy Future: Protecting the Climate, Creating Jobs and Saving Money*, Synapse Energy Economics, MA.

The Climate Group (2017), "Accelerating Change: How Corporate Users Are Transforming the Renewable Energy Market", *RE100 Annual Report 2017*, The Climate Group, London.

van Vuuren, D. (2017), "Research priorities for negative emissions", OECD, Paris.

Wills, W. and C. Grottera (2015), *Economic and Social Implications: Brazilian GHG Mitigation Scenarios to 2030*, IES-Brasil Project, Rio de Janeiro.

World Bank, (2012), *World Development Report 2013*, World Bank, Washington, DC.

Chapter 4: Key insights for policy makers

Authors: International Energy Agency and International Renewable Energy Agency

1. Transformation of the energy system in line with the "well below 2°C" objective of the Paris Agreement is technically possible but will require significant policy reforms, aggressive carbon pricing and additional technological innovation. Around 70% of the global energy supply mix in 2050 would need to be low-carbon. The largest share of the emissions reduction potential up to 2050 comes from renewables and energy efficiency, but all low-carbon technologies (including nuclear and carbon capture and storage [CCS]) play a role.

2. The energy transition will require significant additional policy interventions.
   - Renewables will assume a dominant role in power generation. Skillful integration of variable renewables at very high levels becomes a key pillar of a cost-effective energy sector transition.
   - Power market reform will be essential to ensure that the flexibility needs of rising shares of variable renewables can be accommodated.
   - Ensuring access to modern energy services for those currently deprived remains a high priority, alongside improved air quality through deployment of clean energy technologies.

3. Total investment in energy supply would not need to rise over today's level to achieve climate targets, while there is significant additional investment needed in end-use sectors.
   - Investment needs in energy supply would not exceed the level of investment undertaken by the energy sector today. It requires appropriate and significant policy signals to ensure that investment in low-carbon technologies compatible with the "well below 2°C" objective becomes the market norm.
   - The additional investment needs in industry and households for more efficient appliances, building renovations, renewables and electrification (including electric vehicles and heat pumps) are significant. In order for energy consumers to reap the potential benefits of lower energy expenditure offered by the use of more efficient technologies, policy would need to ensure that the higher upfront investment needs could be mobilised.

4. Fossil fuels are still needed through 2050.
   - Among fossil fuel types, the use of coal would decline the most to meet climate targets.
   - Natural gas would continue to play an important role in the energy transition to ensure system flexibility in the power sector and to substitute for fuels with higher carbon emissions for heating purposes and in transport.
   - The use of oil would fall as it is replaced by less carbon-intensive sources, but its substitution is challenging in several sectors, such as petrochemicals.
   - CCS plays an important role in the power and industry sectors in the IEA analysis while only in the industry sector in the IRENA analysis.

5. A dramatic energy sector transition would require steady, long-term price signals to be economically efficient, to allow timely adoption of low-carbon technologies and to minimise the amount of stranded energy assets. Delayed action would increase stranded assets and investment needs significantly.

6. Renewable energy and energy efficiency are essential for all countries for a successful global low-carbon transition, but they will need to be complemented by other low-carbon

technologies according to each country's circumstances, including energy sector potentials, and policy and technology priorities.

7. The energy sector transition would need to span both the power and end-use sectors.
    - Electric vehicles would account for a dominant share of passenger and freight road transport.
    - Renewables deployment would need to move beyond the power sector into heat supply and transport.
    - Affordable, reliable and sustainable bioenergy supply would be a priority especially in light of limited substitution options in particular end-use sectors

8. Technology innovation lies at the core of the long-term transition to a sustainable energy sector.
    - Near-term, scaled-up research, development, demonstration and deployment (RDD&D)spending for technological innovation would help to ensure the availability of crucial technologies and to further bring down their costs.
    - Not all of the needed emission reductions can be achieved with existing technology alone. Additional low-carbon technologies that are not yet available to the market at significant scale, such as electric trucks or battery storage, will be required to complement existing options.
    - Technology innovation must be complemented with supportive policy and regulatory designs, new business models and affordable financing.
9. Stronger price signals from phasing out inefficient fossil fuel subsidies and carbon pricing would help to provide a level playing field, but would need to be complemented by other measures to meet the well below 2°C objective.
    - Price signals are critical for the energy sector to ensure climate considerations are taken into account in investment decisions.
    - It is important to ensure that the energy needs of the poorest members of society are considered and adequately taken into account.
10. The IEA and IRENA analyses presented here find that the energy sector transition could bring about important co-benefits, such as less air pollution, lower fossil fuel bills for importing countries and lower household energy expenditures. Both analyses also show that while overall energy investment requirements are substantial, the incremental needs associated with the transition to a low-carbon energy sector amount to a small share of world gross domestic product (GDP). According to IEA, additional investment needs associated with the transition would not exceed 0.3% of global GDP in 2050.[104] According to IRENA, the additional investment required would be 0.4% of global GDP in 2050 with net positive impacts on employment and economic growth.

104 The Organisation for Economic Co-operation and Development (OECD) analysis of how the IEA scenarios play out in the broader macroeconomic policy context will be presented in a forthcoming publication titled *Investing in Climate, Investing in Growth*.

Annex A: IEA Methodology

Author: International Energy Agency

World Energy Model

Since 1993, the IEA has provided medium- to long-term energy projections using the World Energy Model (WEM). The model is a large-scale simulation model designed to replicate how energy markets function and is the principal tool used to generate detailed sector-by-sector and region-by-region projections for the *World Energy Outlook* (*WEO*) scenarios.[105] The model consists of three main modules: final energy consumption (covering residential, services, agriculture, industry, transport and non-energy use); energy transformation including power generation and heat, refinery and other transformation; and energy supply. It is updated every year. Among the main outputs from the model are the energy flows by fuel, investment needs and costs, carbon dioxide (CO_2) and other energy-related greenhouse gas (GHG) emissions, and end-user prices. While the general model framework covers 25 world regions, individual countries are also modelled, depending on the specific module of the WEM: 12 in demand; 101 in oil and gas supply; and 19 in coal supply. The current version of WEM covers energy developments by year to 2040. For the specific purpose of this study, a high-level extension of WEM results out to 2050 was conducted, benchmarked against outputs from the IEA *Energy Technology Perspectives* (*ETP*) model.[106] Therefore, results for the period 2040-50 do not reflect a full modelling analysis.

The WEM is a very data-rich model covering the whole global energy system. Much of the data on energy supply, transformation and demand, as well as energy prices are obtained from IEA databases of energy and economic statistics.[107] Substantial additional data are used to generate projections: for example, all end-use sector modules base their projections on the existing stock of energy infrastructure, including the number of vehicles in transport (by type), production capacity in industry and floor space area in buildings. Such data stem from a variety of sources.[108]

The model embodies a variety of modelling techniques. Technology choices, for example, are generally conducted on a least-cost basis, while taking into account policy targets (for example, including energy efficiency and renewables policies, and climate goals). Technology cost evolutions are a function of cumulative technology additions, using typical learning rates from literature. Technology cost reductions vary by scenario as different levels of policy ambition trigger different levels of technology deployment and, hence, different levels of cost reductions.

The model operates in three steps: first, final energy demand projections are generated by fuel and end-use sector, based on projections of sector-specific activity variables drivers (such as steel production in industry, household size in dwellings, or passenger- and tonnes-kilometres travelled in transport), taking into account expected changes in demand structures. Each end-use sector is split into subsectors,[109] which are generally modelled bottom-up with a detailed

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105 For further details on the WEM methodology, see the "WEO Model" section of the World Energy Outlook website: www.worldenergyputlook.org.

106 For details about the *ETP* model, see www.iea.org/etp/etpmodel/.

107 See www.iea.org/statistics.

108 For further details, see the "WEO Model" section of the World Energy Outlook website: www.worldenergyoutlook.org.

109 For example, the industry module comprises the sub-sectors aluminium, iron and steel, chemical and petrochemical, cement, pulp and paper, and other industry. The transport module covers road transport (passenger cars, various truck types, buses and two-/three-wheelers), aviation, rail and navigation. The buildings module separately covers a number of end-uses

representation of technologies that could be deployed to satisfy the energy demand. An additional demand-side response module assesses the amount of electricity demand that could potentially be shifted in time to facilitate higher penetration of variable renewables in power generation.

In a second step, final energy demand is converted to primary energy demand by fuel through transformation modules. The refinery module, for example, projects capacity development and utilisation for 134 individual countries and 11 regions and defines refinery yields, output and trade for the product categories of liquefied petroleum gas, naphtha, gasoline, kerosene, diesel, heavy fuel oil and other products. The power sector module covers 25 regions and ensures that enough electricity is generated to meet the annual volume of demand in each region and that there is enough generating capacity in each region to meet the peak electrical demand, while safeguarding security of supply to cover unforeseen outages. Policies as well as the regional long-run marginal costs of 106 different power plant types determine new capacity additions in each region. The eventual annual level of operation by power plant by region is determined by two modules: a classical merit order module determines a least-cost power mix for each year, differentiating annual electricity demand in four different segments (baseload, low-midload, high-midload and peak load). For selected regions, an additional hourly model (designed as a classical hourly dispatch model, representing every hour of the year) quantifies the challenge arising from the integration of high shares of variable renewables and assesses the measures to minimise curtailment, providing additional insights into the operation of power systems.

In a third step, primary energy demand by fuel is fed into the fossil fuel and biomass supply modules, iterating with demand modules over fuel price assumptions until the level of fuel production from supply models matches demand. The supply models broadly follow a similar methodology across fuels. In the oil supply module, for example, production in each country or group of countries is separately derived, according to the type of asset in which investments are made: existing fields, new fields and non-conventional projects. Standard production profiles are applied to derive the production trend for existing fields and for those new fields (by country and type of field) which are brought into production over the projection period. The profitability of each type of project is based on the capital and operating costs of different types of projects, and the discount rate, representing the cost of capital. The net present value of the cash flows of each type of project is derived from a standard production profile. Projects are prioritised by their net present value and the most potentially profitable projects are developed. Constraints, derived from historical data and industry inputs, on how fast projects can be developed and how fast production can increase in a given country are also applied.

In order to derive insights into other aspects of possible future energy sector developments, the WEM benefits from the coupling with other well-known models. For example, WEM has an active link with the ENV-Linkages model of the Organisation for Economic Co-operation and Development (OECD), which allows the assessment of the macro-economic impacts of different energy sector developments.[110] Similarly, an active link exists with the the Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) model of the International Institute for Applied

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for the residential and services sector including water heating, space heating and cooling, appliances (e.g. refrigerators and washing machines), lighting and cooking.

110 The assessment of the possible macroeconomic implications of different energy sector pathways as projected by WEM is not subject to this report, but will be subject to a study currently undertaken by the OECD under the German G20 presidency. The results of the OECD analysis are not presented here. For details on ENV-Linkages, see Chateau, J., R. Dellink and E. Lanzi (2014), "An Overview of the OECD ENV-Linkages Model: Version 3", OECD Environment Working Papers, No. 65, OECD Publishing, Paris, http://dx.doi.org/10.1787/5jz2qck2b2vd-en.

Systems Analysis (IIASA),[111] which allows for the assessment of future prospects for energy-related air pollutants and the impact on human health.

111 See www.iiasa.ac.at/web/home/research/modelsData/GAINS/GAINS.en.html for details.

Annex B: IRENA Methodology

Author: International Renewable Energy Agency

REmap approach

IRENA has published renewable energy roadmaps for specific countries and regions since 2014 as part of its REmap programme.[112] REmap scenarios represent worldwide renewable energy potential assembled from the bottom-up, starting with separate country analyses done in collaboration with country experts and then aggregating these results to arrive at a global picture. As of early 2017, these analyses cover 70 countries, representing 90% of global energy use.

The REmap approach is an assessment of energy system development, specifically energy supply and demand, the accelerated potential of decarbonisation technologies, and subsequent effects on costs, externalities, investments, CO_2 emissions and air pollution.

The analysis is based on a sector and technology bottom-up approach at the individual country level utilising an internally developed REmap tool. This tool is used to analyse two scenarios:

a) The Reference Case (also called the baseline or business-as-usual), which is based on national energy plans or similar reputable sources that forecast expected developments in energy demand for a country.

b) The REmap Case (also called the decarbonisation case), is an accelerated renewables case based on decarbonisation targets and the REmap technology options assessment approach.

The assessment of both the Reference Case and REmap Case is referred to as the REmap approach, while the additional potentials for accelerating renewable energy, energy efficiency and other decarbonisation options are generally referred to as the REmap Options.

For the purpose of this analysis, the bottom-up approach using the REmap tool for each country is complemented with a top-down global demand assessment done at the sector and sub-sector levels. A combination of both an iterative bottom-up country approach and top-down sector approach allows for a better representation of country plans in energy use forecasts, in addition to a more cohesive global set of technology development assumptions and costs relating to decarbonisation technologies.

To do the top-down assessment, energy demand by energy carrier is grouped into three end-use demand sectors: buildings (including residential, commercial and public), industry (including agriculture) and transport. Two supply sectors are also analysed: power and district heat generation. The REmap scenario has a preference for renewable energy, energy efficiency technologies and sector-coupling solutions, such as electric vehicles, district heating and cooling, and heat pumps, over other decarbonisation approaches such as carbon capture and storage (CCS) and nuclear energy, though these options are also included.

The end-use analysis is carried out at a sub-sector level. Activity level growth rates were estimated for the period between 2015 and 2050. Each end-use sector is divided into the main energy consuming applications. To assess the potential for both energy and materials efficiency, the analysis looks at technology options for reducing energy use for a given level of activity. The technology potential of renewable energy is also analysed at the sub-sector level. The potential

112 For a complete overview of REmap related publications, assessments, datasheets and methodologies, see: www.irena.org/remap.

of the relevant low-carbon technologies for each application is estimated based on market growth rates, resource availability and other constraints.

To assess interactions between the demand and supply sectors, specifically the power sector, additional analysis was carried out. For European Union countries, the PLEXOS dispatch model was used to model capacity requirements in a high renewables scenario (Collins et al. 2016; IRENA, 2017b). For other large regions/countries, the analysis relies on studies and modelling by other institutions (NREL, 2012; CNREC, 2015).

Based on the results of the two scenarios, additional assessments were carried out. The CO_2 emissions have been estimated for both the Reference and Remap scenarios by country, sector and fuel for 2015 and 2050. In addition, the effects on air pollution, and the subsequent benefits for human health, are calculated using a method developed by IRENA with leading experts.[113] The REmap tool also includes a cost and investment assessment[114] and an analysis concerning stranded assets (IRENA, 2017c).

A complete overview of the REmap methodology used in this report, including assumptions used to arrive at the decarbonisation potential, is available in a stand-alone methodology paper (IRENA, 2017a).

The E3ME approach for macroeconomic analysis

The REmap approach does not assess larger, macroeconomic effects. For this purpose, IRENA has conducted an additional macroeconomic modelling exercise. It is carried out by feeding the REmap energy mixes developed for this report into a fully-fledged global macro-econometric model that takes into account the linkages between the energy system and the world's economies within a single and consistent quantitative framework.

The model used, E3ME,[115] covers the complete global economy and is therefore complementary to REmap, which focuses only on the energy sector. E3ME simulates the economy based on post-Keynesian principles, in which behavioural parameters are estimated from historical time series data. Interactions across sectors are based on input/output relations obtained from national economic statistics. The model is flexible and can be tailored to different technological, sectoral and geographical disaggregation. The version used includes 24 different electricity generation technologies, 44 economic sectors and 59 countries/regions globally, which have been selected to be consistent with the REmap G20 analysis.

The model has a proven track record of policy and policy-relevant projects. Those projects include the impact assessments for energy and climate policy carried out by the European Commission; contributions to the Intergovernmental Panel on Climate Change on the economic impacts of climate change mitigation; participation in inter-model comparison exercises in the context of climate change mitigation, both global and regional (e.g. in Latin America); and work on the macroeconomic impacts of energy policy in Japan and in India. In the academic sphere, close to 50 scientific journal and book publications have used the E3ME model.

The basic structure of the version of E3ME used is illustrated in Figure B.1. A full description of the energy sector of each country, derived from the REmap analysis, has been fed into the model (right-hand side of the figure). The left-hand side shows how the main components of E3ME fit together, with arrows showing linkages. For the purposes of this analysis, the links feeding into

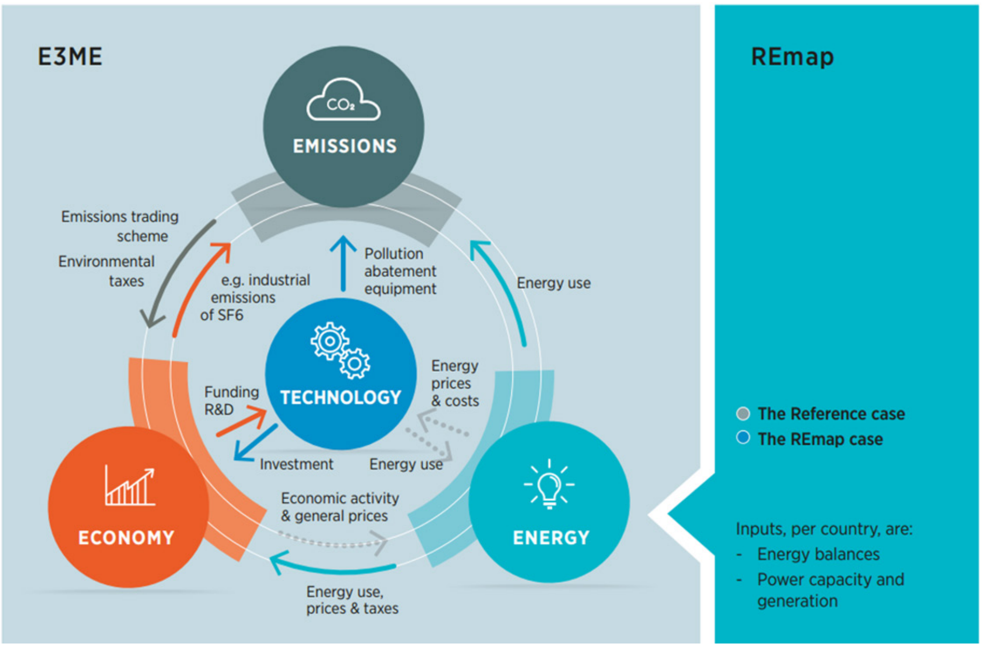
113 For details on the methodology, see (IRENA, 2016b).

114 For the complete cost methodology, see (IRENA, 2014).

115 Developed by Cambridge Econometrics and with a full description at: www.e3me.com.

the energy system have been disabled (dotted grey arrows in the figure) to match and fix the energy sector parameters (e.g. installed capacities, energy mixes) obtained from REmap.

Figure B.1 • IRENA's macroeconomic analysis methodology: REmap results feeding into the E3ME model



In order to strengthen the analysis, IRENA engaged with a panel of seven internationally renowned experts, independent from the modelling team. The experts were strategically selected from diverse countries (Brazil, China, Germany, India, United Arab Emirates, United Kingdom and United States) and from varied backgrounds, (some are experts in fundamentally different modelling approaches, such as computable general equilibrium models [so they can bring different perspectives]). All the experts were requested to critically assess the key assumptions and approach of the analysis, in a review that took place in December 2016. Close to 350 comments were received. Those comments have been incorporated into the macroeconomic analysis and will also inform future work by IRENA.

Compared to the Reference Case, the macroeconomic analysis assumes lower future international fossil fuel prices than the REmap Case. The values used are, respectively, in line with the New Policies Scenario and the 450 Scenario of the *World Energy Outlook 2016* (IEA, 2016). Carbon prices are used and are set consistently with these scenarios (in terms of value, and geographical and sectoral application). The analysis assumes that carbon pricing is revenue-neutral for the government, by using the proceeds to reduce income taxes, in a sort of "green tax reform".

Importantly, a sensitivity analysis has been carried out for the key assumption of crowding out of capital. This is one of the key differences between post-Keynesian and neo-classical approaches to macroeconomic modelling, and is expected to have meaningful effects on the results. Such expectation is grounded on an extensive expert consultation and on previous IRENA analyses with E3ME. While the analysis assumes partial crowding out in the central case, two additional model runs have been done with total and null crowding out. Further methodological details, from previous IRENA work using E3ME, can be found in *Renewable Energy Benefits: Measuring the Economics* (IRENA, 2016a).

References

CNREC (China National Renewable Energy Centre) (2015), *China 2050 High Renewable Energy Penetration Scenario and Roadmap Study*, Energy Research Institute, National Development and Reform Commission, Energy Foundation, www.cnrec.org.cn/english/result/2015-05-26-474.html.

Collins, S. et al. (2016), "Transformation of the European Union's Power Sector to 2030 – Adding Value to IRENA's REmap 2030 Project Using a European Electricity Model", presented at the 35th edition of the International Energy Workshop, Cork, Ireland.

IEA (International Energy Agency) (2016), *World Energy Outlook 2016*, IEA/OECD, Paris.

IRENA (International Renewable Energy Agency) (2017a), *Bottom-up Assessment Methodology of IRENA's Decarbonisation Scenarios*, IRENA, Abu Dhabi, www.irena.org/Publications/ReportsPaper2014New.aspx?mnu=cat&PriMenuID=36&CatID=141&type=all, accessed 13 March 2017.

-(2017b), *Renewable Energy Prospects in the EU: A REmap Anaysis*, IRENA, Abu Dhabi, www.irena.org/Publications/ReportsPaper2014New.aspx?mnu=cat&PriMenuID=36&CatID=141&type=all, accessed 13 March 2017.

- (2017c), *Stranded Assets and Renewables: Accelerated Renewable Energy Uptake and What It Means for Asset Stranding in Energy, Industry and Property*, IRENA, Abu Dhabi, www.irena.org/Publications/ReportsPaper2014New.aspx?mnu=cat&PriMenuID=36&CatID=141&type=all, accessed 13 March 2017.

- (2016a), Renewable Energy Benefits: Measuring the Economics, IRENA, Abu Dhabi, www.irena.org /DocumentDownloads/Publications/IRENA_Measuring-the-Economics_2016.pdf, accessed 13 March 2017.

- (2016b), *The True Cost of Fossil Fuels: Externality Cost Assessment Methodology*, IRENA, Abu Dhabi www.irena.org/DocumentDownloads/Publications/IRENA_REmap_externality_methodology_2016.pdf, accessed 13 March 2017.

-(2014), *Cost Methodology*, IRENA, Abu Dhabi, www.irena.org/remap/IRENA_REmap_cost_methodology_2014.pdf, accessed 13 March 2017.

NREL (National Renewable Energy Laboratory) (2012), *Renewable Electricity Futures Study*, Hand, M. et al. (eds.) Vol. 4, Golden, Colorado, United States.

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April 4, 2014

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Re: PUC Docket Number 13-473 and 13-474

Dear Mr. Hartman,

Please consider the comments below the collective and cumulative concerns and recommendation of Friends of the Headwaters (FOH), a local citizen's group organized for the purpose of protecting Minnesota's resources; advocating for citizen's right to fully participate in its government's decisions and ensuring adherence to all local, state and federal laws in all actions taken in regard to Enbridge Pipeline, (now dba North Dakota Pipeline LLC) and their plans to construct and operate the Sandpiper Crude Oil Pipeline in Minnesota. Friends of the Mississippi have over 600 members and supporters who share the concerns, comments and recommendations expressed below.

We have organized our comments into twelve sections under the following broad categories:

1. Concerns, objections, and failure to provide due process;
2. Quality and scope of alternative environmental reviews;
3. Certain time and resource constraints;
4. Unjustified limited scope of environmental review;
5. Pipeline leak/rupture event impact scenario analysis;
6. Need for additional leak/rupture scenarios unique to sandpiper routes;
7. Bakken sweet crude oil volatility/flammability consideration in leak/rupture scenario development;
8. Dept. of Commerce staff commitment to provide FOE assistance in development of alternative route data;
9. Methods of developing and comparing alternative routes;
10. Cumulative impacts;
11. Financial assurance;
12. Transparency, equal access and equal treatment;

1. CONCERNS, OBJECTIONS, AND FAILURE TO PROVIDE DUE PROCESS

Our primary concern is for what appears to be a decoupling and therefore the confusion of the procedures employed by your Department and the Public Utilities Commission in performing the state's responsibilities under the provisions of the various Statutes and Administrative Rules pertaining specifically to both the need for and the routing of petroleum pipelines in Minnesota.

The effect of the apparent decoupling of the Certificate of Need and Routing permit is the perception if not the reality that the applicant's realization of the pipeline project is but a foregone conclusion and that the routing process is relegated to simply comparing the applicant's preferred route to any other route that can possible manage to clear the myriad regulatory hurdles of requirements for complex supporting data and survive the virtually insurmountable maze of procedural requirements. The process has the appearance of being so favorably stacked in favor of the applicant's preferred route as to discourage the public from mounting the effort necessary to have any other route qualify for serious consideration. In fact, the applicant is acting in ways that would readily lead even the most casual observer to believe that the proposed southern route for the Sandpiper pipeline is a "done deal". Why else would Enbridge representatives gamble so much money to secure landowner easements all along their "preferred" route were they not so confident that the "process" will work in their favor?

FOH is requesting affirmative action on the part of the DOC and PUC that demonstrate that the need and associated pipeline routing process are transparent avoiding even the appearance of a process with a pre-determined outcome. The public has a right to expect a meticulously developed, well coordinated and interrelated need and routing process such that all material evidence is adequately weighed and publically well reasoned throughout.

It is very unclear and disturbing to the public that serious social, economic and environmental considerations seem so narrowly defined and constrained by unreasonable time schedules that favor the applicant at the expense of the public interest. It is unclear who develops the environmental impact information required by rule in the Certificate of Need (CON) process and how this environmental information may differ from the "comparative environmental analysis" or CEA prepared by the DOC that has the appearance of being operative only in the pipeline routing process. It is unclear and somewhat disturbing to realize, if it is true, that the narrow constraints imposed on the CEA document may also constrain the quality of the only environmental decision document available for the parallel but still separate CON process.

Furthermore, FOH is particularly concerned for your Department's actions which may violate the Minnesota Environmental Policy Act (MEPA) in the preparation of the CEA, particularly if the CEA is the only environmental review document made available for the CON decision as well.

It is our belief that while the several recent amendments to Minnesota Statutes you have cited at recent public meetings regarding the Sandpiper project provide for an "alternative" environmental review process for pipelines these Statutes and Rules to not allow for "inferior" environmental review for either the CON or the CEA developed for the Routing Permit.

Our reviews of all pertinent Minnesota Statutes and Rules applicable to the either the determinations of need and/or for the selection of routes for crude oil pipelines find nothing that absolves the applicant or any state agencies from adherence to either the letter or the spirit of certain overarching and vital policy provisions of MEPA. For example, we believe that the applicant and your respective departments as well as commenting state agencies are bound by Subdivision 6, Minnesota Statutes 116D.04 regarding which states:

> **Prohibitions.** No state action significantly affecting the quality of the environment shall be allowed, nor shall any permit for natural resources management and development be granted, where such action or permit has caused or is likely to cause pollution, impairment, or destruction of the air, water, land or other natural resources located within the state, so long as there is a feasible and prudent alternative consistent with the reasonable requirements of the public health, safety, and welfare and the state's paramount concern for the protection of its air, water, land and other natural resources from pollution, impairment, or destruction. Economic considerations alone shall not justify such conduct.

This provision of MEPA sets a very high standard for making a finding that all "reasonable and prudent alternatives" have indeed been considered before any state action may be taken to permit projects such as a crude oil pipeline.

2. QUALITY AND SCOPE OF ALTERNATIVE ENVIRONMENTAL REVIEW

FOH recognizes that the Departments of Commerce and/or the Public Utilities Commission are empowered by certain Statutes to utilize alternative environmental review for certain crude oil pipelines as authorized by Minnesota Statutes 216G.02 pertaining to Routing of Certain Pipelines and Minnesota Statutes 2004, section 216B.2421 that applies to certain large energy facilities and specifically, subdivision 2, subsection 4. specifies that these provisions apply to pipelines such as the Sandpiper.

FOH further recognizes that Minnesota Statutes 2004, section 216B.2421, Subdivision 5 describing environmental review goes on to state:

> [ENVIRONMENTAL REVIEW.] For the projects identified in subdivision 2 and following these procedures, the commissioner of the Department of Commerce shall prepare for the commission an environmental assessment. The environmental assessment shall contain information on the human and environmental impacts of the proposed project and other sites or routes identified by the commission and shall address mitigating measures for all of the sites or routes considered. The environmental assessment shall be the only state environmental review document required to be prepared on the project.

However, while MEPA specifically, in Subdivision 4a. makes provisions for such forms of exclusive “alternative review” as allowed in Statutes 216B, this section of MEPA also makes the intentions of such alternative review quite clear.

> Subd. 4a. Alternative review. The board shall by rule identify alternative forms of environmental review which will address the same issues and utilize similar procedures as an environmental impact statement in a more timely or more efficient manner to be utilized in lieu of an environmental impact statement.

FOH brings your attention to the fact that while the purpose of “alternative review’ as contemplated under Subdivision 4a of MEPA is to allow for “a more timely or more efficient manner to be utilized in lieu of an environmental impact statement, such alternative review is also required to: …“address the same issues and utilize similar procedures as an environmental impact statement…”

3. CERTAIN TIME AND RESOURCE CONSTRAINTS

The expedited time schedules and the omission of certain requirements for publishing of drafts documents and for soliciting public and other agency comments on draft documents are all streamlining of the normal EIS process provided as special privilege for pipelines under MN Statutes 216 G.02. The compression of time-lines and reduction of time and limiting opportunity for public or other agency comments does not excuse the PUC and/or the DOC from preparing robust, thorough and complete environmental review documents for pipelines. If the compressed nine and twelve month schedules provided for in rule and law, respectively for both issuing Certificates of Need (CON) and Routing Permits place constraints on the quality or completeness of the public involvement or the quality and completeness of environmental review portions of these processes it is incumbent on the PUC and DOC to either act to secure the necessary resources to accomplish these tasks within the provided timeframes or grant itself sufficient time extensions to perform the environmental review adequately. Your individual departments have ample provision in rule and law to shift the costs of the accelerated pubic input and environmental review to the applicant as their responsibility in return for the benefits of the streamlined process.

Specifically, in regard to cost constraints, Minnesota Statutes 216G.02 ROUTING OF CERTAIN PIPELINES. Subdivision 3.B Section 6 requires the PUC to:

> (Section 6) provide for the payment of fees by persons proposing to construct pipelines to cover the costs of the commission in implementing this section;

Lacking sufficient resources your departments have little choice, if acting in the better interest of the public than to request additional funding and/or extend the time taken to properly meet these obligations to the citizens of Minnesota.

It is FOH’s understanding of these Statutes and Rules that if at any time during CON or Routing Permit process your respective departments become aware that more extensive public involvement will be needed, or that more detailed information must be analyzed or that more alternative routes than anticipated will have to be evaluated to meet the minimum requirements of MEPA or other applicable rules the Public Utilities Commission on recommendation from the Department of Commerce, in providing such just cause, can extend either of the CON or the Routing Permit schedules. Specifically PUC procedural rules in Section 5 states:

> "(Section 5) provide a procedure that the commission will follow in issuing pipeline routing permits and require the commission to issue the permits within nine months after the permit application is received by the commission, unless the commission extends this deadline for cause;" (emphasis added by FOH)

FOH contends that citizen comments have by appropriate mean requested, sufficiently justified and provided evidence in support to constitute the required "cause" for the commission to extend the several deadlines necessary to allow full and complete public involvement and for expanding the time and resources necessary for preparation of appropriate environmental review documents.

4. UNJUSTIFIED LIMITED SCOPE OF ENVIRONMENTAL REVIEW

FOH finds that the Department of Commerce Environmental Review staff may believe that the Comparative Environmental Analysis for alternative routes and comments from any state or federal agencies or from the general public are necessarily constrained to impacts of pipeline construction only. FOH point out that under PUC Rules 7852.1900 CRITERIA FOR PIPELINE ROUTE SELECTION states in Subpart. 3 Criteria and in section J:

> Criteria. In selecting a route for designation and issuance of a pipeline routing permit, the commission shall consider the impact on the pipeline of the following:
>
> > J. the relevant applicable policies, rules, and regulations of other state and federal agencies, and local government land use laws including ordinances adopted under Minnesota Statutes, section 299J.05, relating to the location, design, construction, or **operation** of the proposed pipeline and associated facilities. (note: bold underlining added by FOH)

Therefore, FOH requests that the Comparative Environmental Review for the preferred route and all alternative routes include all *operational* impacts of the proposed Sandpiper pipeline. Operational aspects of crude oil pipelines over their entire projected life history include the high potential for pipeline failure, rupture, leaks and other releases of product into the environment. Probabilities of these types of releases have been found in other recent pipeline project environmental reviews to be high enough to be considered reasonably predictable impacts of operating crude oil pipelines over their projected lifetimes. These were the findings of a recently published 2014 Federal Environmental Impact Statement (EIS) prepared by the U.S. Environmental Protection Agency (EPA) for the proposed Pebble Mine in Bristol Bay Alaska. The full EIS is available on line at:

http://cfpub.epa.gov/ncea/bristolbay/recordisplay.cfm?deid=253500#Download

In Chapter 11 of the aforementioned EIS the EPA supports this conclusion by statistical analysis of United States, Canadian pipeline operating history as well as data from other countries: The EPA's rather sobering and significant conclusions are shown in two excerpts from the EIS below:

> *"This overall estimate of annual failure probability, coupled with the 113-km length of each pipeline as it runs along the transportation corridor within the Kvichak River watershed, results in an 11% probability of a failure in each of the four pipelines each year. Thus, the probability of a pipeline failure occurring over the duration of the Pebble 2.0 scenario (i.e., approximately 25 years) would be 95% for each pipeline."*

> *"The chance of a large rupture in each of the three pipelines over the life of the mine would exceed 25%, 30%, and 67% in the Pebble 0.25, 2.0, and 6.5 scenarios, respectively. In each of the three scenarios, there would be a greater than 99.9% chance that at least one of the three pipelines carrying liquid would fail during the project lifetime".*

The Bristol Bay EIS goes on to discount the likelihood that improved engineering standards for pipeline materials would reduce pipeline failure rates because engineering has little effect on the rate of human errors leading to leaks and ruptures. See this discussion in a following paragraph:

> *"It may be argued that engineering can reduce pipeline failures rates below historical levels, but improved engineering has little effect on the rate of human errors. Many pipeline failures, such as the cyanide water spill at the Fort Knox mine (Fairbanks, Alaska) that resulted from a bulldozer ripper blade hitting the pipeline (ADEC 2012), are due to human errors. Perhaps more important, human error can negate safety systems. For example, on July 25 and 26, 2010, crude oil spilled into the Kalamazoo River, Michigan, from a pipeline operated by Enbridge Energy. A series of in-line inspections had showed multiple corrosion and crack-like anomalies at the river crossing, but no field inspection was performed (Barrett 2012). When the pipeline failed, more than 3 million L (20,000 barrels) of oil spilled over 2 days as operators repeatedly overrode the shut-down system and restarted the line (Barrett 2012). The spill was finally reported by a local gas company employee who happened to witness the leak. The spill may have been prevented if repairs had been made when defects were detected, and the release could have been minimized if operators had promptly shut down the line".*

The following January 27, 2012 article in the Watershed Sentinel, an online British Columbian Newsletter reviews a 10- year spill history of the Enbridge Pipeline System in the U.S. and Canada demonstrating that Enbridge pipeline leak/spill history is consistent with the data analyzed in the Bristol Bay EIS.

A Decade of Enbridge Oil Pipeline Spills
by Joyce Nelson,

2000: 7,513 barrels. Enbridge reported 48 pipeline spills and leaks, including a spill of 1,500 barrels at Innes, Sask.

2001: 25,980 barrels. Enbridge pipelines reported 34 spills and leaks, totalling 25,980 barrels of oil, including a January spill from Enbridge's Energy Transportation North Pipeline that leaked 23,900 barrels of crude oil into a slough near Hardisty, Alberta, and a September spill of 598 barrels in Binbrook, Ont.

2002: 14,683 barrels. Enbridge reported 48 oil spills and leaks, totalling 14,683 barrels, including a leak of 6,133 barrels in Kerrobert, Sask. in January; a seam failure in May that spilled 598 barrels in Glenboro, Man.; and a pipeline rupture into a marsh west of Cohasset, Minn. To prevent 6,000 barrels of crude oil from reaching the Mississippi River, Enbridge set the oil on fire.

2003: 6,410 barrels. Enbridge pipelines had 62 spills and leaks, totalling 6,410 barrels, including a January spill of 4,500 barrels of oil at the company's oil terminal near Superior, Wisc., and a June spill of 452 barrels of oil into Wisconsin's Nemadji River. In April, an Enbridge gas pipeline exploded, levelling a strip mall in Etobicoke, Ont. and killing seven people.

2004: 3,252 barrels. Enbridge pipelines had 69 reported spills, totalling 3,252 barrels of oil, including a February valve failure in Fort McMurray, Alta. that leaked 735 barrels of oil.

2005: 9,825 barrels. Enbridge had 70 reported spills, totalling 9,825 barrels of oil.

2006: 5,363 barrels. Enbridge had 61 reported spills, totalling 5,363 barrels of oil, including a March 613 barrel spill at its Willmar terminal in Saskatchewan and a December spill of 2,000 barrels at a pumping station in Montana.

2007: 13,777 barrels. Enbridge had 65 spills and leaks, totalling 13,777 barrels of oil, including a January pipeline break near Stanley, North Dakota, which spilled 215 barrels of oil; two pipeline incidents in January/February in Clark and Rusk Counties in Wisconsin which spilled 4,200 barrels of oil; and an April spill of approximately 6,227 barrels of oil into a field down-stream of an Enbridge pumping station at Glenavon, Sask. In November, an Enbridge pipeline carrying bitumen to U.S. Midwest markets exploded near Clearbrook, Minn., killing two workers.

2008: 2,682 barrels. Enbridge had 80 reported spills and leaks, totalling 2,682 barrels of oil, including a January incident at an Enbridge pumping station at the

Cromer Terminal in Manitoba that leaked 629 barrels of crude; a February incident in Weyburn, Sask., which leaked 157 barrels; and a March spill of 252 barrels of oil in Fort McMurray, Alberta.

2009: 8,441 barrels. Enbridge had 103 reported oil spills and leaks, totalling 8,441 barrels, including a pipeline incident at the Enbridge Cheecham Terminal tank farm that spilled 5,749 barrels of oil near Anzac, Alberta; a spill of 704 barrels in Kisbey, Sask.; and a spill of 1,100 barrels at Odessa, Sask.

2010: 34,122 barrels. Enbridge had 80 reported pipeline spills, totalling 34,122 barrels, including a January Enbridge pipeline leak near Neche, North Dakota of 3,000 barrels of oil; an April incident near Virden, Man. that leaked 12 barrels of oil into Bosshill Creek; a July pipeline spill in Marshall, Michigan that dumped 20,000 barrels of tar sands crude into the Kalamazoo River, causing the biggest oil spill in U.S. Midwest history; and a September pipeline spill of 6,100 barrels in Romeoville, Ill.

Total: 132,715 barrels of oil, more than half the Exxon Valdez spill of 257,000 barrels

Sources: Prince George Citizen (March 12, 2010); The Polaris Institute (May 2010); The Tyee (31 July 2010); Reuters (Sept. 10, 2010); Enbridge.com 2010; Vancouver Sun (May 10, 2011); The Globe & Mail (June 17, 2011); Dogwood Initiative

- See more at: http://www.watershedsentinel.ca/content/enbridge-spills#sthash.e8U7c4zM.dpuf

FOH asserts that Minnesota Statute and Rule applicable to pipeline route permit review and comparative environmental analysis both permit and justify inclusion and assessments of impact from predictable events during the life history of the pipeline including the high probability for major leaks and/or ruptures releasing large quantities of crude oil into the environment. These predictable releases of oil are very likely to have significant adverse impacts on persons, property and natural resources along and downstream of each of the several route alternatives evaluated. Comparing these predictable impacts for all alternative routes should be a major factor in final route selection of the Sandpiper pipeline.

5. Pipeline Leak/Rupture Event Impact Scenario Analysis

The Bristol Bay EIS continues in Section 11.2 with identification of 64 streams and rivers as potential product spill receiving waters because they were proposed to be crossed by the pipeline. But there were many more watersheds crossed at points near enough to downstream receiving waters to also be within the impact zone of a predicted pipeline leak or rupture.

In sections 11.3 of the EIS pipeline rupture/leak scenarios are described in detail including extensive treatment of probable duration and volumes of spills and flow times to and extending predictable distances down receiving waters. Impacts are then described for two receiving streams typical of the landscape traversed by the pipeline.

The leak/rupture scenarios are developed fully in terms of:

1. Exposure – the physical mechanisms by which aquatic organisms would become exposed to the spilled product;
2. Transport and fate – the distance down stream the toxic components would travel down stream before dissipating, degrading or diluting below applicable water quality standards for each or most important chemical constituent of the product spilled;
3. Exposure - Response – A full analysis of the product for all toxic components, state and federal water quality standards for these chemicals and laboratory methods used to simulate water column concentrations of each chemical of concern;
4. A review of analogous spills into likely receiving water types including isolated lakes, lake chains, high or low quality streams, wetlands of different types;
5. Risk Characterization –comparing exposure levels to toxicological benchmark levels, duration of risks, actual spill histories including potential for remediation and recovery of spilled product, site specific factors and overall weight of evidence; and
6. The Range of Uncertainties in each of these pieces of evidence.

Scenarios for important Bakken Sweet Crude flowing to receiving rivers, streams, lakes, wetlands or wild rice beds along preferred Sandpiper route (and all accepted alternative routes) could then be developed similar to that developed for diesel fuel spill scenario in the Bristol Bay EIS with similar assumptions and calculations in Table 11-7 from that EIS below:

Table 11-7. Parameters for diesel pipeline spills to Chinkelyes and Knutson Creeks.

Parameter	Spill into Chinkelyes Creek: Chinkelyes Creek	Spill into Chinkelyes Creek: Iliamna River	Spill into Knutson Creek: Knutson Creek
Water Flow			
Discharge (m^3/s)	1.8	22	3.4
Velocity (m/s)	2.2	2.0	2.2
Channel Length (km)	14	7.6	2.6
Pipeline Drainage and Dilution			
Flow rate while draining (m^3/s)	0.035	-	0.023
Flow rate while pumping (m^3/s)	0.005	-	0.005
Release time—draining (minutes)	13	-	7.9
Release time—pumping (minutes)	5	-	5
Volume—total (m^3)	30	-	12
Volume % diesel to water in stream at spill	2.2%	-	0.83%
Mass of diesel in stream at input (mg/L)	17,000	1,500	6,500
Maximum concentration dissolved diesel (mg/L)	1.9–7.8	1.7–7.2	1.9–7.8
Distance traveled during release (km)	1.7		1.1
Travel time to confluence (minutes)[a]	110	64	19
Pipeline and Diesel Specifications			
Length from top of nearest hill to valve (m)	2100	-	810
Elevation drop (m)	150	-	25
Viscosity of diesel at 15°C (cP)	2		
Density of diesel at 15°C (metric tons/m^3)	0.85		

Notes:
Dashes (-) indicate that spill is not directly into Iliamna River, which receives flow from Chinkelyes Creek.
[a] Confluence with Iliamna River for Chinkelyes Creek; confluence with Iliamna Lake for the Iliamna River and Knutson Creek.

Based on these spill parameters similar predictions could be developed for important aquatic plant and/or animal life in the selected receiving waters along each alternative route in the CEA as shown in the following chart from the Bristol Bay EIS that compares the scenarios developed for Alaskan steams to other case histories of similar spills around the country as a means of "ground truthing" or testing validity of their predictive scenarios

Table 11-9. Cases of diesel spills into streams. For comparison, the diesel pipeline failure scenarios evaluated here would release 30 and 8 m³ of diesel into receiving streamflows of 1.8 and 3.4 m³/s for spills into Chinkelyes Creek and Knutson Creek, respectively.

Case	Diesel Released (m^3)	Receiving Streamflow (m^3/s)	Observed Effects
Happy Valley Creek, AK	3.7	14	Significant declines in the abundance and species richness of invertebrates
Camas Creek, MT	Unknown	0.42	Low invertebrate abundance and richness
Hayfork Creek, CA	15	4.1	Large kill of vertebrates and invertebrates
Mine Run Creek, VA	240	1.2	Reduced invertebrate abundance and diversity
Reedy River, SC	3,600	6.4	Near-complete fish kill
Cayuga Inlet, NY	26	1.8	Fish kill and reduced abundance, reduced invertebrate abundance and species composition
Westlea Brook, UK	9.8	1.34	Fish kill, invertebrates severely affected
Hemlock Creek, NY	0.5	0.76	No significant effects on invertebrates

Notes:
[a] Mean flow from NHDPlus v2; others as reported by the authors.

6. NEED FOR ADDITIONAL LEAK/RUPTURE SCENARIOS UNIQUE TO SANDPIPER ROUTES

Sandpiper Leak/Rupture Ground Water Aquifer Contamination Scenario
In the Bristol Bay/Pebble Mine EIS there was no identified need to assess potential for groundwater contamination that might result from a typical leak or spill from the pipelines serving the mines. However, in the case of the preferred route for the Sandpiper crude oil pipeline there are several highly vulnerable aquifers including the Straight River Aquifer near Park Rapids that has been extensively studied.
To fully appreciate the nature and scope of the contamination risk to this important aquifer a set of leak/spill scenarios similar to the surface water impact scenarios used in the Bristol Bay EIS should be developed in the Comparative Environmental Analysis for Sandpiper and any of the alternative routes accepted for consideration in the analysis.

Preparation of groundwater aquifer impact scenarios in susceptible glacial outwash formations that exist along the proposed Sandpiper route are likely to be made significantly more accurate by virtue of extensive study of an historic Enbridge (then dba Lakehead Pipeline Company in Minnesota) pipeline rupture in 1979 west of Bemidji near the small community of Pinewood. The Pinewood study would provide case study calibration data and the equivalent “ground truthing” of predictive groundwater contamination scenarios developed for Sandpiper route alternatives as was recommended in the surface water scenarios above..

A summary of the history and some of the research results applicable and useful in preparation of the Comparative Environmental Analysis for the Sandpiper project is found in a US Geological Survey factsheet found at the website shown below and an excerpt from this factsheet follows:

http://mn.water.usgs.gov/projects/bemidji/results/fact-sheet.pdf

(Excerpt from factsheet)
Description and History of Site
On August 20, 1979 approximately 16 kilometers northwest of Bemidji, Minnesota, the land surface and shallow subsurface were contaminated when a crude-oil pipeline burst, spilling about 1,700,000 L (liters) (about 10,700 barrels) of crude oil onto a glacial outwash deposit (fig. 1). Crude oil also sprayed to the southwest covering an approximately 7,500 m2 (square meter) area of land (spray zone). After cleanup efforts were completed about 400,000 L (about 2,500 barrels) of crude oil remained. Some crude oil percolated through the unsaturated zone to the water table near the rupture site (North oil pool, fig. 1). Some of this sprayed oil flowed over the surface toward a small wetland forming a second area of significant oil infiltration (South oil pool).

The land surface is a glacial outwash plain underlain by stratified glacial outwash deposits. The water table ranges from near land surface to about 11 m below the land surface. About 370 wells and test holes had been installed as of 1998.

Research Results
The fate, transport, and multiphase flow of hydrocarbons depends on geochemical processes and on the processes of volatilization, dissolution, biodegradation, transport, and sorption (fig. 2). An interdisciplinary investigation of these processes is critical to successfully evaluate the migration of hydrocarbons in the subsurface. The investigation at the Bemidji site involved the collection and analysis of crude oil, water, soil, vapor, and sediment samples. The oil phase that occurs as floating product on the water table and as residuum on sediment grains provided a continued source of hydrocarbon to the ground-water and vapor plumes. Knowledge of the geochemistry of a contaminated aquifer is important to understanding the chemical and biological processes controlling the migration of hydrocarbon contaminants in the subsurface. Studies were also conducted to document the concentrations of gases in the unsaturated zone.

Predictable Sandpiper pipeline lead/rupture ground water impact scenarios for susceptible glacial outwash aquifers along the preferred and all alternative routes evaluated could be modeled graphically (as in the figure below from that study) with methods developed in the Pinewood Spill study. Graphics thus developed could be made available in the CEN for the public and regulatory agencies to weigh in making various permit decisions and choices between alternative routes.

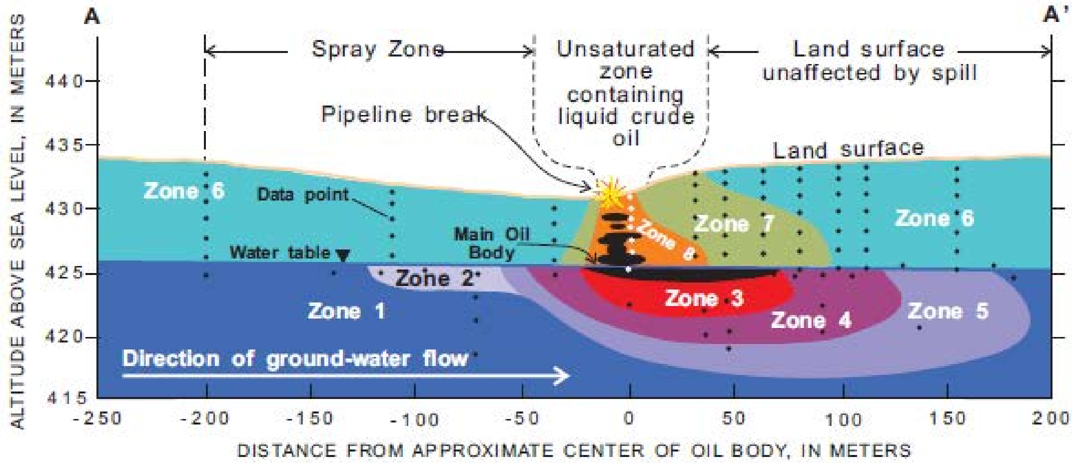


Figure 4. Geochemical zones in the unsaturated and saturated zones at the North oil pool, 1997 (Modified from Baedecker and others, 1993).

Note: Predictive models for groundwater contaminant plumes in leak/rupture scenarios can be used for comparing alternative routes and for setting GIS Spatial Analysis friction parameters discussed elsewhere in these comments.

A brief bibliography of studies of the Bemidji/Pinewood spill site assembled by the U.S. Geological Survey Minnesota Water Science Center that can be used to develop and support groundwater contamination scenarios for selected susceptible glacial outwash aquifers along the proposed Sandpiper route and its alternatives is shown below:

Fact sheet describing results from the Bemidji Toxics project

Toxics Papers:

- "Ground water contamination by crude oil" (146 KB) by Geoffrey Delin and William Herkelrath.
- "Long-term monitoring of unsaturated-zone properties to estimate recharge at the Bemidji crude-oil spill site"(498 KB) by Geoffrey Delin and William Herkelrath.
- "Aromatic and Polyaromatic Hydrocarbon Degradation under Fe (III)-Reducing Conditions" (135 KB) by Robert T. Anderson, et al.
- "Coupled Biogeochemical Modeling of Ground Water Contamination at the Bemidji Minnesota Crude Oil Spill Site" (60 KB) by Gary Curtis, et al.
- "Investigating the Potential for Colloid- and Organic Matter-Facilitated Transport of Polycyclic Aromatic Hydrocarbons in Crude Oil-Contaminated Ground Water" (136 KB) by Joseph Ryan, et al.
- "Determining BTEX Biodegradation Rates Using In Situ Microcosms at the Bemidji site, Minnesota: Trials and Tribulations" (69KB) by E. Michael Godsy, et al.
- "Inhibition of Acetoclastic Methanogenesis by Crude Oil from Bemidji, Minnesota" (143 KB) by Ean Warren, Barbara Bekins, and E. Michael Godsy.

Posters Presented at Technical Conferences:

- "Estimating multiphase hydraulic properties at a crude-oil spill site" by William Herkelrath, Hedeff Essaid, and Leslie Dillard, USGS, Menlo Park CA

  A poster presented at the "International workshop on Characterization and measurement of the hydraulic properties of unsaturated porous media", Riverside, CA, October 22-24, 1997.

Related links that include results from the Bemidji site:

- Fate of Organic Chemicals in Subsurface Environments
- Microbiology and Molecular Ecology studies in Bemidji, MN
- Multiphase flow, transport, reaction and biodegradation
- Comprehensive Organic Analysis of Water
- Transport and Biogeochemical Fate of Organic Substances in Aquatic Environments
- Biogeochemical Controls on Organic Contaminant Degradation in Heterogeneous Near Surface Environments
- Comparative Study of Organic Degradation in Selected Hydrologic Environments

Figures:

- Geochemical zonation (17 KB) diagram.
- Plan view aerial photo from 1991 (85 KB) showing topographic contours and well locations at the site.

7. Bakken Sweet Crude Oil Volatility/Flammability Consideration in Leak/Rupture Scenario Development

Transportation Safety Board of Canada's Operation Service Branch Laboratory Report # LP148/2013 entitled "Analysis of Crude Oil Samples - Montreal, Maine & Atlantic Railway, Train MMA-002 - Date of Occurrence: 06-Jul-2013" which was just released on released on February 6th 2014. The relevance of this report to the Sandpiper routing process Comparative Environmental Analysis is that the train derailment investigated involved a major spill of the same product proposed to be shipped by the Sandpiper, namely Bakken sweet crude oil. The full report is available at:

> http://www.tsb.gc.ca/eng/enquetes-investigations/rail/2013/R13D0054/lab/20140306/LP1482013.asp

Excerpts from the report follow:

> "On 06 July 2013, a unit train carrying petroleum crude oil operated by Montreal, Maine & Atlantic Railway derailed in Lac-Mégantic, Quebec. Numerous tank cars ruptured and a fire ensued.
>
> "Conventional oil, which can range from light to medium in grade, is found in reservoir rocks with sufficient permeability to allow the oil to flow through the rock to a well. The petroleum crude oil on the occurrence train originated from suppliers with producing wells in the Bakken Shale formation region of North

Dakota. The Bakken Shale formation is a tight oil reservoir. Tight oil is a type of conventional oil that is found within reservoirs with very low permeability. Most oil produced from low-permeability reservoirs is of the light to medium variety, with a lower viscosity. "

Elsewhere in this Canadian TSB report Bakken Sweet Crude is compared to the volatility of unleaded gasoline:

"The Environmental Technology Centre (ETC) Oil Properties Database reports the following properties for unleaded gasoline: [45]

Flash point -30°C

Density at 15°C 750 to 850 kg/m^3

Kinematic viscosity <1 cSt at 38°C

"Comparing these values to the occurrence crude oil results summarized in Table 2, it is apparent that the occurrence crude oil's flash point is similar to that of unleaded gasoline. The density results obtained for the occurrence crude oil samples (see Table 10) are also within the range reported for unleaded gasoline. However, unleaded gasoline has lower viscosity than the occurrence crude oil samples."

The Canadian TSB report includes the following pertinent conclusions that would be important in the development of leak/rupture incident response scenarios in the Sandpiper comparative environmental analysis:

"4.3 The occurrence crude oil's properties were consistent with those of a light sweet crude oil with volatility comparable to that of a condensate or gasoline product.

4.6 The large quantities of spilled crude oil, the rapid rate of release, and the oil's high volatility and low viscosity were likely the major contributors to the large post-derailment fireball and pool fire.

4.7 The occurrence crude oil contained concentrations of BTEX that were comparable to typical values reported for crude oils. This explains why concentrations of benzene and other VOCs well above exposure limits were detected at the derailment site."

8. DEPT OF COMMERCE STAFF COMMITMENT TO PROVIDE FOH ASSISTANCE IN DEVELOPMENT OF ALTERNATIVE ROUTE DATA.

FOH has complained strenuously to Department of Commerce, to the Public Utilities Commission and to the applicant that two factors have severely limited its member's ability to identify and develop reasonable and prudent alternative routes for use in preparation of the planned Comparative Environmental Analysis for Sandpiper. Most important among these limitations has been the very short amount of time allotted for the public to prepare route proposals and the withholding by both Enbridge and the two

Departments of certain techical data in the form of Geographic Information System (GIS) data files called "GIS shapefiles" for the proposed Sandpiper route.

Requests by FOH for extensions of time beyond the established deadline of April 4th 2014 for submitting alternative route proposals have been steadfastly refused by Department staff. These denials of FOH's requests for such time extensions, while provided for in applicable administrative rules with showing of cause, have issued from the Department's staff without their providing justification for denying such requests.

FOH takes very seriously all the considerations as described in Subpart 3. that must be taken into account when selecting suitable alternative routes for transporting such hazardous material as Bakken Crude Oil across Minnesota. As required by the rules as set forth in PUC 7852.1400 great multitude of parameters must be considered simultaneously and repeatedly for what could be endless possible routes. Thankfully, technology has recognized the complexity of the task and the enormity of data that one has to consider to meet the rule and Geographic Information Spatial Analysis is one such technology.

From Enbridge's Minnesota Environmental Information Report on Sandpiper submitted to the PUC as part of the company's application it is apparent that Enbridge used Geographic Information System data analysis method similar to the Spatial Analysis referenced above. The following paragraphs are excerpted in part from that report:

> "EPND assessed the route from Tioga, North Dakota to Superior, Wisconsin, with the intent of maximizing existing right-of-way to the extent practicable while identifying specific areas where co-location may not be practicable. The first step in the environmental review of the route and the selection process consisted of collecting publicly available environmental data to identify routing constraints. The sources of data consisted primarily of: Geographic Information Systems ("GIS") digital information layers, including U.S. Geological Survey ("USGS") topographic maps, USGS land use database, U.S. Department of Agriculture ("USDA") Farm Services Agency aerial photography and GIS data, National Wetlands Inventory ("NWI") maps, Minnesota Department of Natural Resources ("MNDNR") Natural Heritage Information System ("NHIS") data, Minnesota Department of Transportation ("MDOT") highway maps, USDA state soil geographic (State Soil Geographic ["STATSGO2"] and Soil Survey Geographic ["SSURGO"]) databases, and other natural feature databases obtained from the MNDNR website and other state and federal sources. Existing major utility rights-of-way also were identified for potential use in co-location.
>
> 2.3.3 Comparison of Route Alternatives
> EPND conducted a detailed quantitative analysis of environmental impacts along each route alternative identified during the routing process. The analysis used the same sources of publicly available environmental data described in Section 2.3.1 to compare a variety of factors, including proximity to existing rights-of-way,

> wetlands, highly wind erodible soils, bedrock outcrops, prime farmland soils, perennial waterbodies, national forest land, tribal land, state forest land, state Wildlife Management Area ("WMA") land, state Aquatic Management Area ("AMA") land, railroads crossed, roads crossed, and other site-specific matters. No field survey data was used in the alternatives analysis as field surveys were not completed along the alternate routes. EPND identified and analyzed four route alternatives, which are presented in the following subsections and shown in Figure 2.3.2-1. None of the route alternatives were adopted as the Project's preferred route."

Enbridge apparently had submitted the GIS information they developed for their preferred route to the PUC including the GIS shapefile they constructed. FOH had hoped to utilize the GIS Shapefiles Enbridge had applied to their alternative route analysis to explore the applicants preferred southern route to any and all alternative routes considered viable by cursory examination of various maps and other resources. However neither Enbridge nor the Department of Commerce (DOC) staff would release the shapefile claiming it was protected information under both Federal and State statute.

FOH was never granted access to the subject GIS shapefile by either Enbridge or Dept of Commerce but did successfully obtain the shapefile from the Minnesota Department of Natural Resources after finding that the data were not protected by either Federal or State Statute as claimed by Enbridge and DOC. Unfortunately, the release of the GIS shapefile for the Sandpiper preferred route was far too late into the comment period for FOH to make productive use of the data.

Having made its case that FOH was severely hindered in its efforts FOH has appealed to DOC staff for assistance in meeting the rigorous criterion that must be met in 7852.1400 Subp. 3. Requirements for other route sources.

> Subp. 3. A person other than one listed in subpart 2 (the applicant) may propose a route or a route segment according to items A to C. In Subpart 3.B. of this rule it states that: "The pipeline route or route segment proposal must contain the data and analysis required in parts7852.2600, subpart 3, and 7852.2700, unless the information is substantially the same as provided by the applicant."

Department of Commerce staff, in a prehearing scheduling conference call in the presence of all the parties to the Sandpiper project and the Administrative Law Judge, Judge Eric Lipman agreed to assist FOH in developing the necessary detailed information necessary to meet the minimum requirements of MN 7852.1400 cited above such that suggested alternative routes put forth by FOH would not be summarily dismissed from consideration for lack of required supporting data analysis required by that rule. FOH is committed to meeting with DOC staff immediately following the April 4th comment deadline. FOH will, under separate cover be submitting alternative routes for Sandpiper before the comment deadline. It was understood that the alternative routes thus submitted by FOH will require the DOC staff assistance offered to meet the criterion in the rule to make them viable per this agreement thus it is expected that the DOC will continue to develop FOH alternatives submitted such that the FOH alternatives will be found acceptable by the commission.

9. METHODS OF DEVELOPING AND COMPARING ALTERNATIVE ROUTES

The applicant, the PUC, the DOC and the public are all confronted with the same challenge. That is to develop alternative routes for Sandpiper that meet the criterion established in MN Rules 7852.1900 CRITERIA FOR PIPELINE ROUTE SELECTION while satisfying the requirement in MEPA for having considered all reasonable and prudent alternatives.

The applicant, having already utilized considerable GIS technology should be well positioned to employ computerized route optimization algorithms to evaluate their preferred route against any and all routes that meet PUC criterion. In fact, they may have already done so during their own comparison of routes. Furthermore, it is the understanding of FOH that the DOC is considering hiring an outside consultant for purposes of assisting the DOC in preparing the Comparative Environmental Analysis. There are many private consultants in the United States performing optimization analysis of linear public and private utilities by applying route optimization software. We would be happy to provide such consultant lists to the DOC staff upon their request.

We provide below, for those who may not be familiar with this technology, a brief description of how Geographic Information Spatial Analysis Systems have evolved into a powerful tool for selecting optimal routes for linear facilities like power lines, pipelines, highways and other utilities. FOH strongly encourages the DOC to specifically contract with outside consultants skilled and experienced in linear facility route optimization to more fully satisfy the requirements in applicable rules and statute to find and select the most reasonable and prudent alternative route for the Sandpiper and all future linear facilities of this nature. It is recommended that the DOC exercise its and the PUC's authority under rule to also develop alternative routes for Sanpiper.

Here is a detailed description of how this technology could be used to satisfy the statutory requirement to examine all reasonable and prudent alternative routes for Sandpiper while adhering most closely to the constraints of time frames provided in rule and law.

5.1.1.20 Graphical Information System

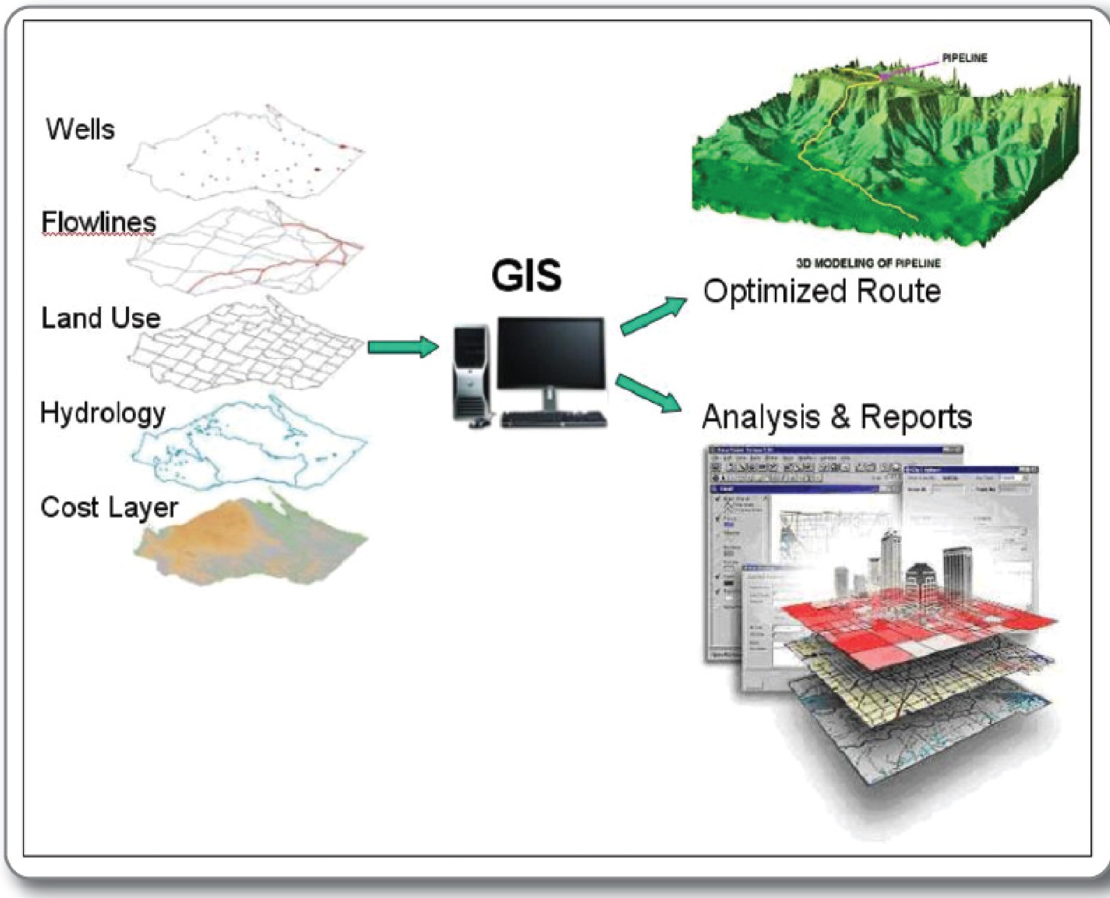
5.1.1.20.1 General

Geographic Information Systems (GIS) are scientific and technological tools that enable the integration of data from different sources into a centralized database from which the data is modeled and analyzed based on its spatial component. GIS-based tools and processes have been extensively used to address the challenges of optimizing pipeline route selection and route networks based on the collection, processing and analysis of spatial data such as topography, vegetation, soil type, land use, geology and landslide areas.

Traditional manual pipeline routing uses available paper maps, drawings, aerial photographs, surveys and engineer experience. GIS techniques combine all of these sources of data in a convenient computer-based information system. The key to the GIS is that it has advantages in terms of speed of data processing and analytical capability.

Fig. 2 is a simplified representation of how data is combined and processed in a GIS to produce models and required outputs. Data, such as well locations, surface topography, land use activities, soil conditions and infrastructure features, are combined based on their spatial component. This enables the engineer to test real-world scenarios within the spatial models.

Fig. 2: Process To Optimize Pipeline Routes



GIS represents an innovative approach to pipeline routing that is both systematic and effective. Optimizing a pipeline route is essentially an optimization between costs of the material and the costs of the construction. Natural and man-made terrain obstructions cause spatial variations in construction cost due to changing features like types of soils, intervals of slope. GIS allows the engineer to use dynamic spatial models to aid in selecting an optimized pipeline route. The GIS software and data enables the processing of a large amount of location-based information to find a least cost path (LCP) between two locations by taking into account natural and manmade obstructions and features.

5.1.1.20.2 GIS Routing Optimization Methodology

The GIS approach to pipeline routing optimization is based on relative rankings and weights assigned to project specific factors that may affect the potential route. The result of this process is a least cost path (LCP) which represents that most economic path between the origin and the destination points of the pipeline.

Fig. 3 is a representation of the methodology flow used to determine the LCP

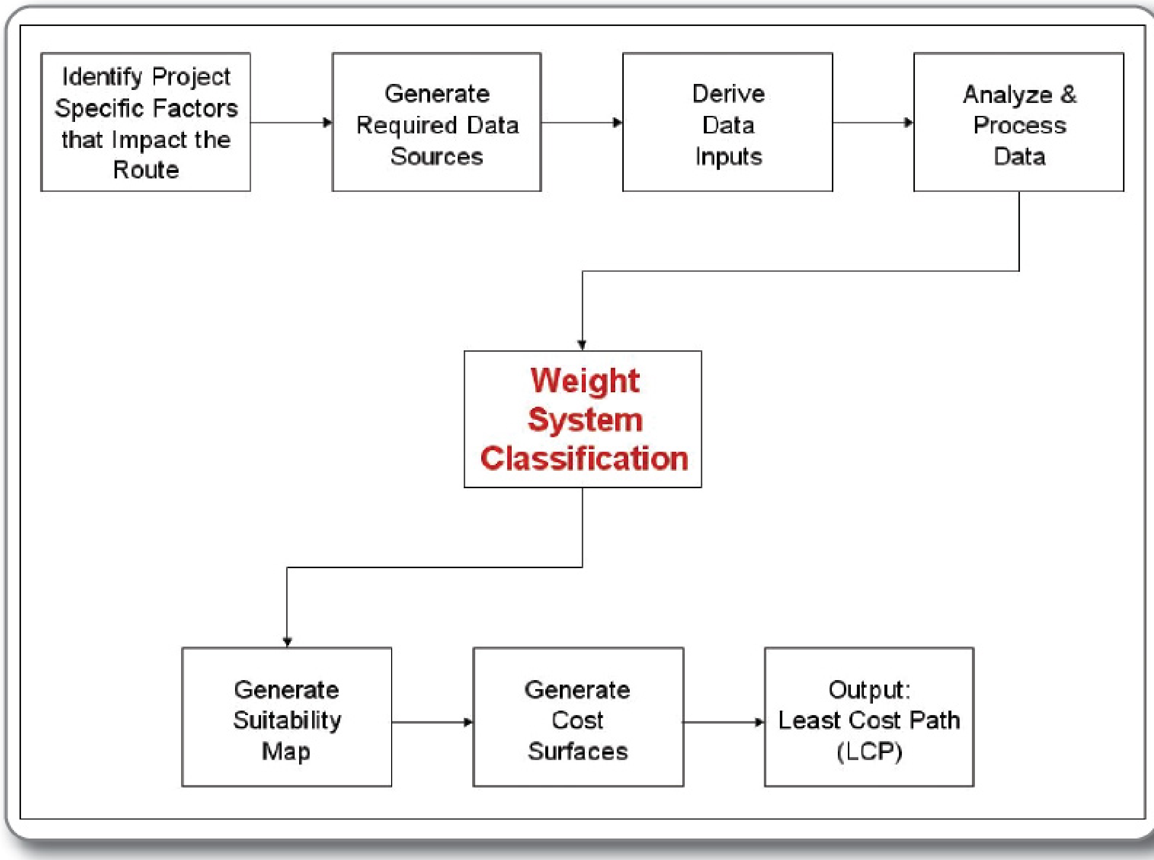


Fig. 3: Pipeline Optimization Methodology

5.1.1.20.3 Identification of Factors Affecting the Route

As mentioned in the previous section on selection criteria the identification of project-specific factors that may constrain or impact on the pipeline is an important step and a vital input to the GIS. Several factors such as geo-hazards, social issues and construction costs impact on the route and need to be taken into account. At this stage a set of rules are determined that will be used in the routing exercise. Input from experienced engineers is required to ensure that the appropriate features are identified and the correct rules established. The accuracy of the subsequent analysis is dependent on the factors being correctly identified as the analysis is only as good as the inputted data. Examples of some factors and rules include:

Factor/Feature	Rule
Roads	• Avoid road crossings • Proximity to roads is important
Railway lines	• Avoid railway line crossings
Rivers	• Avoid river crossings
Urban areas	• Avoid built up/populated areas • Avoid future development areas
Terrain/topography	• Avoid steep slopes • Use flat terrain where possible

Environmental areas	• Avoid highly-sensitive areas
Wetlands	• Avoid wetland crossings
Water bodies	• Avoid water bodies
Surface geology	• Avoid surface/sub-surface rock • Stable soils are important

5.1.1.20.4 GIS Data and Data Sources

Satellite imagery, maps, aerial photography, existing GIS data, LiDAR surveys and traditional geotechnical and topographical surveys are all sources of data that should be gathered and incorporated into the project GIS. The maps, satellite imagery and remote sensed data are scanned and geo-referenced and are then used to derive spatial features such as roads, rivers, urban areas and geological boundaries which form the GIS data to be used in the routing process.

5.1.1.20.5 GIS Data Processing and Analysis

Once the data has been captured it needs to be processed and converted into raster data. The raster data is used to calculate the feature distance cost for each feature – the weighted cost as one moves away from a feature. For example rivers are given a high cost and the further you move away from the river the lower the feature distance cost becomes.

The significance of the effect of a single feature on the pipeline route varies for each feature. For example, it is more important to avoid a deep valley crossing than it is to avoid a road crossing. The analytical hierarchy process (AHP) is one of the structured methods that can be employed to quantitatively rank each of the identified factors. Each factor is assigned a cost value which is benchmarked with typical constructions costs. The input from experienced engineers is vital when it comes to ranking and assigning weights to each layer.

5.1.1.20.6 GIS Suitability Map Generation

After the feature layers have been ranked the data layers are combined together into one single layer based on the numerical value factor derived from the weighting process. The resultant layer is referred to as the suitability layer and this layer forms the basis for the GIS analytical work.

The suitability map is used to create cost maps which related to relative construction costs. The highest costs are in steep mountainous terrain, urban areas, roads and large bodies of water. Moderate costs are associated with wetlands, forests and high slope areas. The lowest costs are to be found in areas of relatively flat bare ground, agricultural land or less dense native vegetation. See Fig. 4 for an example of a cost map.

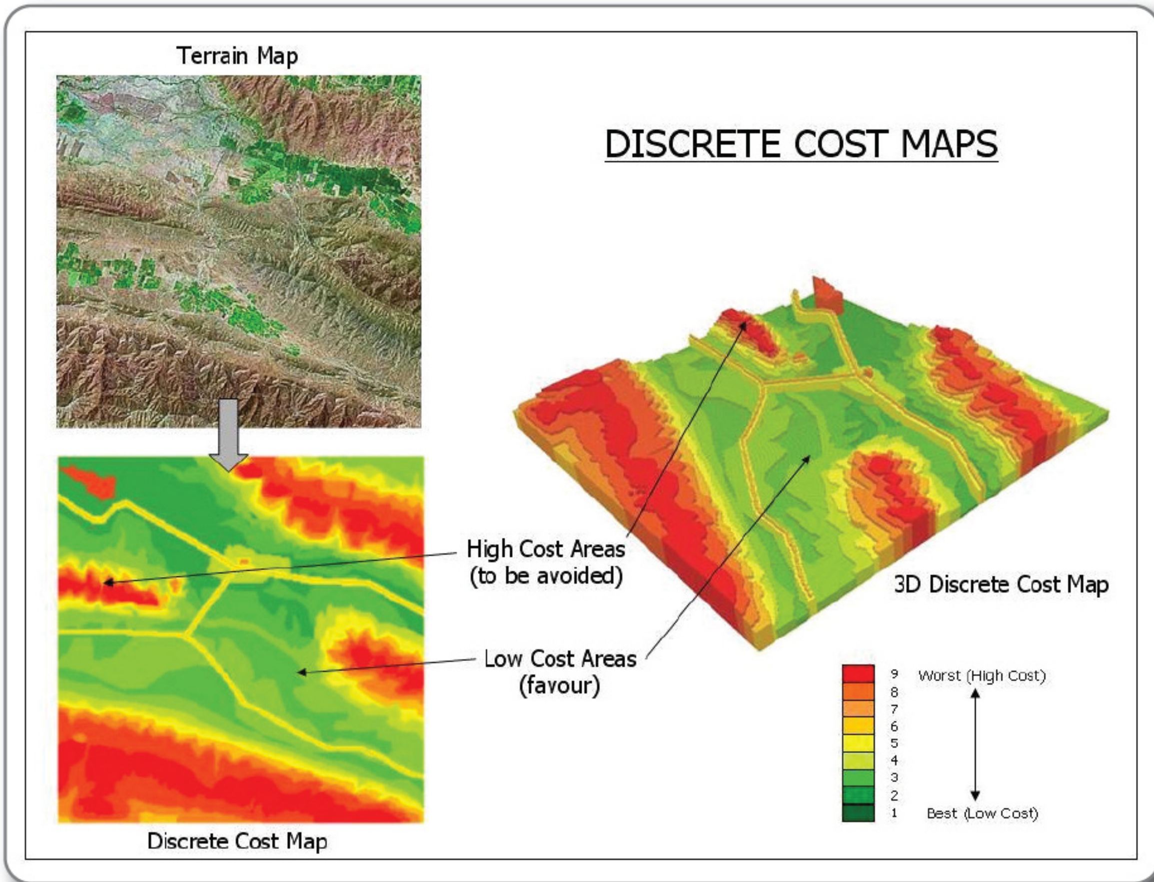


Fig. 4: Discrete Cost Map

The least cost path is the product of the GIS analysis and represents the path of least resistance from the origin of the pipeline along a surface to the destination point.

The strength of the GIS is that re-routes can quickly be incorporated into the system and the implications of the reroutes or alternative routes can be quickly assessed.

The combination of the data layers allows the engineer to test multiple pipeline network design and selection scenarios easily and efficiently. The GIS automatically calculates the lengths of new pipelines or pipeline networks. This allows for rapid total cost calculations and the running of multiple 'what if' scenarios to see the effect of changes to the pipeline design.

A GIS can produce a number of outputs quickly and efficiently in relation to pipeline routing:

- Survey request area delimitation drawings
- Land allocation/permitting drawings
- Pipeline routing drawings
- Alignment sheets (see Fig. 5)
- Tabular outputs (i.e. MTOs)
- Pipeline coordinates

(The GIS Route Optimization shown above is an open source document available on the internet and is not the property of FOH)

It is a vitally important step in employing GIS route optimization methodology that the selection of factors (environmental, demographic, social issues, and others) that are to affect the potential route selected and the weight each of these factors has in the final outcome must be carefully constructed. (See Section 5.1.1.20.2 GIS Routing Optimization Methodology in the method description above). FOH strongly recommends that a Citizen Advisory Committee or other expert panel be assembled to generate a draft set of criterion that includes the mandatory criterion set forth in PUC pipeline routing rules and other factors that may reasonably be considered and suggest a scheme of weighting of these factors to be utilized in identifying the "least cost path" and ranking of all alternative routes being considered for the Sandpiper pipeline.

This draft set of route selection criterion and assigned weights of each factor should be subjected to a full round of public information and comment sessions as required by applicable rules in the routing and/or pipeline need process. After a full public vetting and consensus building process the GIS Route Optimization product or products produced with this final set of weighted criterion would be ready to move forward through the remaining steps of the prescribed permitting process.

Minnesota is fortunate to have had forward looking government agency staff that recognized the importance and utility of providing the public with access to statewide data sets in GIS digital format. The MDNR maintains the state Data Deli system available at: http://deli.dnr.state.mn.us/ and provide links to many other state and federal sources of useful GIS data.

As a special note here, one important criterion that FOH believes has been under represented in past pipeline routing efforts in Minnesota and that must be included here as a heavily weighted routing criterion is groundwater aquifer susceptibility.

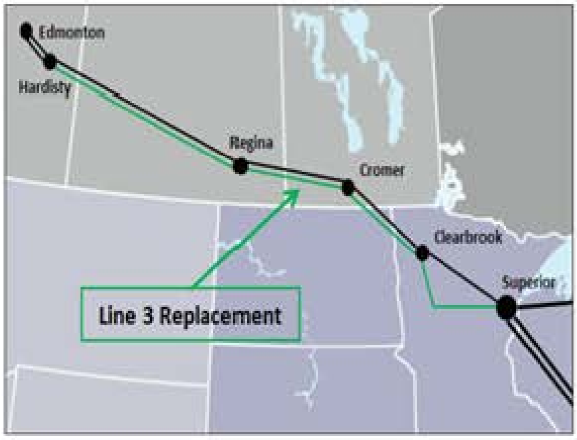
<u>10. CUMMULATIVE IMPACTS</u>

A. Reasonably Foreseeable Future Actions

In an investor conference held on April 2nd 2014 Enbridge announced publically and publically published the company's future plans for expanding pipeline infrastructure in Minnesota. Contained in this published document was a map for the replacement of Enbridge's existing line three which was announce earlier this spring. What was not disclosed in the earlier announcement was that Enbridge's preferred route for the line 3 replacement follows the proposed preferred route for the Sandpiper pipeline. This constitutes a "reasonably foreseeable future action" that must be folded in to any environmental review document assessing impacts of the Sandpiper pipeline including the CEA being prepared by the DOC on sandpiper.

See the cover page with date and authors and the map from page 50 of the Enbridge document.

Line 3 Replacement



The Project:
- Replace 1,031 miles of 34" pipeline with 36" pipeline

Cost:
- U.S. Portion: $2.6 Billion*

In-service date:
- 2017

Status:
- Reassembled successful Alberta Clipper project team
- Securing supply chain
- Known corridor with established relationships

* Project to be jointly funded by ENB and EEP at participation levels to be finalized and approved by a Special Committee of the independent Board of Directors.

B. Impacts of Pipelines on Future Urban or Rural Development

Pipelines become significant impediments to growth and development along their easement corridors. Because of the risk for damage to an operating pipeline, pipeline companies have very strict and complex requirements for granting encroachments into their easements. As a result, it becomes costly and time consuming for local governments to extend roads and underground utilities over a pipeline easement. This has not been factored into the State's process of reviewing proposed pipeline routes because it is outside of their purview. It might prove useful to contact every local jurisdiction along the route to let them know how difficult it will be for them to obtain permission to extend new roads or utilities across pipeline easements and the extra time and expense they can expect. Communities should be alerted to the need for reviewing their comprehensive growth plans and considering future road needs as a relevant issue to evaluate. Areas within orderly annexation districts should consider future private development interests and realize that developers will shy away from parcels with pipeline easements recognizing they are as difficult to deal with as railroads and they can present adverse marketing impacts.

Pipelines have been handled differently by states and larger cities across the country with some establishing conditions and laws to address the above concerns. Minnesota has not yet done that, leaving the local governments simply adversely impacted without compensation. Developing this information in the comparative environmental analysis could be used to both minimize these impacts on local units of government as well as to alert those along the route finally selected of the need to update comprehensive plans and transportation plans to respond to the presence of the new pipeline.

The impacts of the several alternative routes for sandpiper should include these impediments to development as a cumulative impact.

C. Community Preparedness For Pipeline Rupture/Leak Incidents
Scenario development for highly predictable leak/rupture events logically lead to considerations for disaster preparedness needed by communities near the pipeline route. Special training for first responders that alert communities to the volatility, flammability, explosiveness and human exposure concerns would be essential. Rupture/leak disaster preparedness would involve consideration and possible need to procure special fire fighting, remediation and recovery equipment and training local fire departments would need to be alert to and prepared for extraordinarily difficult fire fighting conditions. Consideration of the consequent new burdens and or risks imposed on local fire/rescue personnel and the need for more or specialized equipment posed by having a pipeline transporting hazardous materials near or through their communities should be included in the CEA. Alternative routes could be evaluated to explore ways to lessen or to mitigate these predictable impacts.

FOH recommends that this socio-economic impact be included in the CEA among the potential cumulative impacts of the project.

11. FINANCIAL ASSURANCE

FOH has serious concerns for the apparent ephemeral nature of a Limited Liability Corporation being created by Enbridge for the sole purpose of constructing and operating the proposed Sandpiper and possibly other crude oil pipelines in Minnesota. This is especially true for pipelines intended to transport the extremely hazardous Bakken Sweet Crude, the nature of which is described earlier in these comments. FOH would urge your Departments, if it has such authority, to seriously examine the financial assurance Minnesota citizens will have that North Dakota Pipeline Company LLC will be financially capable and responsible for appropriate response, remediation, and long term care of any pipeline or pipeline product impacts on people, property and/or the natural environment, whether intended or accidental. If neither the DOC nor the PUC have the authority to impose requirements of special financial instruments that can assure such financial assurance exists, FOH requests that your departments work with such agencies that may have this authority or, lacking any such authority in state or federal government, we request that your respective department’s join with FOH to approach the state legislature with draft legislation enabling the appropriate state agency with the necessary authority to require adequate financial assurance from all pipeline companies doing business in Minnesota.

12. TRANSPARENCY, EQUAL ACCESS AND EQUAL TREATMENT

FOH concludes its comments with some remarks about the PUC and DOC "general responsibilities" as provided in rule and principles of good government and citizen's right to basic freedom of speech. We remind you of one of the applicable rules here.

> 7852.4100 GENERAL RESPONSIBILITIES.
> The commission shall monitor the effectiveness of this chapter and shall take appropriate measures to modify and improve the effectiveness of this chapter. The commission shall assist governmental units and interested persons in understanding the rules.

The overall experience of FOH members throughout their involvement in the matter of the proposed Sandpiper pipeline has ranged from frustration to befuddlement, to confusion, rejection, and exclusion. Having our state government department staffs perform in ways that have been outwardly defiant, defensive, obfuscating and off putting has created a deep sense of distrust, suspicion and at times utter outrage. Our members and organization representative's attempts to fully participate in the decision-making process have been rebuffed on numerous occasions.

When FOH members prepared an information display for the public viewing at the several public meetings Enbridge's attorney and both Commerce Department (DOC) and Public Utilities Commission (PUC) staff rejected us advising us that such a display was not allowed in this public forum. This rejection was in spite of the fact that Enbridge was allowed to use similar visual aids in the form of posters, charts, maps and mounted photographs to not only present the facts of their pipeline proposal but to self-promote and embellish themselves as good corporate citizens claiming the company was a stellar corporate citizen with an excellent record of pipeline operating safety. FOH contends that for our state government to create a public forum for the express purpose of receiving public comment on a pending permit action and then deny the public the opportunity to voice its questions, concerns and to counter misrepresentations of Enbridge's safety record utilizing similar media methods is an infringement of citizen's freedom of speech as protected by the First Amendment of the U.S. Constitution.

FOH was denied access to certain technical data including Geographic Information System (GIS) files submitted to the PUC by Enbridge with their application. And when FOH, many individual citizens, a number of state wide organizations representing these citizens as well as Township and County government units requested extensions of comment deadlines to allow disenfranchised "snowbird" citizens opportunity to participate in the important "routing" phase of the project, DOC staff have summarily rejected these requests. DOC staffs defend their refusal to extend timelines as being firmly based on their unswerving intent to honor the compressed timeline set out in recently amended statutes and rules that clearly favor pipeline industry interests over those of the public.

And, to add insult to injury, when the DOC and PUC staff established an on-line public record website that is advertised a “full record” of documents and comments received in the matter of the pipeline project they refuse to post the many petitions they received requesting that timelines be extended. This denies the general public the right to know that if they have made a request for comment period extension that they are not alone. This refusal by government agencies to fully and accurately publish the public record in the manner intended acts to discourage citizens from participating believing that their voices are not being heard. This defiance of citizen’s right to be heard on the part of government agencies not only violates First Amendment rights but works to destroy the general public’s trust in fair and equal treatment under the laws that govern us as a people.

Implore you to acknowledge the respective Department’s responsibility to prioritize the citizen’s rights to know fully about and be effectively involved in all decisions of your respective departments in regard to the Sandpiper project. This has not been our experience with your departments to date. We respectfully resubmit our standing request to meet with the Commissioner of the Department of Commerce and the Executive Secretary of the Public Utilities Commission and department staff with the intent to find ways to improve the public’s overall perception of both the process of pipeline permit review and the manner in which the public is allowed to be fully involved in important government decisions the effect their lives.

This concludes the comments and FOH thanks you and the Department of Commerce for considering our concerns, we look forward to opportunities to fully participate in the remainder of the process.

Sincerely,

Richard Smith, President
Friends of the Headwaters

An Insurance and Risk Management Report on the Proposed Enbridge Pumping Station

Prepared for

The Dane County Zoning and Land Regulation Committee

April 8, 2015

Prepared by:
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Executive Summary

Background

This risk management overview was prepared for the Dane County Zoning and Land Regulation Committee to assist in its review of Conditional Use Permit (CUP) application #2291 by Enbridge Energy Partners to upgrade a pumping station on its existing petroleum pipe line (Line 61) between Marshall and Waterloo, WI. Approximately 12 miles of Line 61 currently transects Dane County and carries tar sands oil from Canada to refineries south of Wisconsin.

I have extensive experience in environmental risk management and insurance. I hold bachelors and masters degrees in risk management and insurance from the University of Wisconsin Madison where I have been a guest lecturer on environmental risk management and insurance topics for 34 consecutive years. My work has included advising and providing technical information to the US Department of Defense, the US Environmental Protection Agency and Department of Energy on environmental insurance issues, successfully placing insurance programs on many of the world's toughest environmental risks, including insuring the remediation of Chernobyl for the World Bank in London, and serving as the managing Director of the Global Environmental Practice Group of one of the world's largest insurance brokerage firms. I have been published in numerous journals and textbooks, including the chapter on environmental insurance in the Chartered Property and Casualty Underwriter (CPCU) 4, *Commercial Liability, Risk Management and Insurance* textbook, and also authored and edited the chapter "Environmental Loss Control" in the *Associate in Risk Management* (ARM) textbook.

Purpose

The objective of this risk management overview is to provide The Dane County Zoning and Land Regulation Committee with information on the risk bearing capacity of Enbridge Energy Partners to address the clean-up and other potential damages resulting from an oil spill at the proposed pumping station upgrade on Line 61. Of specific concern to the County Zoning and Land Regulation Committee are these goals.

Dane County seeks assurances that:

- Enbridge, or other reliable sources, have money available to ensure the timely remediation and restoration of the environment in the event of a spill.
- Money will be available to affected citizens of Dane county to pay for the damages they may incur as a result of an oil spill at the pumping station.
- There will be no unfunded potential liability or expenses to the county for granting a Conditional Use Permit or as a result of a spill from the pumping station.

As specified in the scope of services agreement, this report includes the following: an evaluation of Enbridge’s existing insurance program, including a review of issues associated with Commercial General Liability insurance policies and a determination of the suitability of such policies to cover costs associated with a spill event; an analysis of Enbridge’s offer of indemnity and insurance to Dane County; a summary comparing Enbridge’s current liability insurance policy with the policy forms being litigated over the 2010 spill on line 6B in Michigan; a summary of government sponsored oil spill funds; and, recommendations on the appropriate types and amounts of insurance necessary to cover the costs of response, clean up, and environmental remediation associated with a catastrophic spill event.

Summary of Research Findings and Conclusions

Upon review of a summary of the Enbridge liability insurance program, the Enbridge 2014 financial statements and government sponsored oil spill response programs, I find and conclude that:

- Enbridge is strictly liable under US environmental laws to pay to clean up an oil spill at one of their lines;
- Between the General Liability insurance coverage that Enbridge purchases with its modified Pollution Exclusion, the current liquid assets of Enbridge including profits and the funds available in government sponsored oil spill clean-up funds, there are sufficient liquid assets and other financial resources available in 2015 to fund the remediation of a Maximum Probable Loss (MPL) spill from line 61 in Dane County;
- Enbridge has proven in the past to pay for oil spill clean ups in a responsible manner through a combination of partially recoverable General Liability insurance proceeds and profits from ongoing operations;
- The very healthy financial picture of Enbridge today is not necessarily predictive of the future ability of Enbridge to meet the financial obligations associated with an oil spill over the duration of the Conditional Use Permit;
- Enbridge Energy Partners is only partially insured in both “Limits of Liability” and the scope of the insurance coverage for a known potential magnitude oil spill arising from one of their pipe lines;
- The $700 million of General Liability insurance coverage that Enbridge currently purchases is less than the known loss cost of the $1.2 billion Enbridge oil spill in 2010 on Line 6B in Michigan;
- Enbridge purchases a General Liability insurance policy which contains a pollution exclusion and defined exceptions to the pollution exclusion for spills which meet certain time element requirements;
- There is ongoing insurance coverage litigation associated with the Enbridge Line 6B spill in 2010 that highlights the insurance coverage ambiguity inherent in a General Liability insurance policy containing a Pollution Exclusion exceptions to the exclusion instead of genuine Pollution insurance or more accurately Environmental Impairment Insurance;
- Controversy over these missing coverages in the General Liability insurance policies currently purchased by Enbridge lie at the core of the Line 6B insurance coverage litigation involving $103 in unrecovered insurance proceeds for the Line 6 B spill;
- Subject to the Pollution Exclusion, the Enbridge General Liability insurance policies insure “Property Damages” and do not include specific insurance coverages for clean-up costs, restoration costs and natural resources damages normally associated with an oil spill;
- Enbridge does not currently purchase Environmental Impairment Liability (EIL) insurance on Line 61. In contrast to the General Liability insurance policies which only apply to liability arising from “Property Damage”, EIL insurance policies contain specific insurance coverage for “Clean-up Costs”, “Restoration Costs” and “Natural Resources Damages” associated with an oil spill.

Because the proposed conditional use is of unlimited duration, risk factors which may be encountered decades into the future need to be incorporated into the permitting process today. The county may not be able to add changes to the permit related to risk management issues in the future.
These future risk factors could include;

- The potential (likely) down turn in the use of fossil fuels over time;

- Reduced cash flow and profitability for Enbridge as a result of a general down turn in the throughput of crude oil in pipelines;
- A general down turn in their business would lead to the reduced ability of Enbridge to maintain robust safety and loss control protocols and to upgrade their pipelines over time;
- Over time, the aging pipe line systems would become more prone to spills, and;
- In the above scenario, Enbridge may not have the liquid assets that they have today to pay for a significant spill at the same time they are more likely to have a spill due to aging infrastructure.

Recommendations

In consideration of my research findings and conclusions, and based upon my 30 plus years of experience in the insurance and risk management profession I recommend;

- That Enbridge agree to indemnify and hold harmless Dane County for pollution losses Per the terms as outlined in Enbridge's proposal titled "CONDITIONAL USE PERMIT ("CUP") CONDITIONS";
- That Enbridge procures and maintains liability insurance, including Environmental Impairment Liability insurance, making Dane County an Additional Insured to a level equal to 10% of the Line 6 B loss costs, $125 000,000;
- As part of this overall liability insurance requirement, Enbridge should purchase $25,000,000 of EIL insurance on the proposed pumping station in Dane County
- Technical insurance specifications for General Liability Insurance and Environmental Impairment Liability insurance appear in Appendix A.

There are compelling reasons for requiring Enbridge to obtain environmental insurance as a condition of permit approval. These reasons include;

- Accessing through the insurance underwriting process, an independent and objective evaluation of the environmental risks associated with the Enbridge pumping station in Dane County;
- Back stopping the insurance coverage problems which can arise when a General Liability insurance policy containing a "Pollution" exclusion is relied upon to insure pollution losses from an oil spill. This problem is evidenced by the fact that Enbridge is currently involved in litigation over $103,000,000 in unrecovered General Liability insurance from the 2010 spill on Line 6B. Some lawsuits over the meaning and effect of pollution exclusions in General Liability insurance policies can take 20 years or more to resolve in the courts. Genuine Environmental Impairment Liability insurance is much more reliable than General Liability insurance to pay for pollution losses.

With the exception of the recommended EIL insurance, I believe these insurance recommendations are identical to those previously proffered by Enbridge. The recommendations will not create an undue burden on Enbridge, as the total amount of required insurance on the pumping station would be set at approximately 1/10 the cost of the 2010 Enbridge spill on Line 6B in Michigan which to date has cost $1.2 Billion.

Overview of Risk Management Considerations

Liability insurance as a risk management tool

Insurance is the de facto risk governance mechanism used by parties to gauge the risks of certain endeavors in commerce. A common example of this concept in practice is a banker requiring a borrower to maintain fire insurance on a building the banker is lending money on. By requiring fire insurance on the building the banker does not need to evaluate the relative riskiness of the building being damaged by the fire, the insurance underwriter has already made that determination in the insurance premium charged to insure the building.

If the risk of a fire on the building is low, the insurance premium will be low in relative terms. If the risk is high, the insurance premium for fire insurance will be high. If the risk of fire is so high that it makes the building uninsurable in the informed perspective of the insurance underwriter, the banker will not make the loan. By simply requiring fire insurance the banker accesses the knowledge base of the insurance industry on the relative risk of fires specifically on the building the loan will be made on. As an added benefit, if there is a fire, there will be insurance coverage to pay for the loss. The lender does not need to know anything about fire hazards to manage the fire risk on the building. A simple go or no go on the lending decision relative to the risk that the building will have a fire can be based on the ability of the borrower to obtain fire insurance. Requiring insurance on the building is all the lender has to do to harness the collective wisdom of thousands of fire risk management practitioners in the insurance industry.

In a similar fashion to the banker accessing the insurance industry's vast expertise in fire risks simply by requiring fire insurance on the buildings they lend on, Dane County can harness the knowledge of the insurance underwriting community on the spill risks of pipelines simply by requiring a relatively small amount of EIL insurance on the pumping station.

I am recommending that minimum amounts of liability insurance be maintained by Enbridge over the life of the CUP. Insurance has been utilized in commerce for more than 400 years. Insurance is the one financial mechanism that can be counted on to endure for decades into the future. Insurance is a dynamic financial tool that is able to adapt to new information on risks over time. Simply by requiring insurance be maintained on the pumping station the global knowledge base in the insurance industry on the relevant risks of tar sands oil pumping stations will be accessed by the stakeholders in the pumping station on an annual basis.

Determining the risk - Maximum Probable Loss

It is not the scope of this report to determine the likely costs associated with an oil spill from Line 61 in Dane County, nor am I qualified to make such a determination. However, to accomplish the goals of this report an objective measure of the potential costs resulting from a spill from Line 61 in the county must be made. As a benchmark for a Maximum Probable Loss scenario I used the $1.2 Billion dollar cost already incurred by Enbridge for a spill in 2010 from their Line 6B in Michigan. The spill into a feeder creek at a time of high water ultimately impacted the Kalamazoo River. $1.2 billion is a reasonable Maximum Probable Loss bench mark because the Line 6B spill event actually happened in recent history and it occurred on an Enbridge pipe line in a state with an environment very similar to Wisconsin's. The Enbridge Line 6B spill was the most expensive land based oil spill on record.

Due to the geography of the pumping station in Dane county I have conservatively assumed that the expected loss potential for a spill at the proposed Dane county pumping station will be far less than the $1.2 billion Maximum Probable Loss scenario in today's dollars. In fact the costs associated with on land pipe line spills are likely to be a small fraction of $1.2 billion dollars.

Line 61 with increased pumping capacity will have more oil flowing through it than line 6B did. However, Dane county has considerably less risk than other counties along Line 61 because of the relative distance of the Pumping station to population centers or waterways that have a significant flow rate and the addition of a retaining pit at the pumping station designed to capture 1 hour of pipe line flow as a safety measure. It should be noted that safety measures on pipelines do not always operate as intended. The spill on the Enbridge line 6B lasted 17 hours due to human error in spite of the detection and shut off technologies on the 6B line which were designed to kick in within 5 minutes in the event of a spill. Safety measures at the Dane County pumping station cannot eliminate all risk.

My recommended insurance requirements for the CUP at a total of $125,000,000 in limits of liability are only 10% of the Maximum Probable Loss. This is a very conservative estimate designed to make the recommended insurance coverage on the pump station procurable and affordable for Enbridge, while creating a long term risk management and financial backstop for the county which is unrelated to the future profitability of Enbridge. If the Dane County pumping station was closer to a flowing waterway the suggested limits of liability would be much higher based on the empirical evidence regarding the costs to clean up the Kalamazoo River in Michigan after the Enbridge line 6B spill.

Dane County does not have preplanned financial resources in the form of environmental insurance or other loss reserves to independently respond to a spill event from the pipeline or to defend the county from potential liability in the event the county is vicariously liable for its potential a role in a spill event. However, the way the environmental protection laws have been drafted, the County and local government do not presently have a material statutory role in the remediation process of a pipeline spill. Under the current environmental laws and regulations, oil spill clean-up efforts would be led by the State of Wisconsin with oversight from the Federal government. Government officials in WI also enjoy governmental immunity to relatively low amounts when the damages caused by a pipeline spill are considered.

The available monetary resources to pay for a spill event

To evaluate the risk bearing capacity of Enbridge Energy Partners (EEP) I looked at their available cash flow from ongoing operations (projected $960 million in 2015, see Appendix C), their insurance coverage ($700 million of General Liability insurance with a pollution exclusion and a time element pollution release coverage give back), and potential access to government sponsored petroleum spill response programs ($1 billion per spill plus an inconsequential amount from the State of Wisconsin Spill Fund). These items comprise the liquid assets available for Enbridge today to address the costs associated with a spill from Line 61.

I did not consider the overall net worth of Enbridge in the resources availability evaluation for two reasons. First, these assets are not needed today, and secondly, the valuations of companies change a great deal with the passage of time. The salvage value of buried steel pipes in the face of a general oil pipeline industry wide decline in future decades is highly speculative.

In total there are over $2 Billion dollars in short term funds available today to respond to a spill from Line 61. This amount far exceeds the expected cost of spill in Dane county.

However, this ability to pay for an oil spill through these resources could deteriorate over the life of the proposed conditional use. Profits and access to insurance vary year to year. Spill funds are subject to politics and may not endure over time. For example, the state of Wisconsin is in the process of dismantling its government-sponsored spill program for fertilizer spills in the state. Over a longer time horizon, even federal funds from oil spills may be dismantled. Although access to insurance is not guaranteed over time, insurance does and should play a role in the overall risk management strategy of the stakeholders. The inability to procure insurance is, in itself, a risk management tool. Access to insurance operates as the canary in the coal mine to provide early warning of unusually risky and therefore uninsurable endeavors in commerce to stakeholders in those endeavors.

Future risk factors

A reduction in demand for fossil fuels to address the threat of climate change would change the fundamental business of Enbridge. The core business of Enbridge is essentially to transport fossil fuels through pipelines to processing facilities and markets.

The precipitous decline of the coal industry in the US is a prime example that illustrates this point. Despite the fact that coal has remained unchanged for centuries and powered the industrial revolution for over 100 years, the coal industry has seen over 70% of its valuation evaporate in just 5 years, driven to a great extent over environmental concerns.

All fossil fuel based companies will be subject to the same economic pressures over time if society moves to reduce the green house foot print of energy sources. This trend is already under way as evidenced by the coal industry. Ultimately, that means burning less fossil fuels, which would logically negatively impact the business of crude oil pipeline companies and their future profits.

These factors could adversely change the overall risk picture of a Pumping Station on Line 61 over the course of time;

- A reduction in the amount of oil products shipped through Enbridge pipelines would reduce cash flow and impair the firm’s ability to pay for uninsured spill expenses out of profits;

- Reduced profitability would limit the firm’s ability to maintain robust safety levels that Enbridge prides its self upon today;

- A reduction in the amount of crude oil which is taxed to fund the Federal oil spill response program would reduce the funding levels for these fail safe contingency plans to pay for oil spill clean ups;

- Changes in the global insurance market place and/or the claims experience of Enbridge in particular could impair the firm’s ability to purchase liability insurance to pay for the costs associated with a spill in the future;

- The current and renewal GL insurance policies purchased by Enbridge have the same wording that one of their former insurance companies in the 2010 policy year is using to deny a

$103,000,000 claim made by Enbridge for pollution clean-up costs arising from Line 6B spill in 2010. This insurance coverage dispute is currently being litigated. Lawsuits involving Pollution Exclusions can take decades to resolve. An adverse judgment in this case pertaining to how General Liability insurance policies respond to pollution losses could significantly impair the usefulness of the Enbridge General Liability insurance for future spill events.

- A judge in Alberta, London or New York ruling in insurance coverage litigation over contamination events and pollution exclusions, in a case totally unrelated to Enbridge or even to pipelines specifically, could significantly reduce the insurance available to Enbridge simply by establishing case law precedence that certain environmental damages are not insured by GL policies.

All of these risk factors have the ability to dramatically alter the ability of Enbridge to pay for an oil spill over the extended duration of the proposed conditional use.

As a partial hedge to these changing factors I recommend that the Conditional Use Permit contain insurance requirements for General Liability Insurance and Environmental Impairment Insurance on the pumping station.

Summary and analysis of the current Enbridge general liability insurance program

In lieu of sending over 40+ insurance policies which make up the Enbridge General Liability insurance program, Enbridge sent their senior insurance manager Selina Lim, accompanied by Aaron Madsen of Enbridge and attorney Jeffery Vercauteren of Wythe, Hirschboeck Dudek, S.C. to the American Risk Management Resources Network, LLC offices in Middleton for a meeting with me on March 18th. Ms. Lim came prepared with a summary of their insurance program which included descriptions and references to the items I had requested for the insurance review. We discussed the summarized parameters of the Enbridge General Liability insurance program from her prepared documents.

Enbridge declined to provide the actual insurance policies (42 of them in total) to me for review, claiming that the documents contain trade secrets. Nonetheless, I found their summary of their insurance program to be credible.

I did not read any of the actual liability insurance policies. This amount of detail was not necessary to evaluate the insurance coverage parameters of concern in the Enbridge liability insurance program for a number of reasons, including;

1. Enbridge has a professional insurance manager with more than 12 years of experience and Enbridge utilizes the largest insurance brokerage firm in the world to negotiate their insurance policies. Competent insurance practitioners would purchase insurance exactly as described in the summary documents. In fact, it would be very difficult for Enbridge to do otherwise due to constraints in the insurance market place.

2. The Enbridge General Liability insurance coverage is of the type most commonly used on large companies involved in the oil and gas business. The primary insurance policy is written by a Mutual Insurance company where the policy holders actually own the insurance company. The primary insurance company has a reputation for being liberal with claims payments- a fact that may have created a claims payment problem on a past loss for Enbridge, which is further discussed below. There were no unusual restrictive terms revealed by the insurance manager relative to the pumping station in Dane County, nor would I expect there to be any.

3. The $700,000,000 limits of insurance purchased by Enbridge was confirmed by a certificate of insurance prepared by their insurance broker and is also mentioned in the financial documents from 2014 filed with the SEC.

4. The current insurance policies will expire on May 1st and new insurance policies will be purchased. Where the current insurance policies are a gauge on what insurance Enbridge may have in the future, there are no guarantees that Enbridge will be able to maintain these high levels of insurance in the future. (The recommended insurance levels anticipate this contingency.)

5. It was represented in the March 18th 2015 meeting that Enbridge would renew their insurance on May 1st. It served little purpose to closely review insurance policies that would expire in a few weeks. This highlights the importance of taking a long term view when considering the placement of any insurance conditions on the CUP application.

6. The current Enbridge insurance coverage is largely irrelevant in any decision making of Dane County regarding a long term Conditional Use Permit. Almost all insurance policies only insure for 1 year and must be renewed annually. The insurance market place changes over time and can be subject to considerable variation year to year. Knowing what the insurance coverage is today is not necessarily predictive of what it will be even 2 years from today.

The base General Liability insurance policy that Enbridge purchases follows the usual and customary liability insurance coverage purchased by large companies in the energy sector. The lead insurance company in the Enbridge liability insurance program is AEGIS. AEGIS is a mutual insurance company which is owned by its policy holders. AEGIS is the largest insurer in the energy sector. The other 41 insurance companies "follow form" to the AEGIS base insurance policy language. In essence these "excess" carriers provide their limits of insurance capacity in "Layers" with each layer of insurance mirroring the insurance coverage provided by the primary insurance policy.

In this common structure of building claims paying capacity, the terms of the coverage in the excess layers are determined by the AEGIS primary insurance policy. Therefore, by knowing what the primary insurance policy says, we know what the coverage provided by the Excess insurance policies is as well. This rule holds true as long as no additional exclusions are added to any of the Excess insurance policies in the tower. It was represented by the Enbridge insurance manager that all layers of coverage in their insurance program follow the base AEGIS policy form. This advice is credible because it follows the usual custom and practice in the insurance business.

The current Enbridge primary General Liability policy insures for liability claims arising from;

a. Bodily Injury,
b. Property Damage defined as physical injury to tangible property,
c. Personal injury including libel and slander,
d. In addition to these coverages for claims, the policy insures Defense Costs.

The key coverages in the General liability insurance policy that would come into play in the event of a spill from a pipe line are claims for Bodily Injury, Property Damage and the costs incurred to Defend those claims.

The Enbridge GL policy, like virtually all General Liability insurance policies sold over the past 40 years, has a pollution exclusion. Introduced into the insurance business in 1970, pollution exclusions are the most litigated words in the history of the insurance. Over the past forty years, the legal profession has sent a lot of kids to college by arguing which part of a pollution exclusion, if any, should apply to a loss involving the contamination of things ranging from sandwiches to Superfund hazardous waste sites.

Insurance coverage litigation over the meaning and intent of a pollution exclusion can take decades to sort out in the courts once a claim is denied by the insurance company and the insured sues for coverage under the insurance policy. One prime example of litigation over a pollution exclusion in General Liability insurance policies involved the City of Edgerton, Wisconsin and a Superfund hazardous waste site. The insurance coverage litigation over the meaning and effect of pollution exclusions in the General Liability insurance policies purchased by the city spanned decades in Wisconsin courts. In that case, one of the troublesome clauses was the use of the term "Sudden and Accidental" as an exception to the pollution exclusions in various policy years.

Over decades, teams of lawyers working in hundreds of similar insurance coverage litigation cases were unable to decisively conclude that a sudden pollution even must mean a quick pollution event. To eliminate ambiguity surrounding the term, in 1986 the word “sudden” was dropped from common use as part of the standard exception to Pollution exclusions, in Commercial General Liability insurance policies.

“Sudden and accidental pollution liability” is what Enbridge shows for insurance coverage in their financial statements today. However, the pollution exclusion exemption in the Enbridge policy is not limited to sudden or quick events. A Property Damage or Bodily Injury claim arising from a pollution event that begins and is discovered within 30 days and is reported to the insurance company within 90 days is not excluded by the Pollution Exclusion in the primary Enbridge General Liability insurance policy. Hence the words “sudden and accidental” carry no weight in the current pollution exclusion. A more accurate term to describe the limited coverage for pollution events within the current General liability insurance policy is “Time Element Pollution” coverage.

The “sudden and accidental pollution liability coverage” that Enbridge has today on the General Liability insurance policy is different than the General Liability insurance policies the City of Edgerton had in place during the time the Superfund site was slowly leaching hazardous waste into the ground. However, the reliability of covering a pollution loss through a pollution exclusion is no less complex as evidenced by the $103,000,000 in unrecoverable General Liability insurance as a result of the Enbridge Line 6B spill.

Taking all of this history into account, it is my professional opinion that the county should avoid being completely dependent upon a General Liability Insurance policy containing a Pollution Exclusion as a financial back stop for an oil spill.

How the current Enbridge General Liability insurance policy treats pipeline spills

In the event of a pipe line spill of tar sands oil or other petroleum product, the pollution exclusion on the Enbridge General Liability policy will come into play. The pollution exclusion may not operate to eliminate the insurance coverage for an oil spill, but the exclusion will be one of the determining factors under consideration by the insurance company in their decision to pay a claim or not.

As evidenced by the insurance coverage litigation on the Line 6B spill, insurance companies are not always in harmony on how pollution exclusions should operate. Even insurance companies participating in the same insurance placement can be in disagreement over pollution exclusions.

The pollution exclusion in the Enbridge General Liability insurance applies to all claims arising from the emission, discharge, release, or escape of “Pollutants”. In essence a “Pollution exclusion” eliminates the coverage in the insurance policy for Bodily Injury and Property Damage liability claims if the proximate cause of the loss is the release or escape of “Pollutants”. The damages caused by an oil spill will definitely fall within multiple parameters of a pollution exclusion.

“Pollutants” is a defined word in the insurance policy which essentially boils down to “contaminates”. If a material can contaminate something it can be a pollutant in an insurance policy. In Wisconsin for example, in the Landshire foods case which went to court over the effect of a pollution exclusion, sandwiches contaminated with bacteria have been denied insurance coverage at the appellate court level because bacteria contamination was deemed by the court to be a “pollutant”.

Although the Enbridge insurance policy is purchased in Canada and Wisconsin laws would not apply to any insurance coverage disputes, if sandwiches can be a “Pollutant” in an insurance policy, tar sand oils in a wetland or on farm field would certainly fall under the definition of an excluded “pollutant” in the event of a pipe line spill.

Sudden and Accidental Pollution Insurance?

As Highlighted in Appendix C, why does Enbridge represent that they have sudden and accidental pollution liability insurance when their only liability insurance on Line 61 is a General Liability insurance policy which contains a pollution exclusion? The topic itself confuses most people. The bulk of the answer can be attributed to marketing hype originating from the sellers of general liability insurance policies using insurance slang dating back to the 1970’s. General Liability insurance policies have not used the terms “sudden and accidental” to define an exception to the pollution exclusion since the 1980’s.

Enbridge is not alone in its use of the term sudden and accidental pollution liability coverage, it is commonly used in the oil and gas business to describe a GL policy with an exception to the pollution exclusion for contamination events happening within certain time frames. There is an exception to the pollution exclusion in the Enbridge General Liability insurance policy for pollution losses that happen in certain time frames. By excluding the exclusion for a certain set of circumstances, a double negative creates positive insurance coverage for contamination events that fit the parameters of the exception to the exclusion.

Technically, General Liability insurance policy with remnant coverage under a pollution exclusion and Pollution Insurance should not be confused; genuine pollution insurance, which is more accurately referred to as Environmental Impairment insurance, has specified coverages that are not specifically provided in General liability insurance policies. Another distinguishing factor in genuine pollution insurance is that the coverage only applies to losses caused by pollution events.

There was a point in time where the statement “we have sudden and accident pollution coverage” on a General Liability policy made more sense than it does today. From 1970 through 1986, General Liability insurance policies had exceptions to the pollution exclusion for sudden and accidental releases of “Pollutants”. In those years, pollution exclusions commonly said that the pollution exclusion in the General Liability policy would not apply if the dispersal, release or escape of pollutants that caused the insured damages was sudden and accidental. The words sudden and accidental were actually incorporated into the insurance industry standard pollution exclusion in those years. The problem was “sudden” was an undefined term in the GL policy and insurance companies were stuck with paying for claims at Superfund Hazardous waste sites where the actual pollution went on for decades.

To clarify the intent of pollution exclusions the words sudden and accidental were eliminated from common use in pollution exclusions in 1986. Today when there is an exception to a pollution exclusion in a General Liability insurance policy, the exception to the exclusion for certain types of pollution events is defined parameters measured in hours or days. Because the coverage give back in the pollution exclusion is driven by specified times, the more accurate way to describe the coverage is “Time Element” pollution coverage.

The Enbridge General Liability insurance policy contains Time Element pollution coverage in the General liability insurance policy. The remnant coverage for a pollution event after the exclusion is not just limited to sudden or quick pollution-- a leak could continue for up to 30 days, and the Pollution exclusion in the General Liability insurance policy would not apply to a loss for Bodily injury or Property Damages.

The Time Element Pollution Exception

The Enbridge General Liability insurance policy contains an exception to the pollution exclusion if the pollution event meets certain “Time Element” parameters.
The Pollution Exclusion in the Enbridge General Liability insurance policy will not apply only if;

1. The pollution release begins and is discovered within 30 days and

2. Enbridge reports the loss to the insurance company within 90 days of discovery.

An obvious gap in Enbridge insurance coverage is if a leak is not detected until the 31st day, in which case the Pollution exclusion on the GL policy would come into play and Enbridge would not have insurance assets to pay for a spill. In contrast a good quality EIL policy does not limit the duration of a contamination event in order for the damages arising from pollution taking place during the coverage period of the policy to be insured losses.

The three Levels of Pollution Exclusions in the Enbridge Liability Insurance Policies

There are three exceptions to the remnant Time Element pollution coverage on the Enbridge General Liability insurance policy, the most significant of these exceptions is there is no coverage for Property Damage to the properties owned or leased by Enbridge. In effect how this works is there are 3 negatives in a row in relation to pollution loss involving the pumping station and right of way on the Enbridge GL policy. The Pollution Exclusion, The Time Element Exception to the Pollution Exclusion and then an exception to the Time Element exception that would reapply the pollution exclusion to any Property Damage to the right of way properties that may be affected by a spill. This example illustrates how nebulous insurance coverage can be when exceptions to exclusions are relied upon for insurance coverage on a pollution event as opposed to purchasing genuine EIL insurance which is designed for this purpose.

The Enbridge GL policy is written on an indemnity basis, meaning the insurance companies agree to reimburse Enbridge for losses after Enbridge has paid for them. This is common practice.

The Enbridge liability insurance protection survives the bankruptcy of the insured which is a good feature for Dane county looking decades into the future to formulate a risk management plan.

Differences between General Liability Insurance and genuine Pollution Insurance

For unknown reasons, the terminology Sudden and Accidental Pollution Liability is still used to describe the remnant liability insurance created by the time element exception to the Pollution Exclusion in the General Liability insurance policies commonly purchased by oil and gas companies. Describing an insurance policy that only addresses coverage for pollution events as an exception to a far reaching pollution exclusion is really not “Pollution Insurance”. There are fundamental insurance coverage differences between genuine Pollution Insurance and General Liability insurance which contains an exception to a pollution exclusion. An insurance policy that only addresses coverage for pollution events within the exclusion section of the policy is not genuine pollution Insurance.

A more technically accurate term for “pollution insurance” is Environmental Impairment Liability insurance (EIL) which is sometimes sold under the title Pollution Legal Liability insurance. The sole purpose of EIL insurance is to fill insurance coverage gaps created by the ever present pollution exclusions in property and liability insurance policies. Environmental Impairment Liability insurance has been continuously available in the North America since 1980. The current insurance market capacity for genuine environmental insurance on a pumping station exceeds $100,000,000. That amount of insurance capacity has been available on a newly constructed pipeline pumping station for more than 30 years.

Enbridge does not purchase separate Environmental Impairment Liability insurance. An EIL policy covers Bodily Injury, Property Damages and Defense Costs. The definitions of these terms in EIL policies mirror the definitions commonly used in GL policies. However, the major difference is where a GL policy says there is no coverage for claims arising from pollution, an EIL policy *only* insures claims arising from the release or escape pollution either quickly or over time.

An EIL policy designed specifically to cover claims arising from pollutants provides broader coverage for environmental losses than a GL policy does. A good quality EIL insurance specifically insures Cleanup Costs, Emergency Response Costs, Restoration Costs and Natural Resources Damages within the insuring obligations of the policy. GL polices do not reference these important elements of coverage which will always come into play as a source of damages in a pipeline spill.

Analysis of Enbridge Indemnification and Insurance Proposal to Dane County

Enbridge has offered to indemnify Dane County for any loss the county incurs as a result of the pumping station. Enbridge has also offered to include Dane County as an Additional Insured on the first $100,000,000 of General Liability insurance maintained by Enbridge. Being indemnified by Enbridge is good for Dane County because the indemnity is first dollar protection and makes Dane county eligible to be an Additional Insured on the Enbridge General Liability insurance policy.

Being an "Additional Insured" on the Enbridge General Liability policy is a benefit for Dane County. By being named as an "Additional Insured" the Enbridge liability insurance would defend Dane County in the event Enbridge caused damages to a third party and the third party sued Dane County for the county's contributory role in the Enbridge created loss event.

Being added as an Additional Insured under the Enbridge GL policy should not be confused with being added as a Named Insured to an insurance policy. An Additional Insured cannot make a direct claim for clean-up expenses associated with an oil spill under the General Liability policy. The Additional Insured could make a claim against the Named Insured in which case the named insured may have coverage subject, however, to the effects of the pollution exclusion. But, anyone can make a claim against the Named insured - you do not need to be an Additional Insured to do that.

The main advantage to the county of being an Additional Insured on the Enbridge GL policy is access to Defense Cost insurance coverage and in the event Dane County is held liable for their contributory negligence in a covered GL claim for Enbridge, the Enbridge liability insurance would indemnify Dane County for its stake in that loss. A key point to keep in mind is the breadth of the insurance coverage for the Additional Insured is no broader than the coverage for the named insured with a few possible exceptions unrelated to a pollution loss.

The benefit of the county being an Additional Insured under the Enbridge General Liability insurance assumes that there is no "insured versus insured" exclusion on the Enbridge General Liability insurance policy. If the Enbridge General liability insurance policy contained an "insured vs insured exclusion and the county became an "insured" by being named as an "Additional Insured" if the county made a claim against Enbridge for some reason, the Enbridge insurance policies would not apply to the county claim because one insured is claiming damages from another insured.

The need to avoid an "insured versus insured" exclusion in the Enbridge liability insurance is anticipated in the recommended insurance requirements in Appendix C.

Being an Additional Insured on the Enbridge General Liability insurance policy does not;

- Enable the County to make a direct claims for pollution clean-up under the Enbridge insurance policy;

- Correct for the inherent risk management deficiencies in relying on a General Liability policy to pay for pollution claims as previously discussed.

In reality, Dane County has a very small loss exposure in its zoning role on the pumping station. The county enjoys statutory immunity from liability as a public entity in Wisconsin and is not involved with the operations of the proposed Enbridge pumping station. It is hard to imagine a scenario where Dane County would ever become part of a claim made against Enbridge. But if it ever did happen, being indemnified by Enbridge and being named as an additional insured on the Enbridge insurance policy would be a good thing.

Review of insurance coverage litigation involving the Enbridge Line 6B spill

Because the matter is in active litigation, Enbridge could not provide the requested details on the $103,000,000 insurance coverage case.

However, I discussed the matter in broad terms with the insurance manager of Enbridge in our face to face meeting. In essence there are two central issues in the Line 6B insurance coverage litigation that relate to Dane County prospectively:

1. The insurance policy language that is in dispute over $103,000,000 in unpaid claims under the Enbridge General Liability insurance policy is unchanged today from the insurance policy language in effect during the 2010 policy year.

2. The insurance company is disputing whether the costs form the Line 6B spill is covered "Property Damage" in a General Liability insurance policy.

One common point of contention in insurance coverage litigation involving pollution claims under General Liability insurance policies over the past 30 years is whether a clean-up order from the government constitutes a claim for "Property Damage" under the definition that term in the GL policy.

Because General Liability insurance policies only insure Property Damages, these insurance policies are inherently deficient in their coverage for government ordered Clean-up costs, Natural Resource Damages and Restoration Costs. This is the major motivation behind my recommendation that the Line 61 pumping station be insured under an environmental insurance policy. A genuine EIL policy specifically insures Clean-Up Costs, Natural Resources Damages and Restoration Costs in addition to Bodily Injury and Property Damage Liability.

Of particular significance in this matter, the insurance companies below and above this $103,000,000 layer paid the Line 6B claim which illustrates how unreliable exceptions to pollution exclusions can be to fund pollution losses.

In our meeting it was revealed that the insurance company that they are in insurance coverage litigation over regarding the Line 6B spill is no longer a participant in the Enbridge insurance program. This was to be expected.

Considering these represented facts there was no reason to evaluate the insurance coverage in effect in 2010 versus the coverage in effect today. I was told that the insurance policy language is essentially unchanged from 2010 to today. Which means the same arguments presented by the insurance company that is refusing to pay Enbridge's claim for $103 million could potentially be presented by another insurance company in the future too deny a claim arising from a pipeline spill.

The inherent danger in relying on exceptions to pollution exclusions to pay for pollution losses

The coverage provided by the Enbridge General Liability insurance for pollution damages could change overnight as determined by legal matters completely outside of the control of Enbridge or their insurance companies.

For example on December 30, 2014 the Wisconsin Supreme court determined that manure and nitrates in ground water as a result of farming operations were excluded by the Pollution Exclusion in General Liability insurance policies. Prior to this decision, the precedent case law in WI was that manure was a "product" and there for not excluded as a "pollutant" under the Pollution exclusion in General Liability insurance policies commonly sold to farms. As a result of that Wisconsin Supreme Court decision on the insurance purchased by one farm, on December 31st 41,000 farms in Wisconsin were left clearly uninsured under the General Liability insurance policies for contamination claims arising from manure spreading operations.

In previous decades under various exceptions to Pollution Exclusions in the liability insurance policies sold to farms, many farmers and their insurance agents believed they had "sudden and accidental" pollution insurance as part of their General Liability insurance policy. The belief survived even though the reference to sudden and accidental pollution events was removed from the General Liability insurance policies sold to farms in 1986. In clearing up the confusion over the effects of the Pollution Exclusion, one Wisconsin Supreme Court Justice commented in the December 30th ruling that a common exception to the Pollution Exclusion for certain defined contamination events on the farmers GL policy was "useless" insurance, much to the surprise of the 41,000 farmers and their insurance agents.

Although Wisconsin case law on pollution exclusions should not have a bearing on an insurance policy purchased in Canada, the current Enbridge insurance coverage litigation over $103,000,000 of GL insurance containing a pollution exclusion on the Line 6B spill in 2010 and the proper operation of a Pollution Exclusion in that policy parallels the Wisconsin farm situation. Even if Enbridge prevails in the collection of the $103,000,000 in liability insurance, another litigated insurance coverage case in Canada, New York or London could eliminate the GL coverage for a pollution event for Enbridge and everyone else in that legal jurisdiction who buys insurance dependent upon an exception to a pollution exclusions containing the same language.

The insurance coverage litigation over $103,000,000 of General liability insurance providing Time Element Pollution coverage for only Property Damage illustrates the need for back up Environmental Impairment Liability insurance on the Line 61 environmental loss exposures in Dane County.

The Enbridge general liability insurance policy is missing essential coverages to clearly insure an oil spill event

The track record of the Enbridge General Liability insurance program is that on Line 6 B, all of the insurance companies with the exception of just one company, paid for the costs of clean up to the maximum limits of liability on the insurance policies they sold to Enbridge. However, for the reasons stated above, this could change over time with the development of insurance coverage case law which could be adverse to Enbridge.

The Enbridge General Liability insurance coverage with its Pollution Exclusion and the exceptions to the exclusion if a spill is discovered within 30 days from the start of the spill is missing separately defined coverage parts for:

- Clean-up Costs
- Natural Resource Damages
- Emergency Response Costs
- Restoration Costs

- Coverage for spills longer than 30 days

All of these insurance coverage elements are provided in a good quality Environmental Impairment Liability insurance policy. Which is why I recommend the purchase of EIL coverage on the pumping station and, optionally, the pipe line in Dane County.

The availability of government-backed oil spill funds

There are actually two sources of Government funded spill response programs for oil spills;

1. The Wisconsin Spills Law which accesses general purpose revenues from the state of Wisconsin with an annual allocation of $3.5 million per year, funds are accessed by the WI DNR and;

2. The Oil Pollution Act with a current balance exceeding over $4 billion in the Oil Spill Liability Trust Fund and taxes of more than $300,000,000 annually. Funds for clean-up costs and other damages are accessed by the Federal Government or the State.

There is no apparent government source of funds for a county to respond to a spill event. However, environmental laws do not create a obligation for counties to respond to pollution events the county did not cause.

Considering the magnitude of the Enbridge Maximum Probable Loss potential, by far the more significant and therefore relevant of these two funds is the Federal Oil Spill Liability Trust fund.

After the crude oil spill in Alaska involving the Exon Valdez, The Oil Pollution Act of 1990 was passed and a federally sponsored fund was created for federal and state trustees to respond to the clean-up costs and victim compensation arising from future oil spills, including spills from pipe lines. The Oil Pollution Act does not anticipate a role for local governments in spill response.

The Oil Spill Liability Trust Fund (OSLTF) will pay for costs incurred from tar sands oil spills arising from pipelines. The spill must only threaten a waterway to be eligible for the fund. Threating a water way will be a certainty on any spill from Line 61 in Dane County.

In essence, the idea of the spill fund is to assure that the federal or state authorities (not the county) have the resources necessary to pay for an oil spill.

Recoverable cost from the Oil Spill Liability Trust Fund include:

- Removal Costs
- Real or Personal Damages
- Loss of Profits and/or Income
- Loss of subsistence
- Lost government revenue
- Increase public services
- Up to $500 million in Natural resource damages compensation.

The trust fund does not distinguish between a sudden or gradual spill events.
The funds also survive the bankruptcy of a responsible party who causes a spill.

The Oil Spill Liability Trust Fund is financed by taxes on certain types of unrefined oils, plus fines and penalties imposed by the government on parties responsible for spills. In something peculiar to the definition of the oil that is taxed, tar sands oil is not paying into the fund through taxes.

The trust fund received a recent major influx of money, over $3 billion, from the fines assessed against BP in the Deep Water Horizon oil spill in the Gulf of Mexico.

Payments from the fund are subject to a limit of $1 Billion per incident. “Incident” means any occurrence or series of occurrences having the same origin, involving one or more vessels, facilities, or any combination thereof, resulting in the discharge or substantial threat of discharge of oil.

The $4 billion dollar fund in 2015 back-stops the responsible party’s ability to fund an oil spill clean-up either through cash or insurance recoveries. The parties responsible for the spill must fully reimburse the Oil Spill Liability Trust Fund for any fund monies utilized by the responders to a spill. The funds are still available to responders in the event of the bankruptcy of the responsible party.

Because of the $1 billion cap per incident there would need to be four un-reimbursable spills of at least a billion dollars each before the current funding would be exhausted. A more probable scenario over time would be the political elimination of the fund all together.

The largest on land oil spill in history was the 2010 Enbridge Line 6B spill in Michigan, which has cost Enbridge $1.2 billion to date without the effects of any potential future fines or penalties resulting from the spill. The $4 billion fund subject to its $1billion dollar per incident cap in the short term and foreseeable future has sufficient funding to address all of the costs associated with a spill at a pump station in Dane county even if Enbridge has no cash or insurance available to reimburse the fund.

However, there is no way to reliably predict the status of future funding of the Oil Spill Liability Trust Fund over the term of a conditional use permit.

For More information on the Oil Pollution Act, tar sand oil, taxes and the Oil Spill Liability Trust Fund see Appendix B.

Insurance Recommendations and Conclusions

A long term view on insurance is needed

The current Enbridge Liability insurance program is not very relevant to the actual risk involved with the construction and operation of a pumping station in Dane County decades into the future. Any risk management strategies used by the county to address potential environmental impacts under the Conditional Use Permit need to anticipate changes in a number of variables, including the future economic viability of a pipe line carrying tar sands oil and changes in the insurance market place taking place over that time horizon. Insurance has been around for over 400 years, it is a good bet that insurance will exist as a financial product for the entire period the CUP is in place. Therefore insurance requirements as a condition for the CUP are highly recommended.

Specified insurances as part of a Conditional Use Permit create numerous risk management advantages to Dane County.

- Insurance can adapt to new information on risk over time.
- The limits of insurance can be adapted to future loss costs due to the effects of inflation.
- Insurance underwriters provide an objective 3rd party evaluation of a risk.
- Insurance underwriters have access to an extremely efficient global knowledge sharing network of hazards.
- By accessing one specialized insurance underwriter the collective best practices of multiple companies in the same business, in this case pipe lines, can be utilized for advance loss control.
- By requiring insurance for a particular activity there is no need for the stakeholders in the activity to have expertise in risk evaluation or risk management. The private insurance industry will efficiently take all risk factors into account when offering to insure the activity. By simply requiring robust insurance, the stakeholders access the collective risk management knowledge of thousands of people working in the insurance business in North America alone. A firm like Enbridge would access the global insurance market place. In which case all of the knowledge and experience held by the people that work with insuring pipe lines on a global scale would be brought to bear on a pumping station in Dane County.

Recommended types and amounts of liability insurance

I recommend that Enbridge procure and maintain the following liability insurance policies over the course of the permit duration:

- $100,000,000 limits in General Liability insurance with a time element exception to the pollution exclusion (currently in place), and;
- Environmental Impairment Liability insurance with a $25,000,000 limit

At a limit of $700 million the Enbridge General Liability insurance program, which insures more than 15,000 miles of pipe lines, does not have enough limits to pay for a known magnitude $1.2 Billion loss exposure. Purchasing insurance equal to 100% of the known loss exposure is common practice in insurance. However, it is very possible that Enbridge is already purchasing all of the General Liability insurance capacity available in the world for their operations. Therefore, I do not recommend the purchase of higher GL limits for the operation of the Line 61 Pumping Station.

I conservatively set the liability insurance recommendations at 1/10 the cost of a previous Enbridge spill on Line 6B in Michigan. Being 90% under a known loss event, with many factors being the same between the Enbridge pipe lines in MI and WI, is a very modest level of insurance to ask for.

To supplement the General Liability insurance coverage maintained by Enbridge, I recommend that Enbridge purchase an Environmental Impairment Liability insurance policy on the pumping station in Dane County with a limit of liability of $25,000,000 per loss. If more than one location is insured under this policy, the policy must have an annual Aggregate Limit of Liability of $50,000,000. The Annual Aggregate provision would come into effect if more than one loss is reported under the policy over the policy term. However, the most that would be paid by the policy for a single loss is $25,000,000.

This EIL insurance policy should provide Excess coverage and "Difference In Conditions Coverage" (DIC) for environmental damages over the primary General Liability insurance currently maintained by Enbridge. DIC coverage fills in coverage gaps that the General Liability policy may have for pollution losses.

It would be acceptable if this EIL insurance covered all of line 61 in Dane County. Although the existing pipe line is not part of the permit application, expanding the insurance coverage to include the existing pipeline in Dane County should have no effect on the premium charged for the EIL insurance policy on the pumping station, and the additional insured locations would benefit both Enbridge and Dane County.

Three risk management objectives in these recommendations

There are three risk management objectives in my recommendation that Enbridge maintain a small amount of environmental insurance on the pumping station in Dane County:

1. Back stop the primary Enbridge insurance program with broader insuring obligations than a General Liability insurance policy which only addresses Property Damage and then only if certain Time Elements are met to get around the Total Pollution exclusion in that insurance policy;

2. Access the independent risk evaluation capability of an environmental insurance underwriter over the life of the proposed conditional use;

3. Create a relatively small genuine environmental insurance to backstop potentially unrecoverable General Liability Insurance, the potential inability of Enbridge to pay for a spill clean-up out of profits in the future, or deficiencies in government sponsored oil spill funds.

The recommended $125,000,000 of liability insurance, which includes $25,000,000 of genuine environmental impairment insurance, is readily available in the insurance market place today, and will be available in the foreseeable future. In the event of an oil spill at the pumping station, the county, the state, the federal government and affected third parties could all make claims against Enbridge. The liability insurance policies do survive as an asset in the event Enbridge is bankrupt, so in that sense, the policies could have some value to the county as an asset of last resort to recover damages that Enbridge has caused.

A detailed insurance specification for General Liability and Environmental Insurance on the Line 61 pump station is shown in Appendix A.

Appendix A: Recommended Liability Insurance Specifications

General Liability Insurance
Commercial General Liability Insurance or the equivalent
Insuring the operations and completed operations of the line 61 pumping station in Dane county.
Coverage shall be provided for Bodily Injury Liability, Property Damage Liability and Defense costs.

The pollution exclusion in this policy shall not apply to the escape or release of pollutants or contaminates that begin and are discovered in no less than 14 days and are reported to the insurer within no less than 30 days.

Insurance must be provided by an insurer with an A.M. Bests rating of at least A, XII.

Coverage shall be extended to Dane County as an Additional Insured.
This insurance shall be Primary and Non-contributory to any insurance Dane County may have available.
Any rights of subrogation against Dane County shall be waived.
The policy cannot contain an "Insured vs. Insured" exclusion applying to Dane County as an Additional Insured

The policy shall obligate the insurer to provide 60 days notices of cancellation or nonrenewal to Dane County

Minimum Limit of Liability $100,000,000

Environmental Insurance Specification
Environmental Impairment Liability Insurance, Site Pollution Liability Insurance or the equivalent

Insured Location: The pumping Station on Line 61 in Dane County (optionally the policy may insure the pipe line in Dane County)

Insurance must be provided by an insurer with an A.M. Bests rating of at least A, XII.

Coverages To Be Included:

- On and off site Clean-up expenses
- Damages to Natural Resources
- Emergency response cost to at least $1,000,000
- Bodily Injury Liability
- Property Damage Liability
- Contractual liability naming Dane County as an Additional Insured
- This policy must be Primary and Noncontributory to any insurance Dane County may have access to.
- The policy cannot contain an "Insured vs. Insured" exclusion applying to Dane County as an additional insured.
- This coverage can be excess over other collectable insurance and the deductible or self-insured retention amounts of the underlying insurances
- This policy shall provide difference in conditions coverage excess of the deductible or self-insured retentions in the primary General Liability insurance program.

- This insurance does not need to drop down below the Self Insured Retention amounts on the coverages provided by the Enbridge master insurance program.
- The policy shall obligate the insurer to provide 60 days notices of cancellation or nonrenewal to Dane County.

Limits of liability
$25,000,000 per loss and in $25,000,000 Annual Aggregate for all losses over the course of the policy term.

The pumping station and the pipe line located in Dane County will be considered a single location for the purpose of determining the aggregate limit of liability required.

If said insurance policy insures more than Dane County properties the policy shall have an Annual Aggregate Limit of $50,000,000.

Self-Insured Retention
The maximum self-insured retention on this policy shall be the underlying insurance including the Self Insured retention in the Enbridge Master General Liability insurance program or $1,000,000.

Evidence Of Insurance
Upon request by Dane County, Enbridge shall furnish a certificate of insurance to the county which accurately reflects that the procured insurances fulfill these insurance requirements.

Appendix B: Federal sources of oil spill clean-up cost and victim compensation funding

This reference material is derived from http://www.fas.org/sgp/crs/misc/R43128.pdf
And has been edited for ease of reference in this report.
Oil Sands and the
Oil Spill Liability Trust Fund:
The Definition of "Oil" and
Related Issues for Congress
Jonathan L. Ramseur
Specialist in Environmental Policy
January 22, 2015

"The Oil Spill Liability Trust Fund (OSLTF) provides an immediate source of federal funding to respond to oil spills in a timely manner. Monies from the OSLTF can be used to respond to a wide variety of oil types, including oil sands-derived crude oils.

However, the OSLTF arguably plays a backup role in terms of response funding during many oil spills. The responsible party for an oil spill often provides the primary source of response (i.e., cleanup) funding, and the federal government may recover costs or damages paid from the OSLTF. This was the case with the Enbridge leak in Line 6 B no federal dollars were used Thus, the financial impact to the trust fund could be minimal if the majority of its payments are reimbursed by the responsible parties. Nonetheless, the liability of responsible parties may be limited under certain conditions.
In those situations, the OSLTF could effectively pay—up to a per-incident cap of $1 billion."

Uses of the Fund
"Pursuant to OPA Section 1012, the trust fund may be used for several specific purposes:

- payment of removal costs, including monitoring removal actions, by federal authorities or state officials;

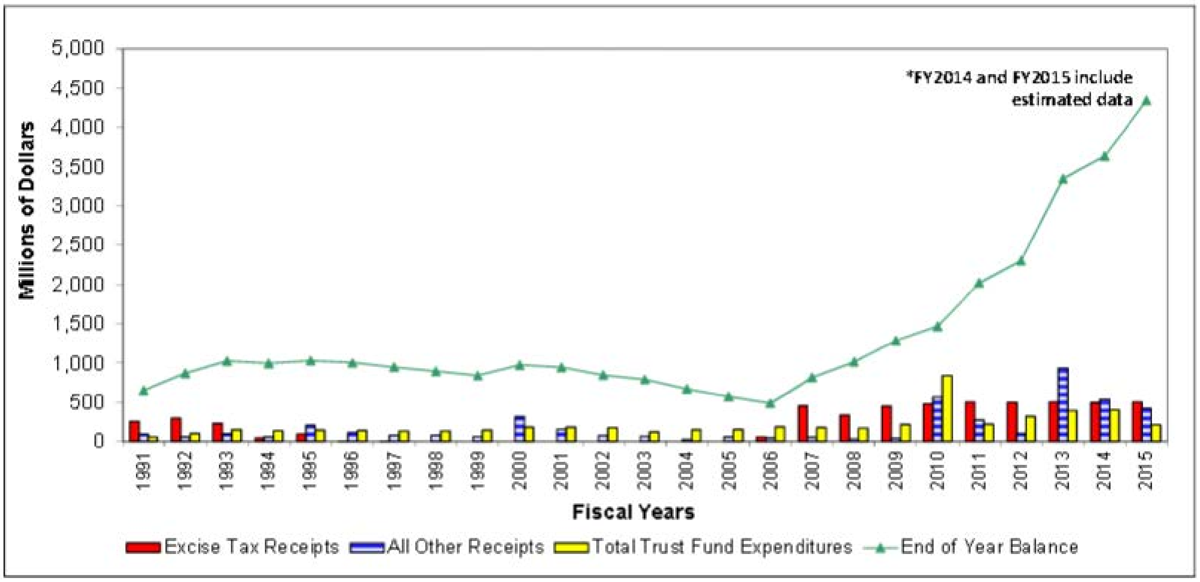
- payment of the costs incurred by the federal and state trustees of natural resources for assessing the injuries to natural resources caused by an oil spill, and developing and implementing the plans to restore or replace the injured natural resources;

- payment of parties' claims for uncompensated removal costs, and for uncompensated damages."

The Oil Spill Liability Trust Fund

Figure 2. Oil Spill Liability Trust Fund

Receipts, Expenditures, and End-of-Year Balances



Source: Prepared by CRS; data from annual Office of Management and Budget, Budget of the United States Government, Appendices.

Notes: The initial gap between the end-of-year balance (line) and the receipts-expenditures columns is due to the FY1991 starting balance of $358 million. The relative increases in "other receipts" in 1995 and 2000 are due to transfers from the Trans-Alaska pipeline fund of $119 million and $182 million, respectively. The increases in expenditures and "other receipts" between 2010 and 2013 are related to the 2010 *Deepwater Horizon* oil spill.

As **Figure 2** indicates, the "other receipts" category has contributed a substantial portion of revenues in recent years, the vast majority stemming from the 2010 *Deepwater Horizon* oil spill. Other receipts include earned interest on the unexpended trust fund balance, fees from fines and penalties, and cost recovery from responsible parties. The trust fund is likely to receive additional revenues related to that incident, particularly from anticipated Clean Water Act civil penalties on BP.

Appendix C: Relevant Enbridge Financial Facts

SEC Filings - Form 10-Q

Enbridge Energy Partners LP filed this form on 5/2/2014

Excerpts taken from the Enbridge 2014 annual report

The Partnership expects adjusted EBITDA for 2015 to increase approximately 12 percent, to between $1.68 billion and $1.78 billion, and expects distributable cash flow for 2015 to increase approximately 15 percent, to be between $900 million to $960 million

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A majority of the costs incurred for the crude oil release for Line 6B are covered by the insurance policy that expired on April 30, 2011, which had an aggregate limit of $650.0 million for pollution liability. Including our remediation spending through March 31, 2014, we have exceeded the limits of coverage under this insurance policy. As of March 31, 2014, we have recorded total insurance recoveries of $547.0 million for the Line 6B crude oil release, out of the $650.0 million aggregate limit. We expect to record receivables for additional amounts we claim for recovery pursuant to our insurance policies during the period that we deem realization of the claim for recovery to be probable.

In March 2013, we and Enbridge filed a lawsuit against the insurers of our remaining $145.0 million coverage, as one particular insurer is disputing our recovery eligibility for costs related to our claim on the Line 6B crude oil release and the other remaining insurers assert that their payment is predicated on the outcome of our recovery with that insurer. We received a partial recovery payment of $42.0 million from the other remaining insurers.

Of the remaining $103.0 million coverage limit, $85.0 million is the subject matter of the lawsuit Enbridge filed in March 2013 against one particular insurer who is disputing our recovery eligibility for costs related to our claim on the Line 6B oil release. The recovery of the remaining $18.0 million is awaiting resolution of this lawsuit. While we believe those costs are eligible for recovery, there can be no assurance that we will prevail in our lawsuit.

We are pursuing recovery of the costs associated with the Line 6A crude oil release from third parties; however, there can be no assurance that any such recovery will be obtained. Additionally, fines and penalties would not be covered under our existing insurance policy.

Enbridge will renew its comprehensive property and liability insurance programs which will be effective May 1, 2014 through April 30, 2015 having a liability aggregate limit of $700.0 million, including sudden and accidental pollution liability. The deductible applicable to oil pollution events will increase to $30 million per event, from the current $10 million. In the unlikely event that multiple insurable incidents occur which exceed coverage limits within the same insurance period, the total insurance coverage will be allocated among the Enbridge entities on an equitable basis based on an insurance allocation agreement the Partnership has entered into with Enbridge, Midcoast Energy Partners, and other Enbridge subsidiaries.

Environmental

Lakehead Line 6B Crude Oil Release

During 2014, our cash flows were affected by the approximate $141.4 million we paid for environmental remediation, restoration and cleanup activities resulting from the crude oil release that occurred in 2010 on Line 6B of our Lakehead system.

In March 2013, we and Enbridge filed a lawsuit against the insurers of our remaining $145.0 million coverage, as one particular insurer is disputing our recovery eligibility for costs related to our claim on the Line 6B crude oil release and the other remaining insurers assert that their payment is predicated on the outcome of our recovery with that insurer. We received a partial recovery payment of $42.0 million from the other remaining insurers during the third quarter 2013 and have since amended our lawsuit, such that it now includes only one carrier. While we believe that our claims for the remaining $103.0 million are covered under the policy, there can be no assurance that we will prevail in this lawsuit.