2050 PATHWAYS: A HANDBOOK

July 2017

2050 PATHWAYS PLATFORM

2050pathways.org

2050 Pathways Platform

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The 2050 Pathways Platform is an initiative that was launched in Marrakech at COP22. The objective of the Platform is to support countries, states, regions, cities and companies seeking to devise long-term, net zero-greenhouse gas, climate-resilient and sustainable development pathways. For further detail on the Platform, please visit the UNFCCC webpage. The 2050 Pathways Platform is supported by the French Ministry of Europe and Foreign Affairs and the European Climate Foundation.

This technical paper presents guidance on how to conduct 2050 pathways analyses. It suggests criteria, principles and building blocks for a successful development of pathways, as well as selected illustrations. It is intended to be read together with: ***Why Develop 2050 Pathways?*** This paper is under the responsibility of the 2050 Pathways Platform secretariat and does not commit the Platform members or its partners. Figures and illustrations including those from the Deep Decarbonization Pathways Project do not represent government positions.

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I. Introduction

The Paris Agreement has set the collective goal to hold the increase in global average temperature to well below 2°C and to pursue efforts to limit the temperature increase to 1.5°C. This will require global peaking of greenhouse gas emissions as soon as possible and a rapid reduction to achieve a balance between anthropogenic emissions and removals by sinks in the second half of the century. A number of countries, regions, cities and companies, including members of the 2050 Pathways Platform, have started charting their long-term low-greenhouse gas development strategies in that spirit. Others are also embarking on this exercise, facing the challenge of an uncertainty-ridden, multi-dimensional quantification exercise combined with the need to generate a long-term pathway, one that reflects a variety of socio-economic objectives and different stakeholders' interests in order to pave the way for robust policy choices.

Mid-century pathways, a response to the Paris Agreement's Article 4.19 call on Parties to elaborate long-term low greenhouse gas development strategies, are an opportunity to explore long-term policy and technology options without the constraints of near-term inertia. The proposed 2050 pathways methodology will nevertheless also help governments and organisations identify important decisions to be taken in the near- to medium-term to deliver on their long-term ambition.

Who should read this handbook?

The primary audience for this handbook is national or local governments developing 2050 pathways as 2050 Pathways Platform members, as well as other entities or experts interested in learning more about the technical aspects and design process of a 2050 pathways study.

What are the goals of this handbook?

Provide guidance for developing 2050 pathways: This handbook is a reference guide that describes "how to develop 2050 pathways" in a way that enables creation of the benefits described in the companion Platform document on "why develop 2050 pathways?" It presents key principles of pathways studies that can be adapted for different circumstances and is not meant as a set of mandatory guidelines. Examples are also presented as illustrations; they do not represent official country or local government positions.

Facilitate communication during pathways development: Transparent communication among Platform members, decision makers, stakeholders and technical teams on the key components of 2050 pathways is essential to positive outcomes. This handbook indicates a general development process to ensure that their input is incorporated into the design and implementation of the technical study.

Enable collaboration on 2050 pathways across Platform members: This handbook provides a common language for describing 2050 pathways in order to support a structured technical dialogue among Platform members that can help to align visions and increase ambition. Pathways studies could vary widely given the diversity of local situations. A common approach to describing analytical methods, assumptions and results can facilitate communication, mutual learning and sharing of best practices among Pathways members and other interested parties.

What is beyond the scope of this handbook?

Governments and private entities thinking about their long-term low-carbon future present a broad variety of situations in terms of size of economy, resources and sectoral diversity, institutional setting, technical capacity, and margin for manoeuvre. The handbook, although it provides questions to help organisations, governments and other entities in the elaboration of their pathways, cannot therefore present a comprehensive coverage of what 2050 pathways may entail. The following considerations are important in that respect:

Different stages in the elaboration of pathway: Some governments can build from existing long-term low-greenhouse gas emission scenarios into a policy discussion with stakeholders. Alternatively, they could be interested in exploring the detailed technical feasibility of sectoral changes coming out of these strategies (Can the region rely on a majority of variable renewable energy? What regulatory and infrastructure changes may be required?). Others may have undertaken analyses for their nationally-determined contributions (NDCs) but have yet to agree and implement appropriate policies or to explore the longer-term implications of these choices. The prominence of the climate agenda in different governments or entities will also vary, affecting how a 2050 pathway study will develop. The guidance provided in this handbook can support pathways development from different starting points but will, of course, need to be adjusted to national circumstances.

No predetermined process for stakeholder engagement: The engagement of stakeholders in a discussion or validation of the pathways will also strongly depend on context, including the institutional setting of the analysis (Who is in charge of the exercise? Who does it need to involve and at what stage? Have similar processes been in place already, e.g. for the elaboration of NDCs or low-emission development strategies – LEDS?) and political economy considerations (Which sectors or actors stand to “win” or “lose” in the low-carbon transition? What has been their stance in this debate? When and how does the national or local government wish to include them in the exercise?).

Accounting for adaptation needs: A number of countries already face serious climate change impacts and pressing adaptation needs (120 countries explicitly refer to adaptation in their NDCs). In some cases, development choices are already constrained by changes in local climate (e.g. irrigated agriculture as droughts become more frequent and rainy seasons shift or the reconstruction of infrastructure in regions exposed to extreme events). The pathways analysis can reflect available national and regional information on adaptation and climate resilience in future scenarios and how they affect mitigation and development strategies. Adaptation is, however, an issue that deserves more specific attention than can be given in the analysis of future greenhouse gas mitigation options; it also necessitates mobilizing different scientific and policy expertise. A dedicated effort will be needed to support countries in the elaboration of appropriate adaptation strategies, as these will be an integral part of their future development choices. The Platform intends to fill this gap in its future work but these aspects could not be reflected appropriately in the present document.

Governments and corporations: Companies will adopt a very different approach to the elaboration of their 2050 pathways, as it will need to combine strategic business considerations, targeted communication with shareholders and other stakeholders, and specific reporting formats. The models used to describe national long-term strategies would also be of limited use in modelling the long-term emissions of companies, whether they are in the primary sector, industry or services. The specificity of corporate actors could not be reflected in this handbook. However, the handbook can be of use for corporate actors' understanding of how the governments of countries where they have operations will elaborate 2050 pathways and how they may want to be engaged in the exercise.

Lastly, the majority of the illustrations and many of the methodological insights presented here are drawn from the Deep Decarbonisation Pathways Project (DDPP). This process that took place before COP 21 and generated a wealth of insights on tested methods as different country teams struggled and progressed on similar issues around building 2050 decarbonisation pathways.[1] This provides a very sound starting point, in particular for organisations that are now embarking on their 2050 pathways.

What are the contents of this handbook?

The handbook has four main sections which describe a common framework for developing 2050 pathways, including general principles, building blocks and engagement strategies, along with examples of how these elements have been

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[1] http://deepdecarbonization.org/countries/. The examples drawn from the Deep Decarbonization Pathways Project do not reflect individual countries' positions on long-term GHG strategies.

applied in different contexts and various resources for supporting pathways development. The sections are briefly described below.

Section II. Common Framework for 2050 Pathways

This section describes a common framework for developing 2050 pathways derived from the experience of pathways studies in different contexts. This framework includes the *criteria* of relevance, clarity, practicality and credibility, some general *principles* of pathways development, and a set of analytical *building blocks*.

Section III. Principles of 2050 Pathways

This section describes principles for developing 2050 pathways: integrating climate mitigation and socio-economic objectives, combining backcasting with an analysis that describes physical transformations, using rigorous methods that are specifically suited to answering clearly defined questions, and embedding the analysis in an engagement and communications strategy. This should be accompanied with a proper scoping of the issue to ensure that methods (models, data) are adequate to solve the identified questions.

Section IV. Building Blocks of 2050 Pathways

This section describes three essential building blocks of 2050 pathways analysis: narratives (qualitative descriptions of 2050 pathways) models (pathways described in quantitative terms) and means of clearly communicating quantitative results (e.g. dashboards). The building blocks work together in a process of iterative development that engages those who lead the pathway process, stakeholders and analysts in close communication, and enables technical communication with external audiences and networks. This facilitates both "horizontal" coordination (pathways for different jurisdictions at the same level, such as cities) and "vertical" coordination (pathways for nested jurisdictions, such as nation-state-city).

Section V. Examples: Applying Common Framework in Different Contexts

This section describes how the common framework is *applied* in different contexts, drawn from the pathways developed by different organizations participating in the 2050 Pathways Platform. Examples include pathways for energy, AFOLU, and/or waste emissions, CO_2 and/or other GHGs, economy-wide and/or individual sectors, national, state and/or city scales, and a wide variety of socio-economic objectives.

II. Common Framework for 2050 Pathways

Criteria, principles, and building blocks. The experience of pathways studies in different contexts provides a common set of principles for the development of 2050 pathways. These principles include the criteria for effective pathways, a general approach to pathways development and the building blocks of the analysis.

The following **criteria** describe what is required for 2050 pathways to be successful, based on past experience:

- *Clarity* is required regarding the objectives of the process, the questions being asked, the methods used to answer those questions and the description of results.
- *Relevance* requires that the pathways are transformational in terms of their impact on emissions, address concerns about societal impacts and are communicated to audiences in terms they understand.
- *Practicality* means that the study is scoped in a manageable way, that results are described in concrete physical terms and that the analysis provides useful guidance for implementation.
- *Credibility* requires that the analysis is robust, that methods used are the right ones to address the questions asked, that analytical tools and data are transparent and that scientific scrutiny is invited and taken seriously.

The following **principles** are proposed as a general approach to 2050 pathways analysis that ensures the criteria of clarity, relevance, practicality and credibility:

- *Socio-economic* (e.g. growth, equality, inclusiveness) and *emissions objectives* are incorporated side by side as integral parts of the analysis.
- *Backcasting* involves starting with the desired end state and working backwards to the present in order to identify necessary conditions for ambitious scenarios.
- Analysis focuses on the *physical transformation*s required to meet long-term emissions and socio-economic goals, taking into account evolutions in technologies and business models.
- Pathways development is embedded in a process that engages stakeholders in the analysis and promotes communications about the findings and related governance, planning and implementation processes.
- The scope of the pathway analysis, i.e. research and policy questions, objectives and boundary conditions should be done in combination with the identification of the analytical toolkit.

The principles of 2050 pathways are embodied in three **building blocks** of the pathways design process:

- Creation of narratives describing possible futures.
- Analysis and modelling of scenarios based on those narratives.
- Use of dashboards for communicating assumptions that underlie the analysis and results in tangible terms for different stakeholders.

The sections that follow describe the application of these principles in more detail, including practical recommendations and lists of questions to be considered before undertaking a 2050 pathways study.

III. Principles of 2050 Pathways

1. Meet both climate mitigation and socio-economic objectives

By making socio-economic goals integral to the analysis, 2050 pathways describe what is required to achieve a low carbon transition while also reaching desired societal outcomes.

Successful 2050 pathways should combine emissions goals with socio-economic objectives, incorporating both in the analysis rather than treating them as independent. Socio-economic objectives will, of course, vary across countries and regions, depending on income levels, local conditions and societal aspirations. In some places, the priority may be economic growth or jobs while, in others, it may be improved health, energy access for the poor or pollution reduction. Resilience to future climate change could also be an essential dimension of the pathway. The ability of the study and supporting modelling tools to credibly reflect some of these dimensions over the long run needs to be clarified early in the process. Complementary analyses could be undertaken in parallel, pending the availability of relevant data, appropriate modelling tools and resources. Whatever the priorities, their integration into the analysis will enhance the relevance of pathways to local concerns and policies.

In general, this means translating socio-economic objectives into quantitative terms. A low-carbon transition takes place within a context of changing macroeconomic conditions, evolving infrastructure, demand for energy services, and activities that produce emissions, all of which can be modelled. When a socio-economic vision is described in concrete terms such as GDP growth, square meters of floor-space per person, passenger-km traveled, or households with access to electricity, these can be made into modelling constraints, along with emissions reduction goals. The resulting pathways show how a low-carbon transition can be achieved whilst also reaching development goals, since these are embedded in the analysis.

For developing countries, achieving development and climate objectives together may require external financial resources and technologies. A 2050 pathway analysis can help specifically identify these needs, including what is additional to business-as-usual GHG-intensive futures. Accomplishing this starts with articulating and quantifying socio-economic goals for specific dates in the future. These can build on existing NDC and LEDs goals, insights from participants in the analysis, official government documents or the Sustainable Development Goals. The metrics used to express the vision should be reported throughout the timeline of the analysis, both as indicators of social progress and as drivers of emissions.

Questions to consider when starting the analysis:

- What socio-economic factors significantly affect emissions outcomes?
- What socio-economic priorities can be adequately reflected in pathways scenarios? (e.g. growth, inclusiveness, access to energy or clean water)?
- What metrics should be used to track progress toward these visions?
- What are the policy goals related to achieving these visions?
- What specific resilience and adaptation issues may be included in the mitigation pathways analysis? Is data available for that purpose?

2. Use backcasting to guide the analysis

2050 pathways are not forecasts but backcasts that establish a 2050 objective and ask what steps are needed to get there. Backcasting helps to indicate transformational decisions and significant barriers.

Backcasting is proposed as an effective method to explore ambitious low-emission strategies: a desirable future is defined quantitatively, in line with a first evaluation of a meaningful contribution to the Paris Agreement goal and the analysis identifies how to get there. The backcasting approach can start with a specific level of emissions and socio-economic development indicators at a specific future date and examine the policy, infrastructure, public choices and investment steps needed today to achieve these outcomes. Pathways are hence not forecasts of the future but rather what-if explorations of possible scenarios.

Insight from backcasting is essential for evaluating the consequences of near-term policies and investments for achieving long-term goals. Though 2050 may seem far away, the operating lifetimes of much of the infrastructure and equipment that produce emissions (power plants, buildings, industrial boilers and heavy duty vehicles) are long compared to the time remaining between now and mid-century. 2050 pathways make the long-term emissions consequences of these decisions explicit. The analysis can highlight policies and investments that reduce emissions incrementally in the short term but are not compatible with long-term goals, posing the risk of stranded assets or missing emissions targets (e.g. coal to gas substitution in power generation).

Backcasting requires quantitative emissions targets. These can come from a variety of sources. Some jurisdictions have already made long-term pledges with an explicit emissions target that can be the basis of a pathways study. Where no such emissions targets exist, they can be set bottom-up. In this regard, it is useful to build from provisional orders of magnitude based on a scientifically-derived benchmark, such as average per capita emissions in 2050 consistent with 2°C/1.5°C. We refer to these as attractors. Targets can be adjusted based on what is learned from initial analysis employing the attractor value. Attractors can also be used for other metrics, such as sectoral emissions or energy intensities, providing a sense of direction for mitigation measures in early stages of the analysis.

Questions to consider when starting the analysis:

- What is the mid-century vision that this pathway is designed to reach?
- What is the emissions target for this analysis? If no target is set, what information can be used to develop a plausible "attractor" for initial use?
- What level of sectoral and temporal granularity is needed to understand the steps along this pathway in sufficient detail?
- What information is needed to understand the long-term consequences of near-term policy and investment decisions facing our jurisdiction?
- What kind of data (e.g., equipment lifetimes, stocks, vintages) and analytical tools are needed to provide this information?

3. Describe the physical transformation required to meet 2050 objectives

2050 pathways describe the physical changes in infrastructure and technology required to implement carbon and development goals. These changes are tracked over time using a set of common metrics.

The 2050 pathways analysis can be most useful via the translation of climate mitigation and socio-economic goals into a believable case for a long-term low-carbon and socio-economic transformation. This is in contrast to analyses that have a short term, incremental, and macro-economic or financial focus. This approach aims at helping stakeholders develop a realistic understanding of what a low-carbon future requires in terms of infrastructure stocks, technologies (including required technological breakthroughs) market structures, behavioral changes, and investment over time, starting from an accurate description of present day conditions. It translates emissions trajectories (which can be fairly abstract) into fleets of equipment such as solar panels, electric vehicles and heat pumps, as well as the timing of their acquisitions and their operation. For some economies, land use-based activities are another integral part of the transformation.

Analytically, a focus on physical implementation of a low-carbon development scenario requires sufficient granularity to inform real-world decisions in terms of changes in the infrastructure that produces emissions, the technologies required, and the costs entailed. The level of detail chosen for the analysis should also take into account a country's or region's concern about future climate resilience, as certain infrastructure choices that commit an economy over several decades will have strong bearing on the vulnerability to future climate change (see, for instance, the issue of reduced power plant efficiency as cooling water temperature rises). Assumptions on changes in market structures, business models, and consumer behavior may also be of interest as administrations make policy design choices.

The art of modelling the physical transformation lies in determining the appropriate level of detail. A 2050 pathways study should include a minimum level of physical representation reflected in a common set of economy-wide and sectoral indicators. A useful lesson from earlier exercises is the recognized role of three pillars in deep decarbonization for the energy sector, to which one should add a fourth pillar of land-use sectors. With respect to the energy pillars, bottom-up pathways and other modelling analyses have demonstrated that high levels of energy efficiency, electricity decarbonization, and fuel switching to electricity are critical to achieve a low-carbon transformation of the energy sector. Pathways analyses would therefore usefully include metrics such as energy use per ton-km of freight, the electric generation mix, and energy types in key end-uses, whose progress over time is a fundamental element of 2050 pathways. Similarly, key land-use indicators could include surface of agricultural land vs urban areas, food vs animal feed vs fuel crops production, forested areas, to name a few.

Questions to consider when starting the analysis:

- What metrics and level of granularity are needed to understand and communicate the physical transformations in this pathway, as well as other socio-economic dimensions ?
- What aspects of a low-carbon transformation are most important to the audience of this study? Is land use expected to play an important role?
- Are high-level metrics adequate for this study or is a detailed representation of physical stocks required?
- What are the policy options for implementing the “four pillars” in this economy?

4. Link the analysis to engagement and communications

Conducting the pathways analysis in conjunction with a strategy of stakeholder engagement and external communications ensures 2050 pathways are relevant in their local context.

2050 pathways studies will occur in different circumstances, with different degrees of involvement of stakeholders in the process and different audiences for the results. In general, an analysis conducted in concert with an engagement and communications strategy will be more effective in educating audiences and influencing decisions than an analysis performed in isolation. There are at least four kinds of communications to consider when planning the study.

Communication has to be organized within pathways teams, i.e. the leaders of the pathways process (e.g. government decision-makers in relevant departments) and analysis teams. Main discussion items will include the broad objectives of the study, research and policy questions, audiences of the work, the presentation of results and the integration of feedback, in addition to deliverables, data access, analytical tools, etc.

The involvement of stakeholders in pathways studies requires a two-way communication to solicit their input and feedback and to report progress and results. Narratives are a key strategy for engaging stakeholders in pathways design. Stakeholders can include other government departments or local governments, public and private companies, non-governmental organizations, institutional investors or trade unions.

Communication with broader audiences such as legislators, journalists, consumers, taxpayers, ratepayers and voters will benefit from relating 2050 pathways to their concerns beyond mitigation, such as development, available income or health.

Networks and governments that wish to collaborate through the Platform will be better able to coordinate efforts by agreeing on methods for sharing and discussing pathways, including technical communications using common dashboards and quantitative metrics.

Linking analysis to stakeholder communications requires intentional design that is proactive about timing and opportunities for input and kinds of input sought. It also requires investment in “speaking the language” of the stakeholders and in situating the pathways study within their policy processes and political contexts. Sophisticated two-way communications can entail a major commitment of time and resources and needs to be taken into account early in the process.

Questions to consider when starting the analysis:

- Who leads the pathways process and how does it define communication needs?
- Who are the key audiences and stakeholders?
- How is it best to communicate with these audiences and stakeholders?
- What input is needed from them, and when and how should it be provided?
- What are the best formats for reporting progress and results to different audiences?
- What are the policy priorities of key audiences, and how do these relate to 2050 pathways?

5. Scope the issue before conducting the analysis

Successful 2050 pathways are based on robust and transparent analysis. This starts with a careful scoping of research and policy questions, results metrics, data availability, and analytical tools.

To be successful, 2050 pathways must be able to demonstrate that claimed results, such as emissions reductions from specified measures, make scientific sense, are technically feasible, and add up correctly. Scientific credibility is based on robust, transparent, and repeatable analysis. For this reason, the pathway analysis needs to start with a careful scoping to ensure that the study asks the right questions and uses the right methods in order to answer them.

The policy and research questions should be analytically tractable and illuminate the challenges and opportunities of 2050 pathways. This implies engaging stakeholder concerns as a means to ensure the robustness of the approach. At the same time, the long-term horizon of the pathways analysis should help to avoid a focus on narrow or short-term interests. Current policy questions may need to be put in the context of a long-term transformation, asking when new policy directions will be needed to trigger appropriate investment decisions. The identification of questions raised by 2050 pathways should be accompanied by defining the quantitative metrics needed to describe pathway inputs, assumptions and results in a way that rigorously answers the identified questions (e.g. is biomass-based energy production presented alongside implications in terms of land-use? Is there an appropriate representation of the electricity grid investment needs required to support variable renewable sources?).

Analytical approaches and modelling tools should be selected for their ability to produce the required quantitative metrics at a suitable temporal, geographic and sectoral resolution. The process of matching research and policy questions to analytical tools can help to identify resource and capacity challenges, such as whether current tools are adequate or new tools are needed, or what skills or forms of technical assistance may be needed to perform the analysis.

Data availability should be assessed early on as it determines how granular the analysis can be. Understanding what data is readily available, what could be made available and what is not available at all will determine what analysis can be done in a robust manner, what requires simplified treatment and what should be excluded from the analysis. For governments that lack their own data in key policy areas or sectors, international, sectoral and proxy datasets from governments with similar conditions can be used in an initial phase.

Questions to consider when starting the analysis:

- What are the research or policy questions to be addressed by the analysis?

- What methods, tools, and expertise are required to answer these questions?
- What metrics will be used for the quantitative inputs and results?
- What data sources are available and what is their quality?
- What are the constraints and boundary conditions of the analysis?
- What are the main uncertainties relevant to the analysis?
- What examples of similar analyses are available to use as templates?

IV. Building Blocks of 2050 Pathways

The central tasks of 2050 pathways development are the creation of narratives describing potential routes to a low-carbon future, the quantitative representation and modelling of those narratives, and the construction and use of dashboards containing the key metrics and indicators for communicating results. These are the building blocks for all 2050 pathways, though the specifics may vary.

1. Narratives

Creating 2050 narratives, stories that describe the transition to a low-carbon, sustainable future, and the key choices along the way, helps to engage stakeholders, formulate research questions, and define the scenarios and metrics used to assess alternative 2050 pathways.

Narratives are stories that describe the transition to a low-carbon future that meets socio-economic goals. The exact form of narratives depends on the participants and circumstances but, in general, they should aim to be qualitative descriptions accessible to a wide audience. Narratives are meant to provide the conceptual basis of quantified scenarios that are explored and tested through modelling, with the results expressed in a set of agreed metrics for comparison and evaluation. Narrative creation and modelling are iterative activities, as interim modelling results are used to refine narratives and vice-versa.

Narrative development is a centerpiece of the pathways process. It provides an opportunity for engagement as different participants (leaders of the 2050 pathways process, business, government and local government decision makers, other important stakeholders, technical experts and the analysis team) share their vision of change and how it relates to their priorities and concerns. Discussing alternative futures and options for getting there helps to formulate research and policy questions. Discussing what details are important helps to determine the granularity of the analysis and the kinds of tools and data needed. Discussing how to compare different pathways and how to measure progress will also help to define what quantitative metrics are needed (e.g. the timing and magnitude of investment in major low-carbon infrastructure, the land area devoted to afforestation vs agriculture, etc.) More broadly, the elaboration of narratives for 2050 pathways also allows exploring different visions of society, bifurcations required to realize them, and their implications.

It is typical in 2050 pathways studies to develop several different scenarios that explore technical or policy alternatives or assumptions about future conditions. Comparing the areas of emphasis in different narratives can help identify the dimensions along which the modelled scenarios should differ. Since looking decades into the future necessarily involves many uncertainties, a key role for narratives is to identify which uncertainties may have the greatest potential impact, which strategies are the most robust under a range of future outcomes, and how evolving conditions and information (for example, about technology costs) could affect those strategies. Testing these assumptions analytically can provide some of the most useful findings of 2050 pathways.

2. Models

Models are mathematical representations of physical and economic systems used to explore and test 2050 pathways scenarios. Models are chosen based on their fit with research and policy questions and their ability to produce the necessary quantitative outputs.

In 2050 pathways analysis, mathematical models are used to anchor narratives about a low-carbon transformation in physical and economic reality. Their role is to start from an accurate description of present conditions, flesh out the technical details of pathways scenarios, check their internal consistency, test their feasibility *vis-à-vis* socio-economic objectives, and help develop better scenarios. Models cannot provide infallible answers but can reveal the important features of different pathways, generate ideas for new scenarios, and support problem identification and problem-solving.

Many types of analytical tools and methods have been used in pathways analysis, with different functionalities and levels of complexity. These include energy system models, integrated assessment models, macroeconomic models, and many types of specialized sectoral applications, from electricity dispatch models to land-use models. What is needed is not the “best model” in the abstract, but the “best fit” given analysis priorities, technical capacities and data availability. The analysis process should not start with a model and look for questions it can answer but, rather, with the questions that must be answered to achieve the goals of the process. The right analytical toolkit is best discovered through the process of developing narratives, posing research questions, defining key metrics, assessing data needs and availability, and reviewing existing analyses and the tools and people involved.

Complexity in modelling for its own sake is no advantage; models that simplify some aspects of a problem to make it tractable may be more suitable. Simple models, such as spreadsheet calculators, can be very effective in translating qualitative narratives into quantitative language, providing basic familiarity with scenarios before entering into deeper complexity, understanding what kind of analysis is needed to produce the necessary metrics and indicators, identifying problems and priorities for further study, and simply determining if claimed results "add up." However, it should be understood when simplifications no longer apply. More sophisticated models may be needed to reveal the dynamics and non-linear behavior of complex systems, provide counterintuitive insights, explore the implications of uncertainty and risk, and engage experts and decision-makers in their own technical language.

Across all types of modelling, transparency is essential to the success of 2050 pathways. Various audiences and stakeholders should have a common understanding of the main dynamics underlying modelling results (e.g. is future energy demand driven by a detailed description of energy-using equipment or aggregate variables such as income? Is the supply of land for agriculture fixed or responsive to food prices? Is the penetration of variable renewable technologies based on detailed "load curves" or on observed performance in most advanced countries?). Transparency and quality control of modelling assumptions and their sources are critical if people other than the modellers are to understand, challenge or accept the results. It is also important to maintain proper documentation of the analysis, especially if it is meant to be revisited further down the line.

3. Dashboards

Dashboards are data tables describing 2050 pathways in quantitative terms. A common dashboard allows the assumptions and results of different pathways studies to be communicated and compared, even when different models are used to produce them.

Dashboards are meant as data tables and simple illustrations showing time series of key metrics and indicators from a 2050 pathways analysis. They are tools for communicating pathways assumptions, results and narratives to both internal stakeholders and external audiences, including those involved in parallel pathways processes in different jurisdictions. Although dashboards are not meant as the only communication tool of pathways analysis, the common technical language derived from creating and using dashboards is fundamental to achieving many of the benefits of the pathways process, such as mutual support on policy and sharing best practices.

The design of dashboards should be transparent and not tied to any particular modelling approach. It should feature information produced by any reasonable method as long as the data provided fits the template. The selection of metrics and indicators used in the dashboard should not be driven by what a given model is capable of producing but by the research and policy questions and the desired outcomes of the pathways process, and the type of data needed to support these. The necessary resolution of time, spatial and sectoral dimensions must be determined in the context of a specific analysis.

Dashboards are used for many functions within the analysis including as a basic accounting framework independent of models, a "consistency-check" vehicle that helps ensure the alignment of scenarios and modelling with the research questions, a troubleshooting tool to identify missing values, outlier results and unreasonable assumptions, and a "quality check" instrument to ensure the selection of models that can actually produce the necessary dashboard metrics and indicators.

Key metrics and indicators in dashboards include the following time series (see also example in Figure 4 in Section V.):

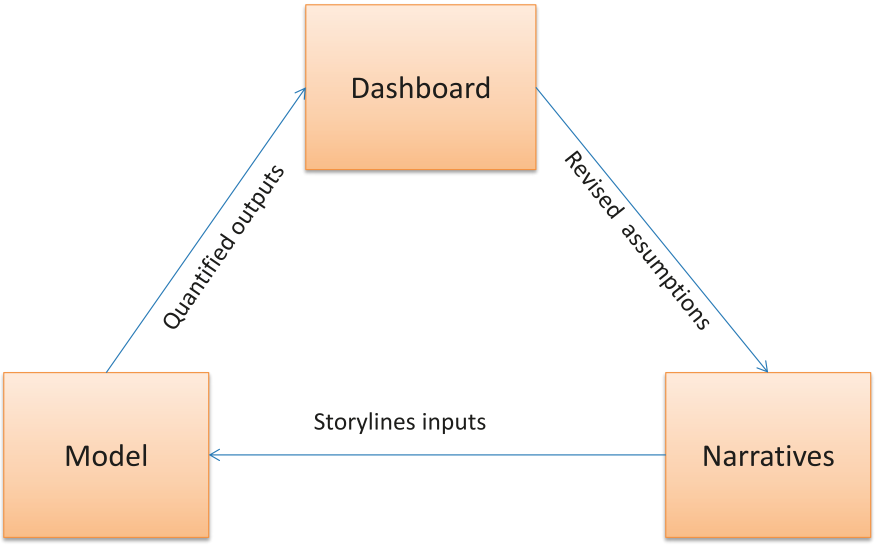
- *Emissions drivers*, which should be sufficiently disaggregated to reveal the leverage points for curbing emissions, and have the right dimensions to represent mitigation strategies, targets or attractors (e.g. the carbon intensity of electricity generation).
- *Socio-economic indicators*, which are used to measure progress towards non-emission targets and capture key elements of the interplay between emission reductions and broader social context, as expressed by stakeholders (e.g. value added by sector).
- *Physical and economic parameters,* which describe the stocks and flows of the current system and mitigation measures with sufficient granularity to concretely show the transformations involved.

4. Visualizing the Process: How the Building Blocks Can Work Together

Narratives, models and dashboards are essential building blocks of 2050 pathways design. The narratives describe the strategy and models translate these elements into a consistent scenario with well-defined objectives expressed in quantitative metrics. These metrics are reported in the dashboard where the outcomes of the scenario can be assessed and compared to other scenarios.

To develop ambitious scenarios and inform ambitious policy agendas, the building blocks framework can work in iterations until socio-economic and emissions objectives are met, as defined by the attractors and targets.

The figure below provides a schematic of how the building blocks work together, including the interactive process in which analysts, stakeholders and outside experts review initial results and use them to revise storylines.



5. Using Dashboards to Coordinate Across Networks and Jurisdictions

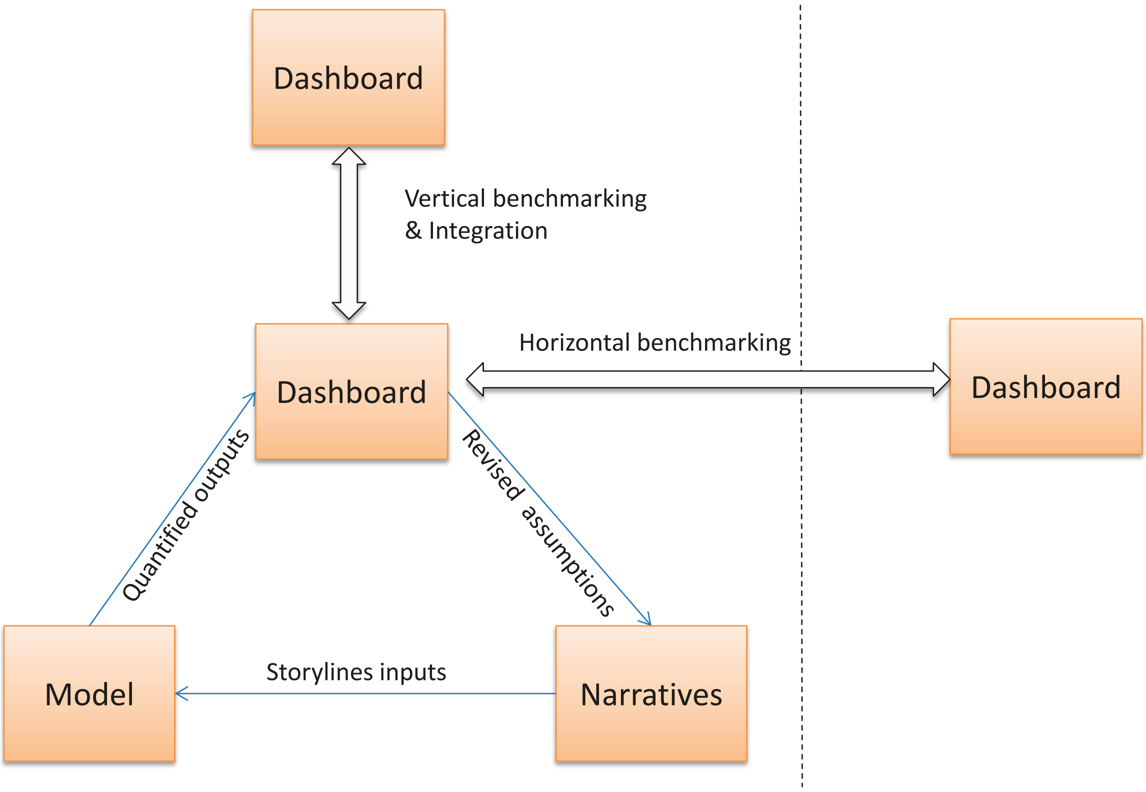
The building blocks structure facilitates collaboration among different entities developing pathways in parallel. Experience has shown that, whilst each entity is free to adopt the assumptions and methodologies that work best in their context, collaborative development can drive major improvements in pathways quality, ambition and relevance. Knowledge sharing on approaches and methods helps push the frontiers of collective knowledge and helps actors move outside the comfort zone of their usual assumptions and methods. The collective discussion among members of their respective narratives, underlying assumptions and results is an important part of the 2050 Pathways Platform's value.

Dashboards are the key to this collaboration process as the common language of technical communications by which different pathways can be explained, critiqued and compared. Collaborations, whether they are between cooperating governments or among networks, can be classified into two types:

For *horizontal* learning: Communication across pathways at the same level of jurisdiction, such as among different countries – identical dashboards allow for comparison and aggregation of the results. Actors working on pathways at the same jurisdictional levels will benefit agreeing early on a common dashboard.

For *vertical* learning: Communication within jurisdictions at different levels, such as a city within a state, or a state within a country – dashboards at one level can provide inputs into those at another level. In this case, it is valuable for actors from these different levels to coordinate how the elements reported in their dashboards correspond to those in others, creating a "dictionary" across different dashboards.

The linkage of a pathways process to horizontal and vertical collaborators via their dashboards is illustrated in the figure below.



Note: Benchmarking can be used to bring coherence across individual pathways, either to account for geographical unity (e.g. the carbon content of electricity in a state within a country) or to foster ambition as members discuss differences in performance of key metrics e.g. energy consumption per square-meter in residential buildings or penetration of electric vehicles (see Figure 2 for further examples).

6. Brief Summary of Key Steps in 2050 Pathways Process

- Questions to ask before starting the process:
    - What are your objectives for developing 2050 pathways?
    - Are these objectives agreed upon by everyone involved?
    - Do the methods and process support these objectives?
    - What do you control as a jurisdiction and what is in the control of others?
    - What capacities and resources do you have and what do you lack?
- Set the main parameters of the study
    - Develop research and policy questions, constraints and boundary conditions for the analysis.
    - Determine quantitative long-term socio-economic objectives and emissions targets.
- Create the "building blocks"
    - Develop a frame (e.g. based on the four pillars) for the elaboration of narratives and the identification of important elements from them.
    - Build a dashboard for entering and transparently displaying quantitative indicators to express the input values (e.g. economic growth) assumptions (e.g. energy efficiency progress in various end-uses) and results of the analysis.
    - Select the models and other analytical tools that best match the policy and research questions, technical capacities and data availability.
- Use the building blocks
    - Create qualitative narratives about a low-carbon, sustainable development future.
    - Create scenarios that express the narratives and constraints in quantitative terms and provide the categories needed to address the research and policy questions.
    - Conduct modelling of the scenarios, including technical and qualitative review of the results.
    - Report the dashboard variables and compare the outcomes with targets/benchmarks/attractors.
- Iterate on the steps above as needed.
- Display results and provide interpretations for different audiences.

V. Applying the Common Framework: Examples in Context

This section shows how the common framework for 2050 pathways has been applied to different contexts at the national and subnational levels. Examples illustrate application of both the building blocks (narrative, dashboard, and models) and the general principles, including backcasting, integration of socio-economic and emissions objectives, and focus on physical transformation. These examples do not reflect the positions of countries or regional governments on future emissions levels.

1. National Pathways

1.1 Deep Decarbonization Pathways Project

The Deep Decarbonization Pathways Project (DDPP) is an international research collaboration exploring how individual countries can transition to a low-carbon economy consistent with limiting anthropogenic warming to less than 2°C while meeting their socio-economic objectives. In 2015, each of the sixteen country research teams published 2050 pathways for their own countries, in most cases with several alternative scenarios, in order to inform decision makers about the technology, investment and policy implications of different options for meeting these objectives.

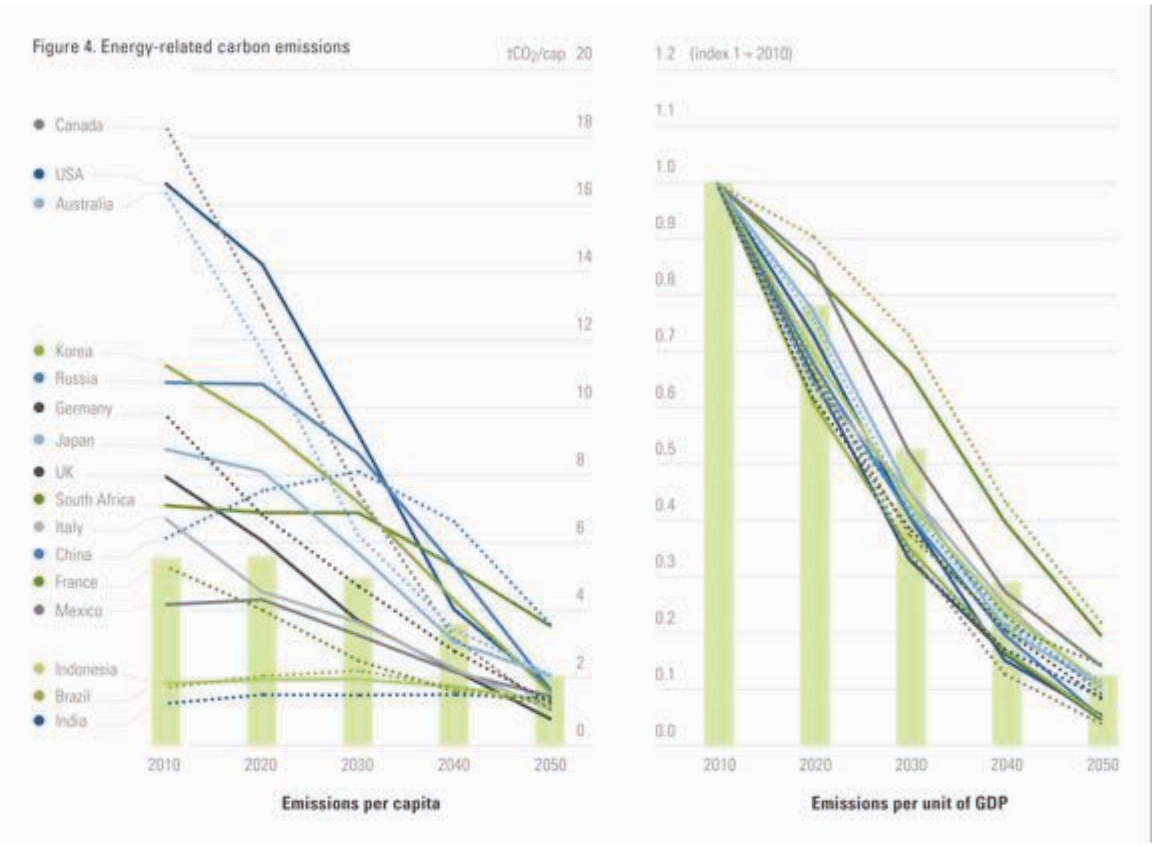
The pathways developed by the teams all incorporate backcasting analysis and integrated socio-economic and emissions objectives. The DDPP process emphasized the three building blocks of narratives, modelling and dashboards which were essential to transparent sharing of results, data and best practices across a dispersed network. These building blocks supported an iterative process that improved technical quality and increased ambition over time.

Backcasting, targets, and "attractors"

Consistent with the bottom-up approach of the Paris Agreement, the DDPP teams set their own emissions targets and socio-economic objectives as the end points for their backcasting analyses. The teams agreed to a common focus on CO_2 from energy in the year 2050, although individual teams were free to include other emissions objectives. In order to encourage adequate ambition without dictating targets top-down, the teams adopted an emissions "downward attractor" that served as a non-binding point of reference. A value of 1.6 tonnes of CO_2 from energy per person in 2050 was adopted to represent average global per capita emissions consistent with 2°C (based on the IEA 2DS scenario and a UN global population forecast).

The resulting trajectories of energy-related CO_2 emissions per capita for each country are shown in Figure 1a. Some countries' pathways reached or exceeded the *ex-ante* 1.6 tonne benchmark whilst others did not reach it but the overall trend toward the attractor is evident. The comparable levels of ambition are further indicated by the parallel, steeply decreasing emissions intensities of GDP in all 16 countries (Figure 1b) In a number of cases, teams adopted two emissions targets side by side – the 1.6 tonne value plus the target already adopted by their country's government, such as 80% reduction in net CO_2e from all sources below 1990 levels by 2050 (as commonly used by G7 countries) or the 'Factor 4' in France, the '14 Gt' carbon budget in South Africa, and a 2°C-compatible national carbon budget developed by the Climate Change Authority for Australia.

Figure 1a. Use of Downward Attractor in Setting Emissions Target; 1b. Decoupling of Emissions and GDP.



Attractors were also used by the DDPP to provide an initial benchmark for sectoral ambition. Figure 2 shows the indicative values of emissions intensity or energy intensity used as attractors for DDPP analyses for electricity, transportation and industry, based on values from the IPCC Fifth Assessment Report consistent with 2°C scenarios. As with the emissions attractor, teams were not required to adopt these values but most of the country pathways do fall within these ranges.

Figure 2. Use of Downward Attractor in Setting Sectoral Benchmarks.

Sector	**Sub-sector / Region**	**Indicator**	**Benchmark in 2050 Median value**	**Benchmark in 2050 Range**
Electricity generation	–	gCO_2/kWh, note: net negative (biomass with CCS) was not used in the DDPP except by the UK	20	-30 – 50
Transport	Passenger transport	(GJ/person kilometer, index 1=2010 value)	0.75	0.58 – 0.78
	Freight transport	(GJ/tonne-kilometer, index 1=2010 value)	0.65	0.45 – 0.9
	Total Transport	(tCO_2/GJ, index 1=2010 value)	0.7	0.6 – 0.85
Industry	Cement	tCO_2/ton	–	0.24 – 0.39
	Iron and steel		–	0.47 – 0.84
	Paper		–	0.16 – 0.20

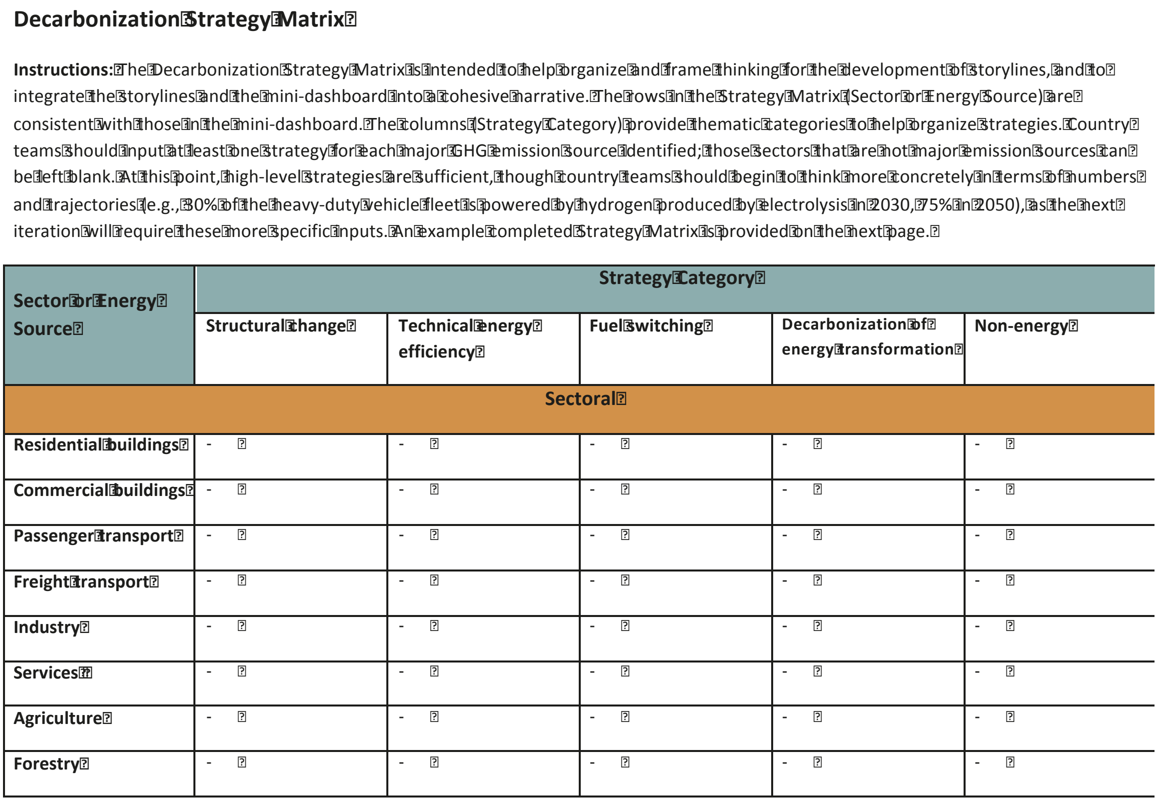
Narratives

DDPP teams used narratives to develop and communicate their 2050 pathways. In most cases, these narratives are of two types. The first is a "national priorities" narrative, expressing national socio-economic aspirations over time. In many cases, the areas of emphasis were chosen by the teams to serve as entry points for dialogue with stakeholders within their countries. The relative priorities varied from country to country, ranging from economic growth and jobs to energy access and pollution reduction.

The second is a "deep decarbonization" narrative, focusing on the technical aspects of a low-carbon transition. Across the different country teams, this narrative addressed the physical transformation of energy supply and end use infrastructure, such as power plants, passenger and commercial vehicle fleets, buildings, and industrial equipment. The details of this transformational narrative differ from country to country based on national circumstances in areas such as existing infrastructure, natural resources, technology availability, and financial capacity.

The combination of these two narrative streams helps to explain the different pathways scenarios developed by the teams. As an intermediate step, the DDPP developed a "DDPP strategy matrix," a compact, high-level description of the low carbon transition in each sector, to be completed by each team as a visualization exercise prior to in-depth development of scenarios (Figure 3). For each sector, the teams were asked to report the key components of their strategies for implementing the three pillars of decarbonization (energy efficiency and conservation, end use fuel switching, and decarbonization of energy supplies) along with mitigation of non-energy emissions for teams undertaking that analysis.

Figure 3. DDPP Decarbonization Strategy Matrix.



Decarbonization Strategy Matrix

Instructions: The Decarbonization Strategy Matrix is intended to help organize and frame thinking for the development of storylines, and to integrate the storylines and the mini-dashboard into a cohesive narrative. The rows in the Strategy Matrix (Sector or Energy Source) are consistent with those in the mini-dashboard. The columns (Strategy Category) provide thematic categories to help organize strategies. Country teams should input at least one strategy for each major GHG emission source identified; those sectors that are not major emission sources can be left blank. At this point, high-level strategies are sufficient, though country teams should begin to think more concretely in terms of numbers and trajectories (e.g., 30% of the heavy-duty vehicle fleet is powered by hydrogen produced by electrolysis in 2030, 75% in 2050), as the next iteration will require these more specific inputs. An example completed Strategy Matrix is provided on the next page.

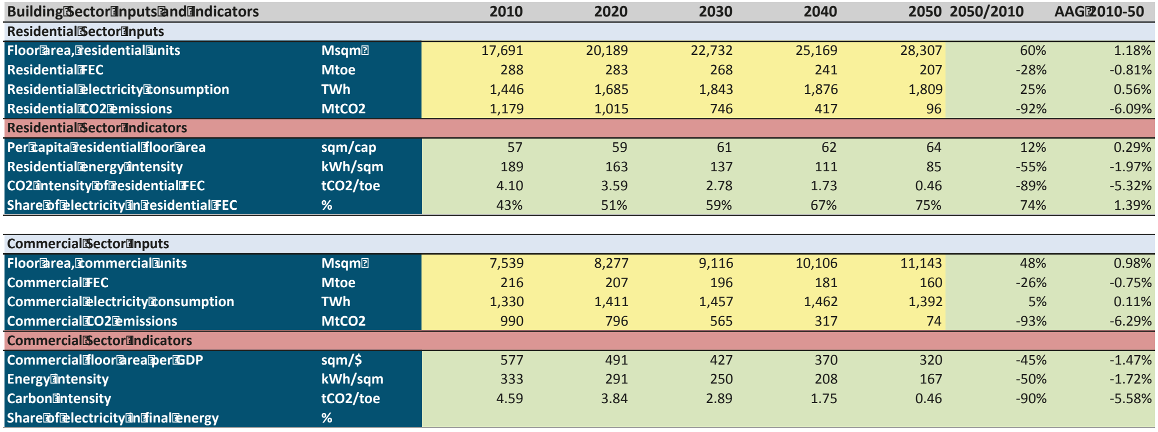
Sector or Energy Source	Strategy Category				
	Structural change	Technical energy efficiency	Fuel switching	Decarbonization of energy transformation	Non-energy
Sectoral					
Residential buildings	-	-	-	-	-
Commercial buildings	-	-	-	-	-
Passenger transport	-	-	-	-	-
Freight transport	-	-	-	-	-
Industry	-	-	-	-	-
Services	-	-	-	-	-
Agriculture	-	-	-	-	-
Forestry	-	-	-	-	-

Dashboard

The DDPP dashboard is a spreadsheet containing quantitative values that describe the energy transitions in the DDPP's 2050 pathways. The metrics employed were determined jointly by the country teams and constitute the minimum shared technical content provided by all teams for their scenarios. Many country analyses are broader and more detailed than what is represented in the dashboard's data, but this common representation of underlying data has proven adequate for meaningful technical and policy dialogue.

The DDPP dashboard contains time series data to 2050 for four types of metrics: economy-wide indicators (population, GDP, energy demand, electricity demand and carbon intensity of electricity), activity, energy intensity and fuel mix for energy demand (buildings, transport and industry) and energy supply (electricity, liquids, and gases) as well as important infrastructure and equipment (generation capacity, vehicle stocks and fuel supply capacity). A screen shot of part of the DDPP dashboard is shown below (Figure 4).

Figure 4. Screen shot of one section of DDPP dashboard.



Building Sector Inputs and Indicators		2010	2020	2030	2040	2050	2050/2010	AAG 2010-50
Residential Sector Inputs								
Floor area, residential units	Msqm	17,691	20,189	22,732	25,169	28,307	60%	1.18%
Residential FEC	Mtoe	288	283	268	241	207	-28%	-0.81%
Residential electricity consumption	TWh	1,446	1,685	1,843	1,876	1,809	25%	0.56%
Residential CO2 emissions	MtCO2	1,179	1,015	746	417	96	-92%	-6.09%
Residential Sector Indicators								
Per capita residential floor area	sqm/cap	57	59	61	62	64	12%	0.29%
Residential energy intensity	kWh/sqm	189	163	137	111	85	-55%	-1.97%
CO2 intensity of residential FEC	tCO2/toe	4.10	3.59	2.78	1.73	0.46	-89%	-5.32%
Share of electricity in residential FEC	%	43%	51%	59%	67%	75%	74%	1.39%
Commercial Sector Inputs								
Floor area, commercial units	Msqm	7,539	8,277	9,116	10,106	11,143	48%	0.98%
Commercial FEC	Mtoe	216	207	196	181	160	-26%	-0.75%
Commercial electricity consumption	TWh	1,330	1,411	1,457	1,462	1,392	5%	0.11%
Commercial CO2 emissions	MtCO2	990	796	565	317	74	-93%	-6.29%
Commercial Sector Indicators								
Commercial floor area per GDP	sqm/$	577	491	427	370	320	-45%	-1.47%
Energy intensity	kWh/sqm	333	291	250	208	167	-50%	-1.72%
Carbon intensity	tCO2/toe	4.59	3.84	2.89	1.75	0.46	-90%	-5.58%
Share of electricity in final energy	%							

Note: FEC means final energy consumption

The dashboard has played two main roles in the DDPP exercise. The first role is enabling technical interactions among DDPP country teams which used different modelling tools and analytical approaches by providing unambiguous descriptions of each team's scenarios. This allowed comparisons across scenarios developed with dissimilar methods, facilitating rapid adoption of new technical information and best practices in modelling. This creates an iterative process of reporting and revising, resulting in more ambitious mitigation scenarios and the aggregation of results across scenarios and countries needed to assess the global implications of bottom-up national pathways.

The second role of the dashboard is communication outside the DDPP network, including domestic stakeholders within each country, as well as other interested audiences such as the international scientific and policy communities. For example, the dashboard is the source of information about country pathways displayed in the data visualizations on the DDPP website. This information has been used in analysis conducted by third parties, including national governments developing mid-century strategies.

Models

The DDPP teams used a wide variety of modelling approaches in developing their 2050 pathways. This is partly a reflection of the tools that each team was familiar with before joining the DDPP and partly a reflection of the different methods required to perform the analyses called for by different pathways narratives. Teams used (or developed their own) energy system models, macroeconomic models, integrated assessment models, and land use models to investigate the various national priorities in their pathways. Many also used a spreadsheet model called the "DDPP Calculator" for initial scenario development. The models used by the DDPP teams, organized along a bottom-up/top-down axis, are shown in Figure 5.

Figure 5. Models used by DDPP country teams.

Accounting	Bottom Up	BU based hybrid	Mixed linked BU+TD	Top Down based hybrid	National IAM
PATHWAY (US)*	MARKAL-TIMES (UK) CA-TIMES (Cal) MARKAL Stochastic (UK) MARKAL (UK) ESME (UK) LTMS (SA)	CIMS (CAN-CHIN) MARKAL-ED (UK) MARKAL-MACRO (UK) MARKAL-ED (CHIN) MARKAL-MACRO (CHIN)	Pop, Buildings, Trans, CGE (JP) MARKAL-AIM-Snapshot (IN) IPAC (BU-CGE) (CHI)	IMACLIM-R (FR) MIT-EPPA (US) MRN-NEEM (US) ADAGE (US) THREE-ME (FR) REMIND-D (GER) GEMINI (Swiss)	GCAM-IIM (IN)
US* Indonesia South Korea Mexico	UK* Russia	Canada*	Australia Japan Italy China South Africa India	France* Brazil Canada	None

1.2 Aggregate Results

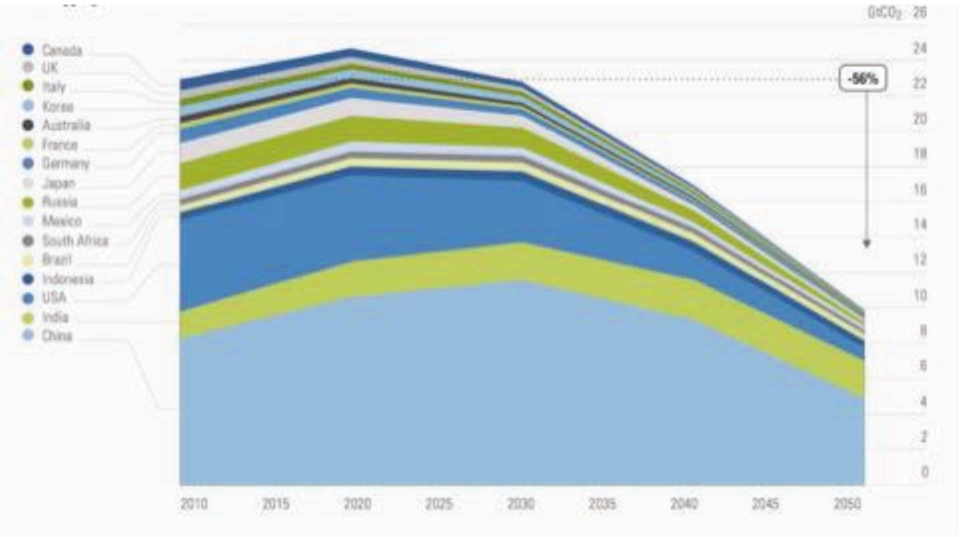
Examples of cross-cutting results derived from aggregating or comparing individual country pathways data reported in the dashboard include:

- Emissions
- Economic growth
- Mobility
- Deep decarbonization metrics (the three energy “pillars”)

Emissions

Figure 6 shows energy-related CO_2 emissions across the 16 DDPP countries. When extrapolated to include emissions from non-DDPP countries and other sources, cumulative global CO_2 emissions by 2050 fall in the range of 50% likelihood of staying below 2°C, based on IPCC assessments. This demonstrates that the bottom-up DDPP approach produces scenarios in the right ballpark for climate stabilization, even though emissions targets are not enforced *ex ante* or top-down.

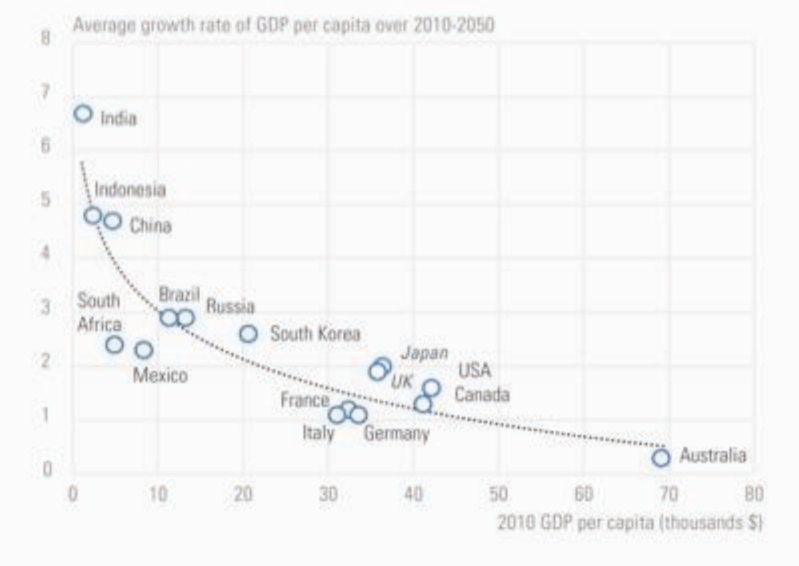
Figure 6. Emissions Trajectories (Energy-related CO_2) for 16 DDPP countries, 2010 to 2050.



Economic growth

Economic growth rates were a concern for all sixteen countries represented in the DDPP. The growth rates used in the modelling were chosen by the country teams based on their own domestic economic analysis. All teams assumed continued growth to 2050 but at different rates that generally follow the initial level of economic development. Figure 7 shows average growth rates used in the pathways analysis during 2010-2050 plotted against per capita GDP in 2010. Low and middle-income countries in the global south, starting from a lower level of GDP per capita, assumed higher growth rates to meet development objectives. The highest income countries assumed average per capita growth rates of 2% per year or lower.

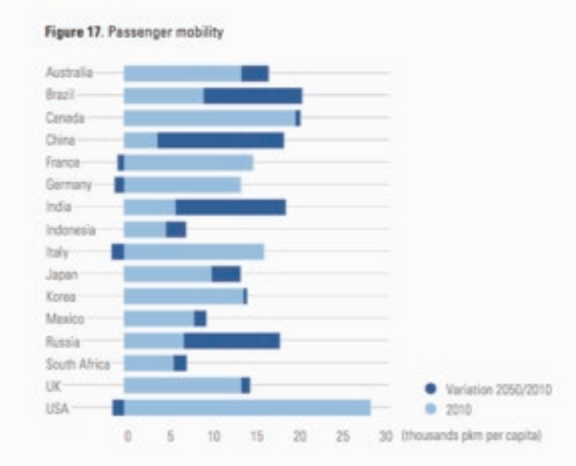
Figure 7. Average Growth Rate of GDP per Capita, 2010-2050, for each DDPP Country.



Mobility

Mobility, measured in passenger-kilometers per capita, converges over time in the 16 DDPP country pathways (Figure 8). In general, mobility in developing countries with lower initial access to energy services tends to catch up to the levels in industrialized countries. India and China's relative increase in mobility are the highest amongst the 16 countries, reflecting their low starting point, whilst mobility slightly declines in the US, France, Italy and Germany from their high 2010 levels.

Figure 8. Changes in Passenger Mobility Across DDPP Countries, 2010-2050.



Mitigation strategies

All 2050 pathways that meet deep decarbonization goals are based on the "three pillars" of energy efficiency and conservation, deep decarbonization of energy supplies (electricity and fuels), and switching of energy end-uses to low-carbon energy supplies. Whilst all pathways require these three elements, they were implemented in very different ways and to different degrees by the DDPP country teams, as shown by the indicative metrics in the dashboard (Figure 9). For electricity decarbonization, Figure 10 illustrates a high diversity in generation mix across the 16 countries, based on national circumstances, resources, and preferences.

Figure 9. Three Pillars of Deep Decarbonization: Indicators Across 16 Countries.

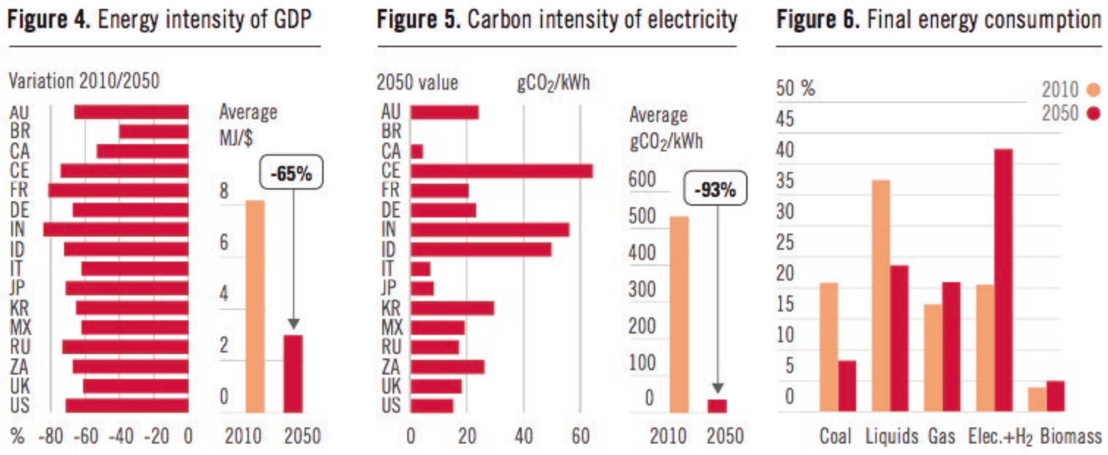
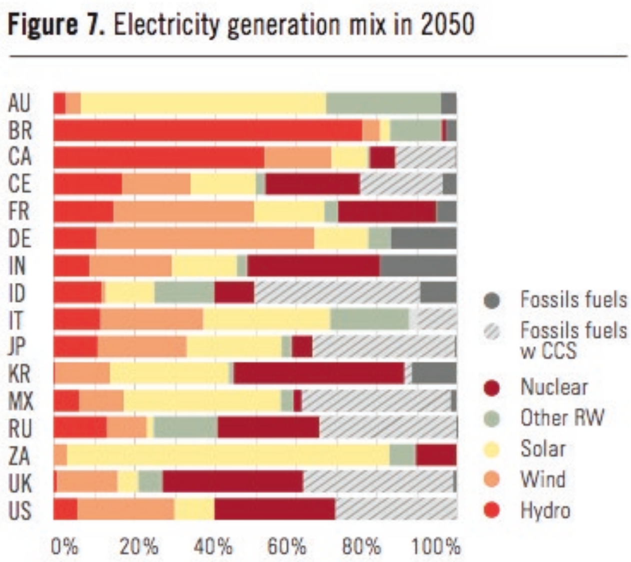


Figure 10. Variations in Electric Generation Mix in 16 DDPP Countries.



1.3 Examples from individual country pathways

Socio-economic priorities

The examples that follow show analyses of national social and economic priorities emphasized by different DDPP country teams in their 2050 pathways narratives:

- Labor force transition in South Africa
- Energy access in India
- Air pollution in India
- Energy diversification and economic resilience in Russia

Labor Force Transition in South Africa

The coal industry is a major contributor to the South African economy and employer of less-skilled workers. The South African DDPP analysis developed two scenarios showing how decarbonization can be achieved whilst absorbing this labor force. One pathway centers on promoting sectors that are less GHG intensive but can absorb lower-skill labor, whilst the other centers on improving the education system and enabling growth in low-GHG sectors that require higher-skilled labor. The results of the analysis show that in both scenarios there can be simultaneous improvements in both carbon and socio-economic indicators (Figure 11).

Figure 11. A Key Theme of Pathways Analysis: Labor Force Transition, South Africa.

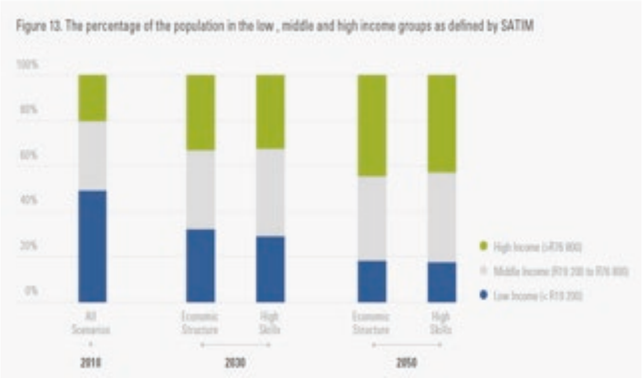
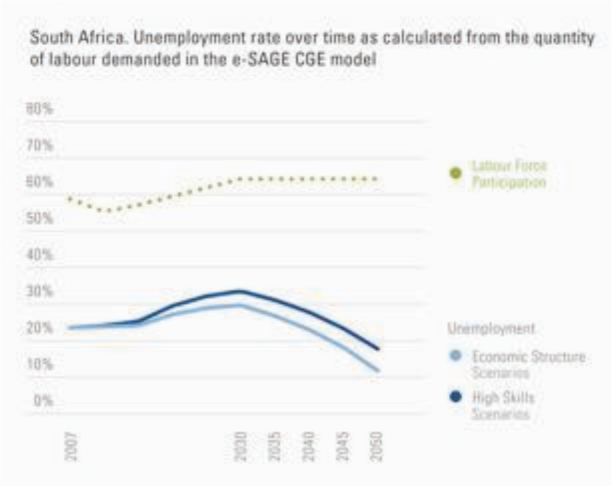


Figure 13. The percentage of the population in the low , middle and high income groups as defined by SATIM



South Africa. Unemployment rate over time as calculated from the quantity of labour demanded in the e-SAGE CGE model

Energy Access in India

A key objective for India is expanding access to basic energy services for the large share of its population that currently lack them. In transportation, this means incorporating a large expansion of passenger mobility into low-carbon pathways. The India DDPP team constructed two pathways, a “conventional” pathway focused strictly on decarbonization and a “sustainable” pathway that reflects a more comprehensive strategy for sustainability. In the case of mobility, the sustainable pathway emphasizes public transit investment so that growth in private vehicles is substantially lower than the conventional pathway (Figure 12). India's pathways also incorporate a large expansion of electricity generation to meet electricity access needs (Figure 13).

Figure 12. Expansion of Passenger Mobility as a Key Theme of Pathways Analysis in India.

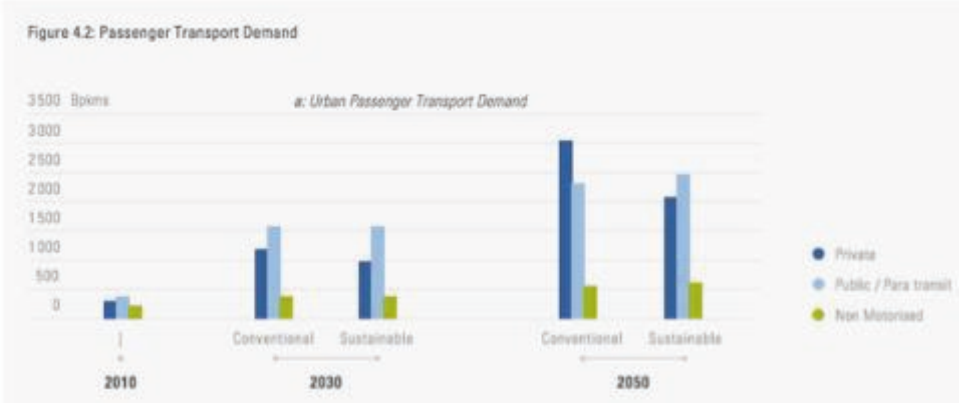
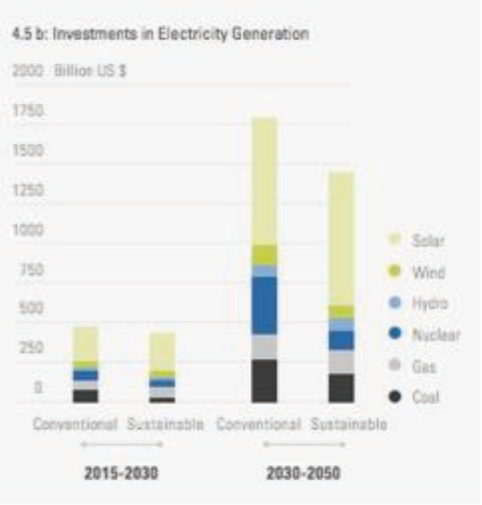


Figure 13. Expansion of Power Generation as a Key Theme of India Pathways.

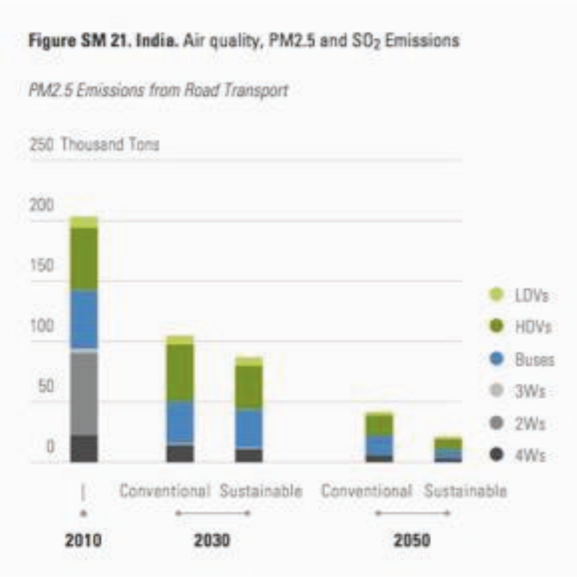


Air Quality in India

A transition away from fossil fuel combustion can generally bring air quality improvements but the India DDPP study focused on the relative air quality benefits of "conventional" decarbonization pathways that focus solely on carbon mitigation versus "sustainable" decarbonization pathways that integrate carbon mitigation with other sustainable development goals. For particulate matter (PM 2.5) largely from motorized transport, the study shows that both pathways deliver substantial improvements even with greatly expanded mobility (see previous example on

India’s energy access). However, the sustainable pathway which augments a shift away from fossil fuels with energy efficiency, dematerialization and other strategies, produces the largest improvements (Figure 14).

Figure 14. Air Quality in Pathways Analysis, India.



Physical transformation and sectoral strategies

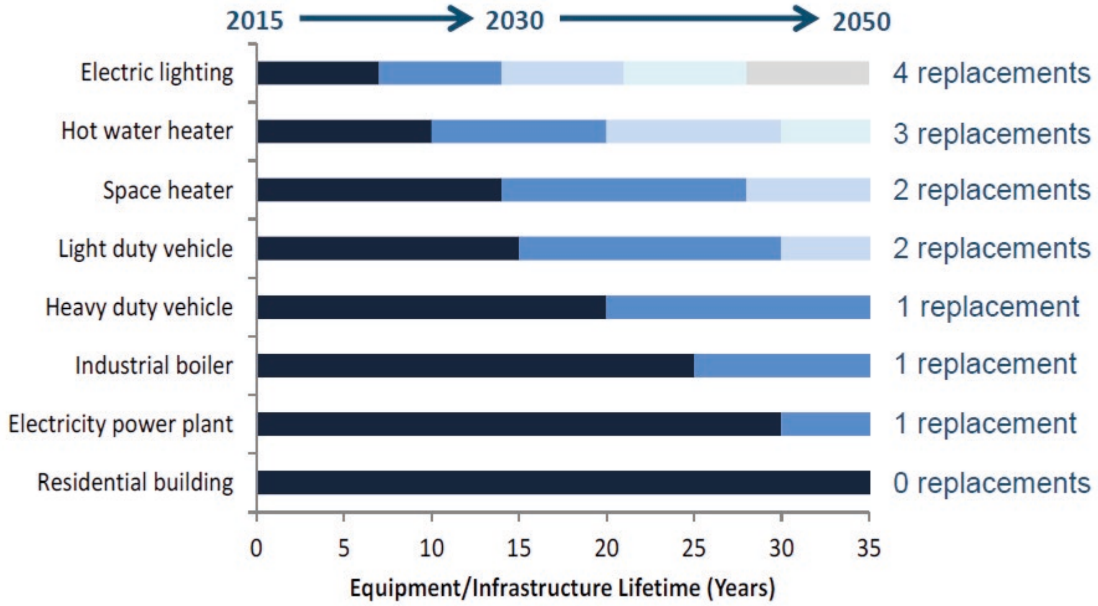
The examples that follow show analyses of physical decarbonization challenges and sectoral strategies emphasized by different DDPP country teams in their pathways narratives. The examples include:

- Infrastructure replacement in the U.S.
- Transition from coal in China
- Oil production transition in Canada
- Building energy efficiency in France
- Electricity mix and grid balancing in the U.S.
- Sustainable forestry in Indonesia

Infrastructure Replacement in the U.S.

A key issue in the U.S. pathways analysis is the timing of the replacement of energy infrastructure, as many of the most important equipment and infrastructure stocks have lifetimes comparable to the time remaining between now and mid-century (Figure 15). If long-lived stocks (power plants, buildings, freight vehicles, and industrial boilers) are replaced with inefficient, high carbon technologies, either emissions targets won’t be met or early retirement of the replacements will be required. The U.S. DDPP team developed the Energy Pathways model to track these infrastructure stocks and calculate the emissions and cost consequences of different replacement strategies. The analysis shows it is possible to meet U.S. emissions goals without early retirement but only by timely replacement with efficient, low-carbon technologies.

Figure 15. Replacement Opportunities in Energy Infrastructure, 2015-2050.



Transition from Coal in China's Buildings and Power Generation

Coal is China's dominant fuel for heating buildings and generating electricity but ambitious clean energy policies are rapidly increasing the share of low-carbon technologies. The China DDPP team's 2050 pathways feature a continued ambitious expansion of low-carbon technologies and replacement of coal at the end of its economic lifetime. Since China's building and power plant fleets are of recent vintage, they will remain in service for a long time unless retired early. The China pathways are highly instructive in illustrating the role of infrastructure inertia in slowing the reduction of carbon intensity these sectors, even with ambitious policies (Figure 16 and Figure 17).

Figure 16. Low-carbon Transition in China's Electricity Generation.

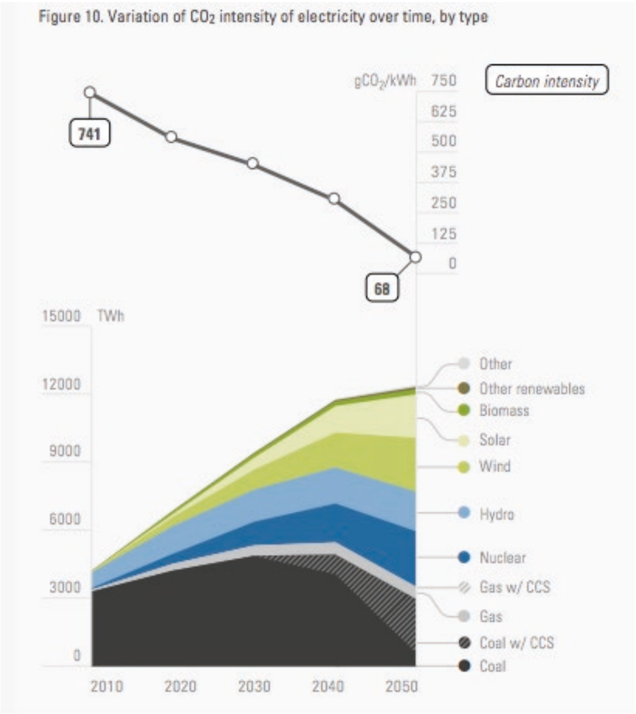
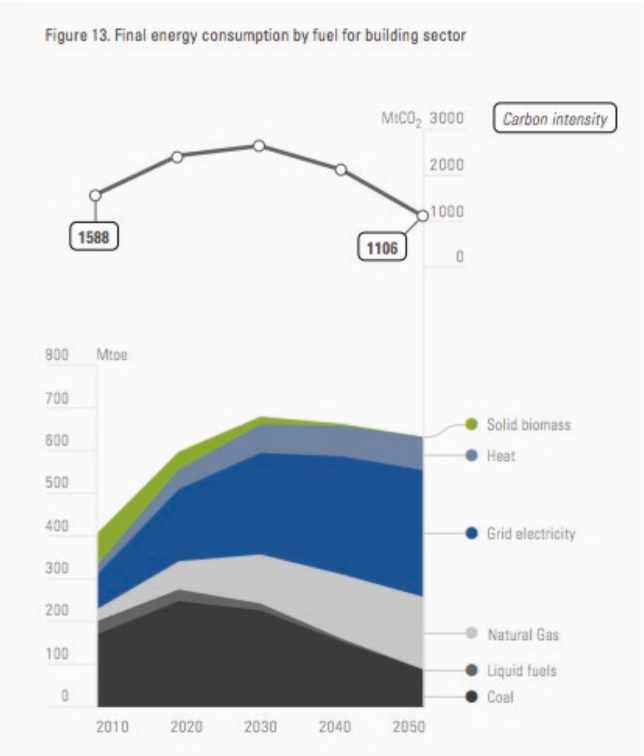


Figure 17. Low-carbon Transition in China's Buildings (Final Energy Consumption).



Building Energy Efficiency in France

Heating of residential buildings is responsible for a significant share of final energy consumption in France. As in many other developed countries with mature infrastructure, the core of the building stock was built decades ago with little attention to energy conservation. Increasing the energy efficiency of buildings is a key component of 2050 pathways for France. The France DDPP team developed two pathways, one focused primarily on reducing final energy consumption through efficiency (EFF scenario) and one with more emphasis on a diverse set of low-carbon energy supplies (DIV scenario). These show that pathways emphasizing ambitious reductions in energy consumption have much higher requirements for rates of thermal retrofits of existing buildings (Figures 18 and 19) likely requiring new policies to support up-front investment costs of retrofits.

Figure 18. The Retrofitting of Buildings as Key Theme of Pathways Analysis, France.

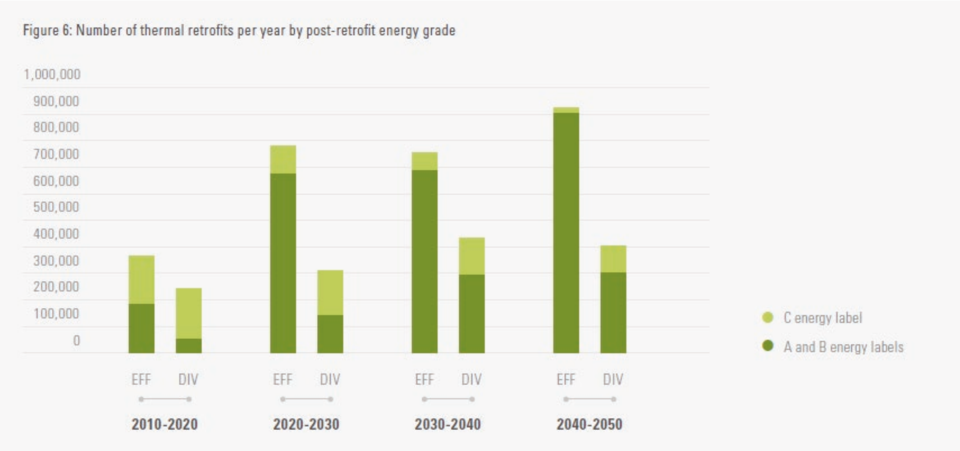
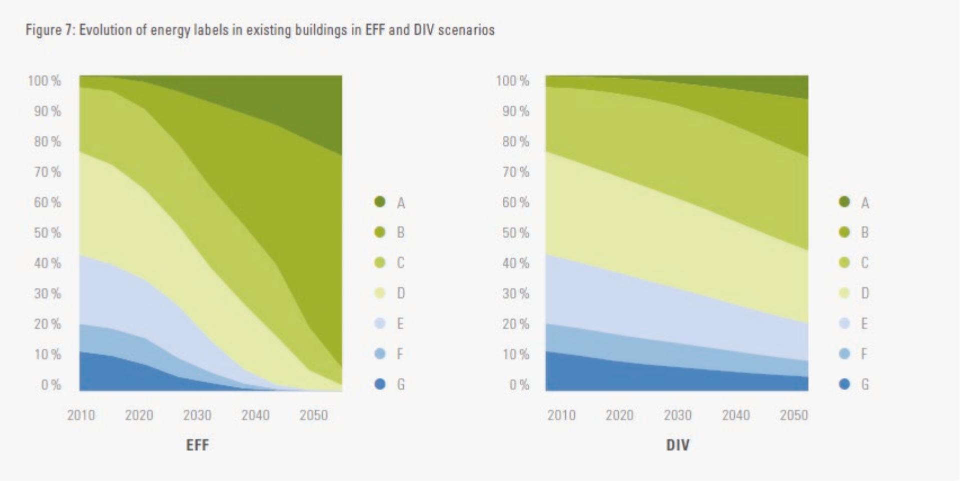


Figure 19. Building Stock Efficiency in Pathways Analysis, France.



Electricity Generation and Grid Balancing in the U.S.

A main concern of the U.S. DDPP pathways is demonstrating that electricity generation scenarios are technically feasible. The pathways feature four different electricity generation mixes; renewable, nuclear, CCS, and a mixed case (Figure 20). Across all cases, electricity generation increases dramatically, despite high levels of energy efficiency, due to electrification of end uses in transportation, buildings and industry. To explore balancing requirements for high levels of intermittent renewable generation, the U.S. DDPP team developed an hourly dispatch model. They found that a high renewables system can be balanced economically by a combination of flexible demand, energy storage, natural gas generation, and curtailment, with production of hydrogen and synthetic natural gas from electricity becoming increasingly important after 2030 (Figure 21).

Figure 20. Electricity Generation Mixes in U.S. Pathways.

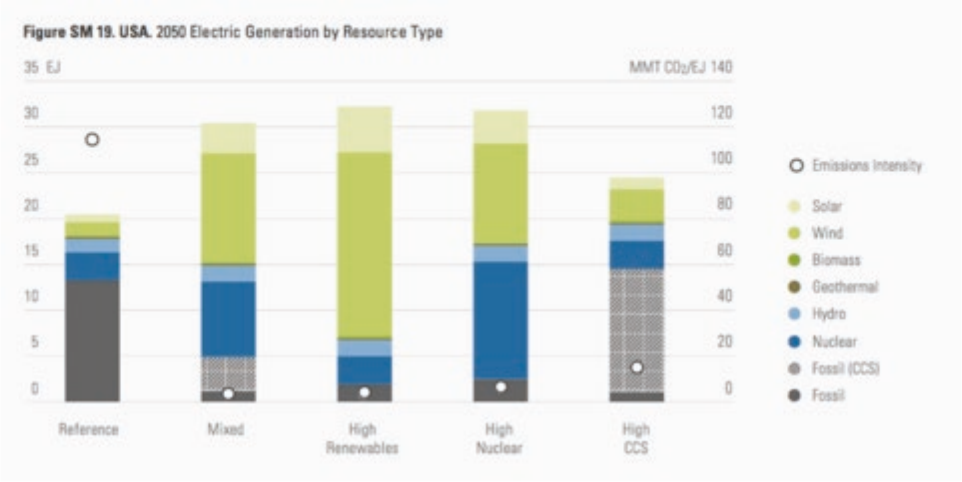
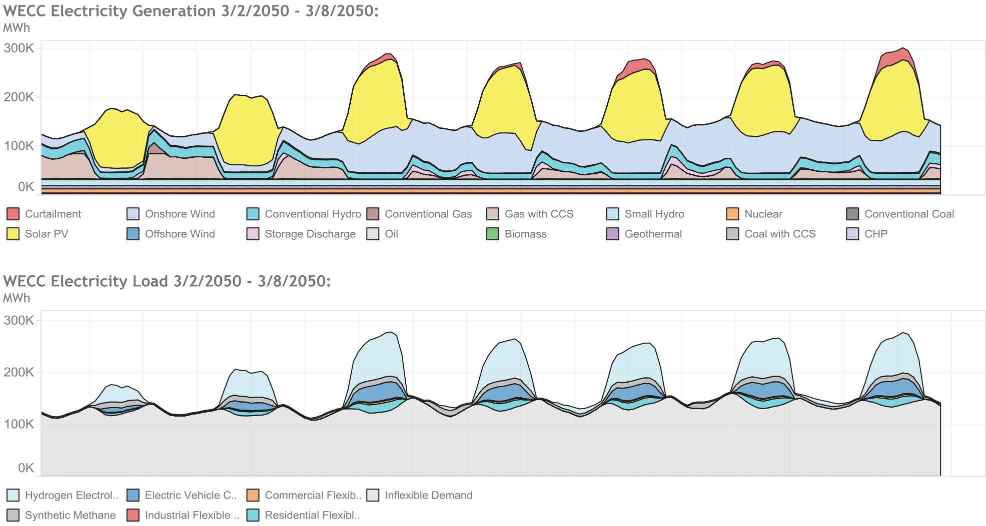


Figure 21. Hourly Electricity Dispatch in Western U.S. in March 2050.



Cost and investment

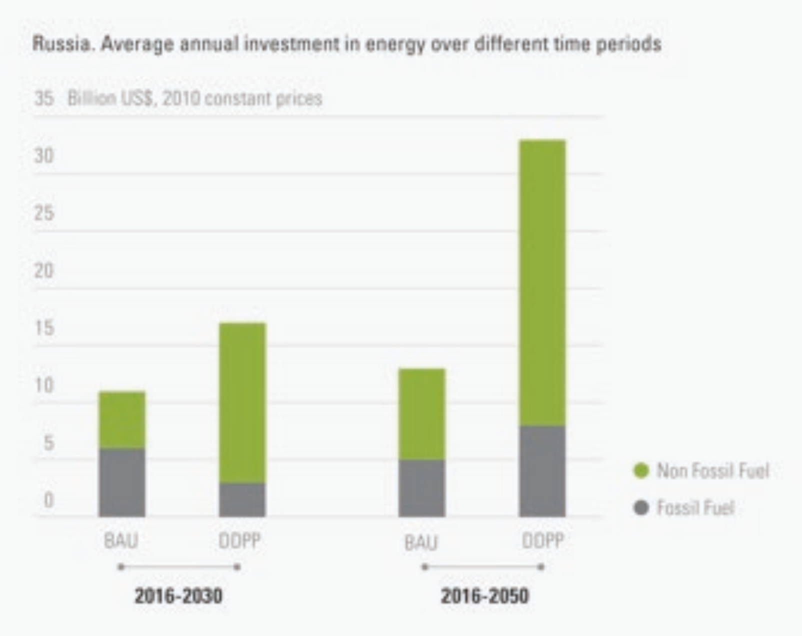
The examples below illustrate analyses of costs and investment requirements highlighted in DDPP country pathways:

- Investing in energy diversification in Russia
- Household energy cost in Australia

Investing in Energy Diversification in Russia

The Russian government has initiated an economic modernization policy to move the Russian economy away from dependency on revenues from oil and gas and towards a diversified economy based on high technology and innovation. Among the key elements of this policy are improvements in energy efficiency and nuclear technology. The Russia 2050 pathways focus on investments in low-carbon technologies that are consistent with diversification of the energy system and economic resilience (Figure 22).

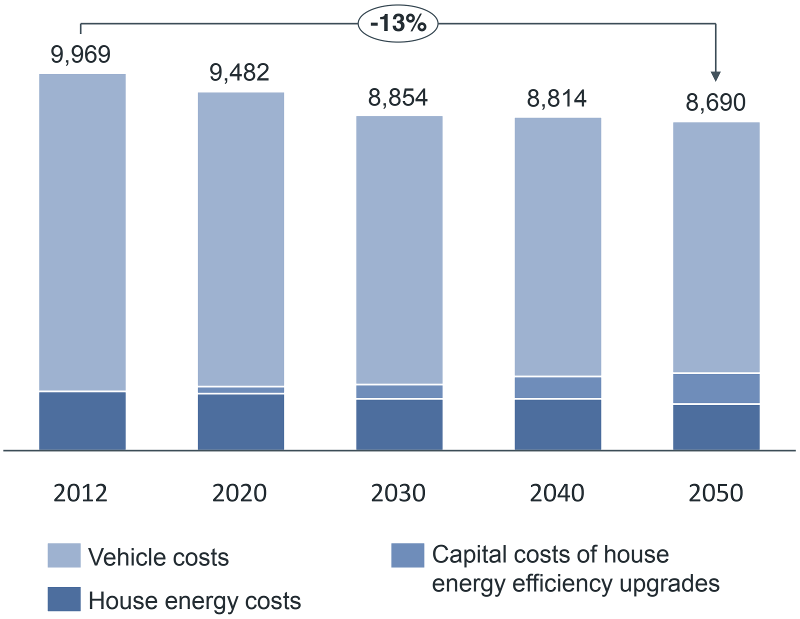
Figure 22. Average Annual Investments in Energy as Key Theme of Russia Pathways.



Household Energy Costs in Australia

A key concern in Australia is the cost of deep decarbonization to households. The Australian 2050 pathways analysis found that ambitious energy efficiency combined with use of decarbonized energy sources in residential buildings and personal transport, reduced emissions whilst also reducing the net cost of energy for households. In buildings and transportation, higher unit costs for clean energy were offset by greater efficiency, leading to lower net costs (Figure 23).

Figure 23. Average Annual Energy and Personal Transport Costs per Household (2012 A$).



Energy and transport costs per HH
-13%

GDP per HH
+55%

Energy costs as a % of GDP per HH
-44%

Fossil Fuel Producer Transitions

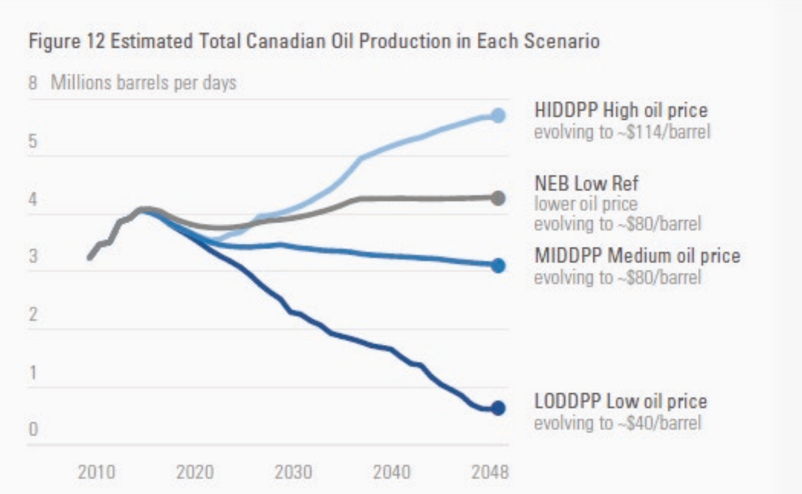
The examples below illustrate analyses of potential impacts of deep decarbonization on fossil fuel producing countries in DDPP country pathways:

- Oil production in Canada
- Unrecovered coal resources in Indonesia

Oil Production in Canada

Canada's carbon-intensive primary extraction and heavy industry sectors are vulnerable in a decarbonizing world. However, pathways analysis shows that the economy can be made more resilient if carbon policies as strong as, or stronger than those of its trading partners, are adopted in time. Figure 24 shows Canadian oil output under different scenarios, all of which can lead to continued rates of high GDP growth despite reduction in oil revenues.

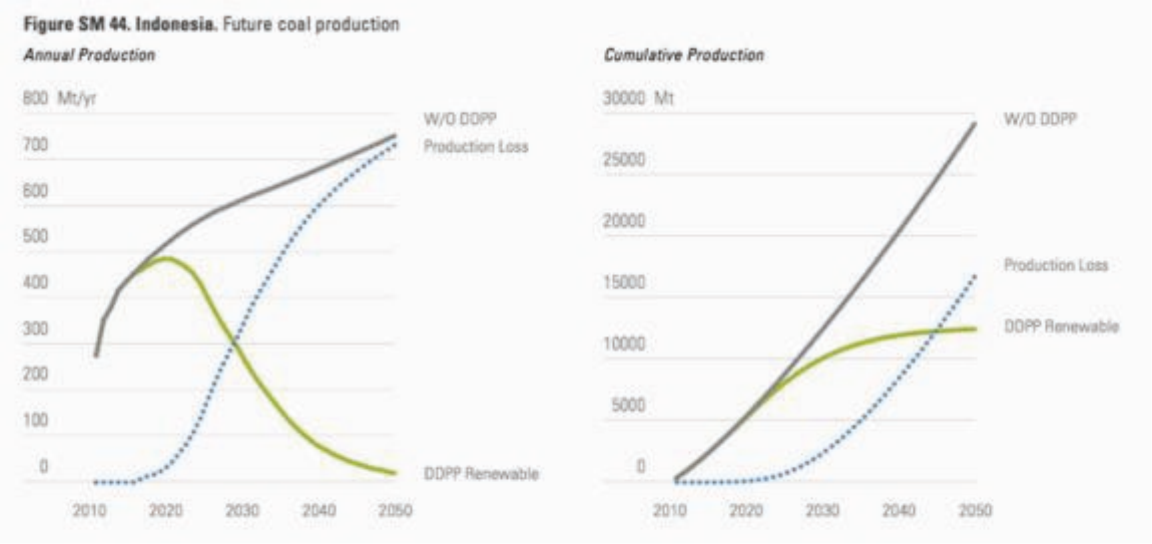
Figure 24. Country-Specific Scenarios for Fossil Fuel Production Transition as Key Theme of Pathways Analysis, Canada.



Unrecovered coal resources in Indonesia

Indonesia's 2050 pathways feature a large-scale deployment of renewables and nuclear power as a substitute for coal, resulting in a cumulative reduction in coal production from 2016 to 2050 of around 14 billion tonnes (Figure 25). The low-carbon economy offsets losses in the coal sector through the creation of a domestic renewable energy industry and decreased dependence on coal export revenues, whose decline over the last 10 years as a result of the drop in Chinese demand have affected Indonesia's growth rate.

Figure 25. Use of Coal Resources in Indonesia Under Deep Decarbonization.



Agriculture, forestry, and land use

AFOLU pathways in Indonesia

The Indonesian 2050 pathways study indicates that the AFOLU emission can be reduced significantly and, possibly, become net negative by 2050. The strategies include improving land and forest management, use of land with low soil carbon stocks for agriculture and timber plantations, and improved mitigation policies (including a moratorium on peatland permits and restoration of peatland).

Figure 26. AFOLU Emissions in Pathways Analysis, Indonesia.

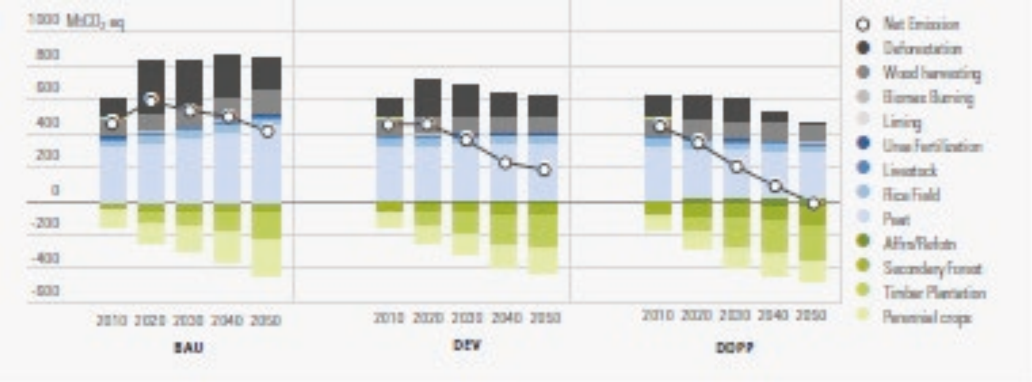
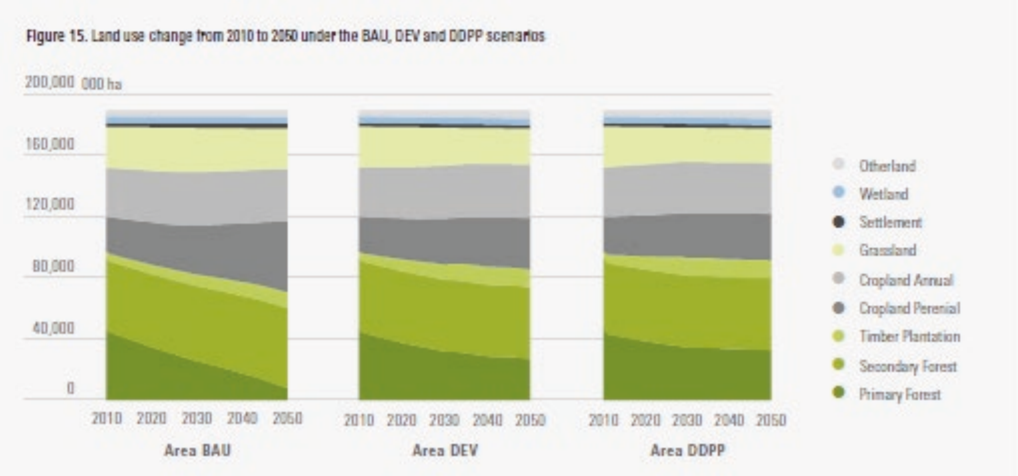


Figure 27. Land Use Change in Pathways Analysis, Indonesia.



2. Subnational pathways

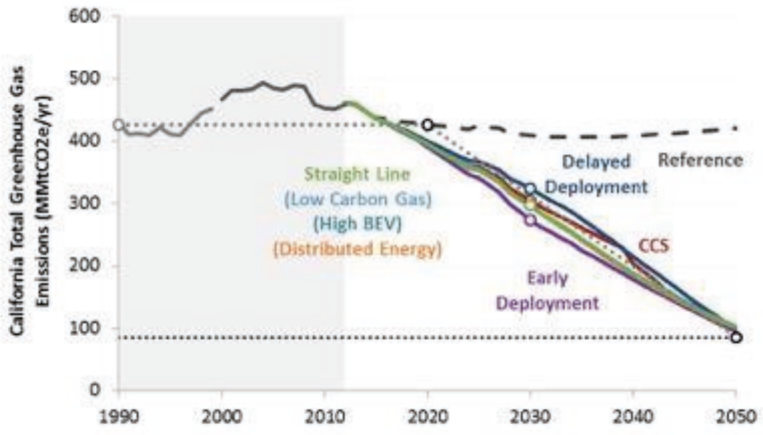
2.1 California

The state of California is a global leader in 2050 pathways studies which play an important practical role in state climate and energy policy. Pathways analysis has been used to set emissions targets and inform sectoral policies in transportation, electricity, buildings, industry, and land use. Official pathways studies have been commissioned by the state government and complemented by analysis from academia, NGOs, and the private sector. California, as a founding member of the Under 2 MOU coalition, supports other sub-national governments in developing 2050 pathways to increase ambition and inform implementation.

Backcasting, narratives, and key metrics

A pathways study for state government, based on backcasting from the state's long-term emissions target (80% below 1990 levels by 2050) was used to develop a mid-term target (40% below 1990 by 2030) that forms a stepping-stone between current policies and the mid-century goal, whilst helping stakeholders visualize the choices, challenges, and opportunities along the way. Six scenarios were developed that reflect likely narratives of deep decarbonization in the state. These include a central case that would reduce emissions at a continuous rate from present day to the mid-century goal ("straight line" scenario) and three variants with different technology emphases (low-carbon pipeline gas, high electric vehicle and high distributed solar) along with two scenarios that employ the same measures as the central case but either accelerate or delay their implementation in the near term (Figure 28). All of these scenarios assumed the same level of economic activity and demand for energy services as in a reference case with business-as-usual emissions.

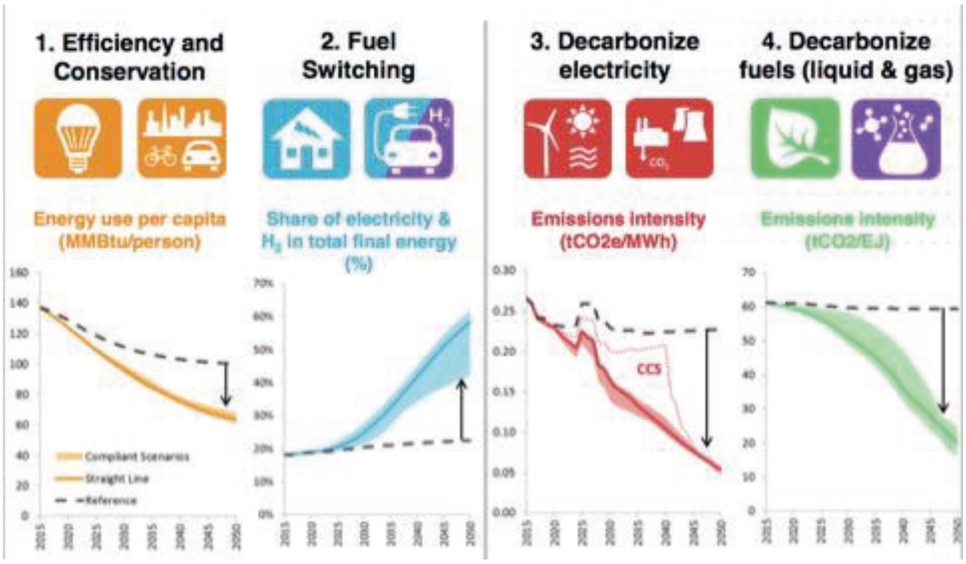
Figure 28. California 2050 Pathways Scenarios: Four Reduce GHG Emissions at a Continuous Rate From Present to the 2050 Target, and Two Accelerate or Delay Reductions.



Energy and Environmental Economics (E3)

The California pathways study above found that deep emissions reductions must be founded on four key elements: energy efficiency and conservation, fuel switching, electricity decarbonization, and fuel decarbonization. These elements are the same as the "three pillars" discussed elsewhere, with electricity and fuel broken out separately. Quantitative values for each of these metrics across all scenarios (Figure 29) show the minimum benchmarks that must be reached each year, regardless of the pathway chosen, for the 2030 and 2050 targets to be met.

Figure 29. Four Key Elements of California 2050 Pathways.

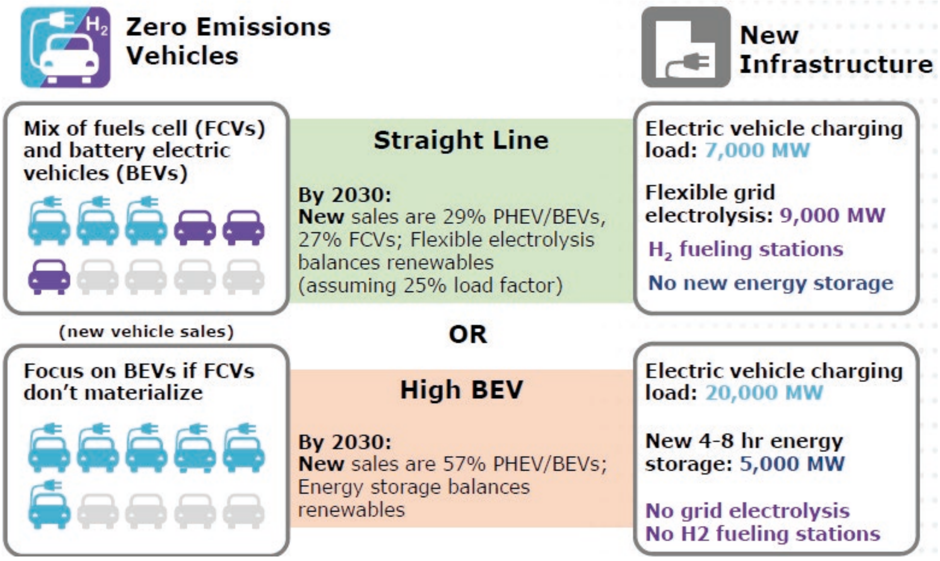


Energy and Environmental Economics (E3)

Physical transformation

One role of California's 2050 pathways analysis is the identification of how different decarbonization paths taken in one sector could affect those in other sectors. For example, a future low-carbon light duty vehicle (LDV) fleet may consist of different shares of electric vehicles (EVs) and hydrogen fuel cell vehicles (FCVs) depending on consumer adoption. This potential "fork in the road" for LDVs would clearly affect vehicle manufacturing but it could also significantly affect the electricity system, which would need to support high levels of vehicle charging in a high EV case, high levels of grid electrolysis in a high FCV case, or medium levels of both in a mixed case (Figure 30). This demonstrates the need for coordinated planning and investment across two sectors, transportation and electricity, that presently have little connection in terms of markets or governance mechanisms.

Figure 30. Two Scenarios of Low-carbon Light Duty Vehicle Fleets in California and Their Implications for Demand on the Electricity System in 2030.



By 2030:
New sales are 29% PHEV/BEVs, 27% FCVs; Flexible electrolysis balances renewables (assuming 25% load factor)

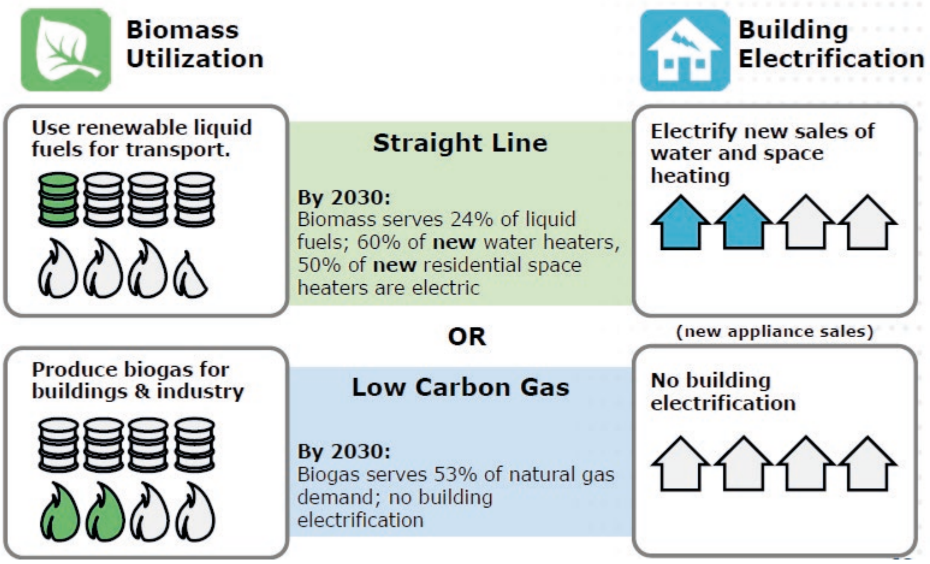
Electric vehicle charging load: 7,000 MW
Flexible grid electrolysis: 9,000 MW
H_2 fueling stations
No new energy storage

By 2030:
New sales are 57% PHEV/BEVs; Energy storage balances renewables

Electric vehicle charging load: 20,000 MW
New 4-8 hr energy storage: 5,000 MW
No grid electrolysis
No H2 fueling stations

Another "fork in the road" for California concerns a choice in decarbonization strategies for buildings between electrification of end uses such as space heating, water heating, and cooking and the continued use of gas combustion for these purposes, with low-carbon pipeline gas derived largely from biomass replacing fossil natural gas (Figure 31). This demonstrates the potential need for coordinated planning and investment in several areas: utility distribution systems (electricity vs. pipeline gas) primary energy supplies (wind and solar vs. biomass) and demand side strategies for buildings (electrified appliances vs. high thermal efficiency).

Figure 31. Two Scenarios of Decarbonization in Buildings and Their Implication for Low-carbon Energy Supplies in 2030.



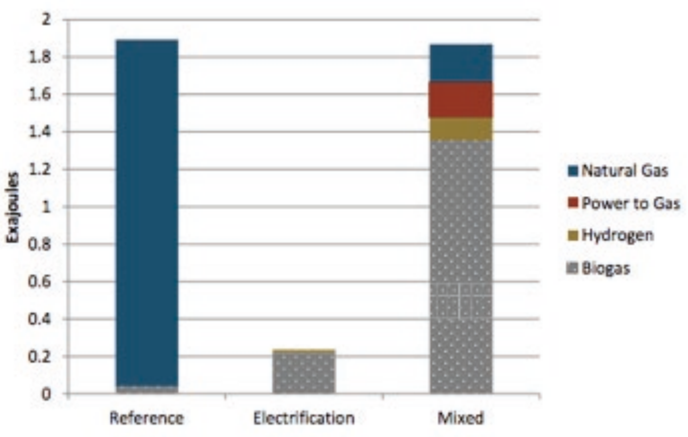
By 2030:
Biomass serves 24% of liquid fuels; 60% of **new** water heaters, 50% of **new** residential space heaters are electric

By 2030:
Biogas serves 53% of natural gas demand; no building electrification

Business pathways

To explore the electrification versus decarbonized pipeline gas question from the business perspective, the largest natural gas distribution utility in the U.S, Southern California Gas Company (SCG) commissioned its own 2050 pathways analysis of California. This study explored potential outcomes for future pipeline gas technology and sales under different deep decarbonization strategies in California. Figure 32 shows two deep decarbonization scenarios in 2050, a high electrification case that shows drastically reduced demand for pipeline gas, and a case with pipeline gas derived more than 90% from biomass and electricity that maintains combustion end-uses. The study showed the potential for the gas pipeline to store hydrogen and synthetic methane produced from electricity, providing energy storage for seasonal renewable over-generation along with a low-carbon fuel.

Figure 32. Composition of California Pipeline Gas Supply for Four Scenarios (2050).



Energy and Environmental Economics (E3)

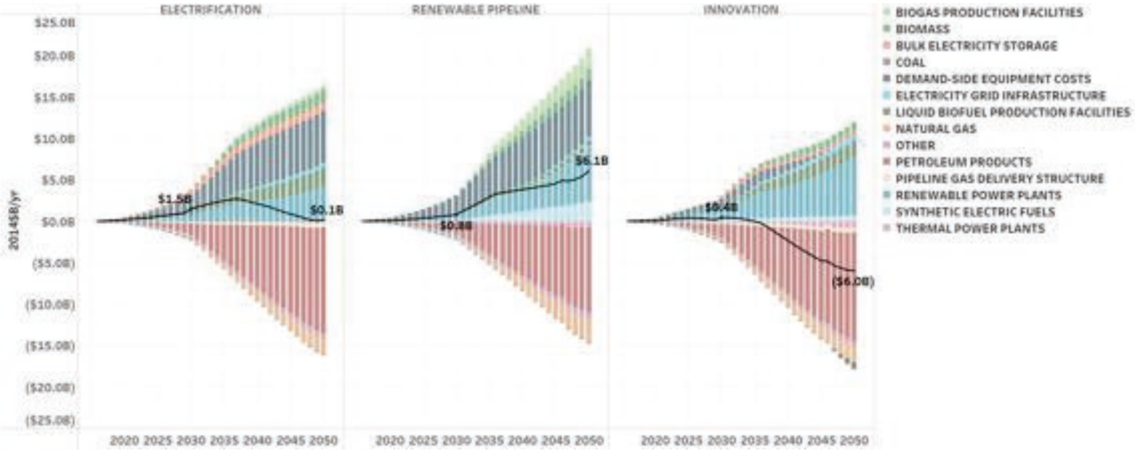
2.2 Washington

The state of Washington, a member of the Under 2 Coalition, has conducted a 2050 pathways study to better understand its options for achieving emissions targets already legislated, and more stringent ones proposed, whilst simultaneously meeting its economic growth objectives. Washington wants to demonstrate leadership on climate policy and to capitalize on its competitive advantage in already having the lowest-carbon electricity in the U.S.

Cost and investment

The Washington study developed three pathways scenarios based on backcasting from the state's long-term emissions goal of 80% below 1990 by 2050. The scenarios are electrification (which shifts end uses that currently combust fossil fuels to low-carbon electricity) renewable pipeline (which maintains combustion end uses by decarbonizing the pipeline gas) and innovation, which features technology breakthroughs. The net cost of energy supply and end use in each of these scenarios is shown in Figure 33. Positive costs are primarily for low-carbon and efficient technologies, while negative costs are primarily for avoided fossil fuels. Net costs for all scenarios are less than 1% of projected gross state product. The innovation scenario shows increasing economic benefits over time, arising in large part from deployment of autonomous, shared low-carbon vehicles.

Figure 33. Net Energy System Costs for Three Deep Decarbonization Scenarios.



Evolved Energy Research

The impact of these pathways on household costs for energy services (home heating, cooling, cooking and lighting plus personal transportation) is shown in Figure 34. Increased costs for electricity and low-carbon vehicles and equipment are offset by avoided costs of fossil fuel purchases.

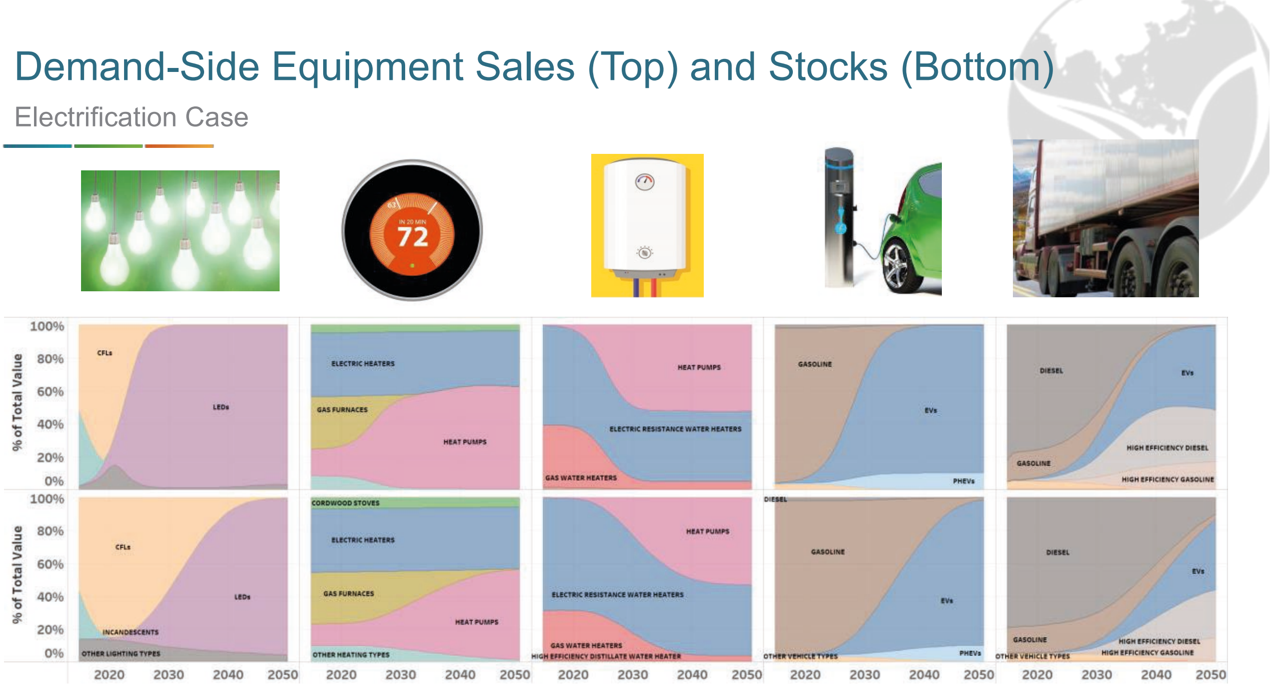
Figure 34. Household Net Costs of Energy Services for Washington State Deep Decarbonization Scenarios in 2030 and 2050 (US$ per Month).

Evolved Energy Research

Physical transformation

Some indicators of the physical transformation required to achieve the state's 2050 emissions goal, expressed in annual sales and total stocks of important low-carbon end use equipment (residential building equipment, passenger and freight vehicles) are shown in Figure 35. The rapid transitions shown are technically feasible but will require high rates of consumer adoption.

Figure 35. Equipment Sales and Stocks: Residential Lighting, Heating, and Water Heating, Light-duty and Freight Vehicles Towards Deep Decarbonization Goals in Washington State.



Residential lighting, residential space heating, residential water heating, light duty vehicles, medium & heavy-duty vehicles

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