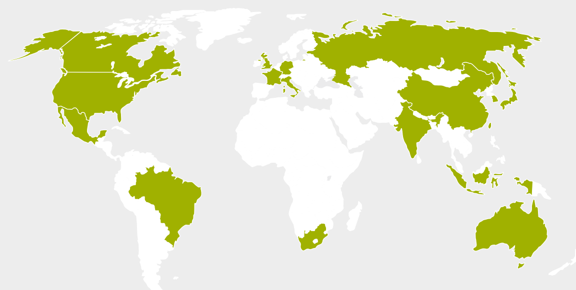
DDPP
DEEP DECARBONIZATION PATHWAYS PROJECT

2015 report

executive summary

pathways to deep decarbonization



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SUSTAINABLE DEVELOPMENT SOLUTIONS NETWORK
A GLOBAL INITIATIVE FOR THE UNITED NATIONS

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IDDRI

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SUSTAINABLE DEVELOPMENT SOLUTIONS NETWORK
A GLOBAL INITIATIVE FOR THE UNITED NATIONS

The Sustainable Development Solutions Network (SDSN) was commissioned by UN Secretary-General Ban Ki-moon to mobilize scientific and technical expertise from academia, civil society, and the private sector to support practical problem solving for sustainable development at local, national, and global scales. The SDSN operates national and regional networks of knowledge institutions, solution-focused thematic groups, and is building SDSNedu, an online university for sustainable development.

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1 What is the DDPP?

Purpose: The Deep Decarbonization Pathways Project (DDPP) is a collaborative global research initiative to understand how individual countries can transition to a low-carbon economy consistent with the internationally agreed goal of limiting anthropogenic warming to less than 2 degrees Celsius (°C). Staying within this limit requires global net emissions of greenhouse gases (GHG) to approach zero in the second half of this century. This will entail, more than any other factor, a profound transformation of energy systems, through steep declines in carbon intensity across all sectors, a transition we call "deep decarbonization".

Organization: The DDPP consists of research teams from 16 countries representing 74% of current global CO_2 emissions from energy: Australia, Brazil, Canada, China, France, Germany, India, Indonesia, Italy, Japan, Mexico, Russia, South Africa, South Korea, the United Kingdom, and the United States. The teams consist of scholars from leading research institutions in their respective countries, who are acting independently and do not represent the official positions of their national governments. The DDPP is convened by the Sustainable Development Solutions Network (SDSN) and the Institute for Sustainable Development and International Relations (IDDRI) and coordinated by a joint secretariat of these organizations.

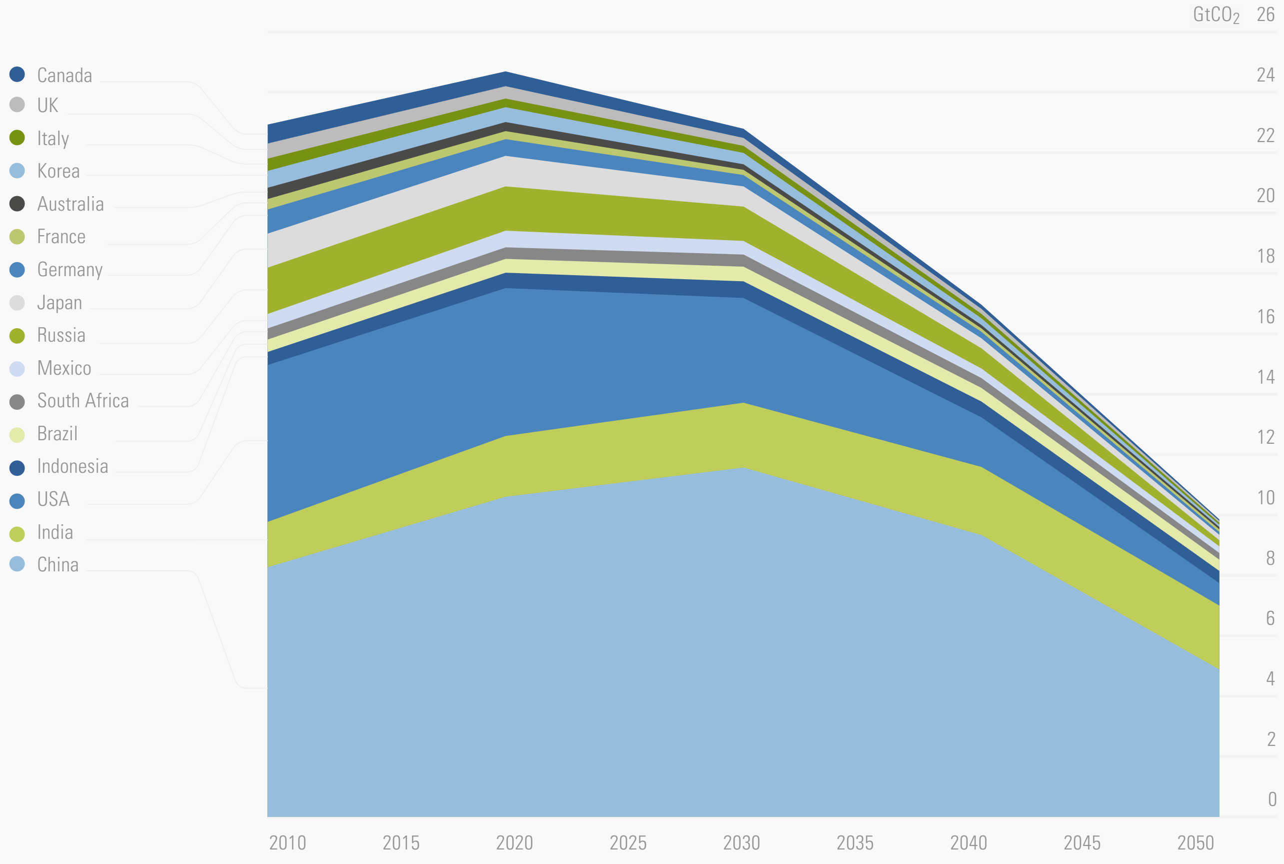
Approach: The DDPP fills a gap in the climate policy dialogue by providing a more concrete understanding of what is required for countries to reduce emissions consistent with the 2°C limit. The research teams develop "deep decarbonization pathways" (DDPs)—sector-by-sector blueprints of changes over time in physical infrastructure such as power plants, vehicles, buildings, and industrial equipment—that inform decision makers about the technology requirements and costs of different options for reducing emissions. DDPs are not forecasts of future outcomes, but "backcasts" that begin with an emissions target in 2050 and determine the steps required to get there. Country teams are autonomous in defining their targets, choosing their analytical methods, and incorporating national aspirations for development and economic growth in their scenarios, along with other features of national context such as existing infrastructure, technology preferences, and natural resource endowments. At the same time, the DDPP is highly collaborative, with transparent sharing of methods, tools, data, and results among the country teams.

Results: Formed in October 2013, the DDPP issued a report on the first phase of its work at the United Nations Climate Summit in September 2014, at the invitation of Secretary General Ban Ki-moon. This report summarized the initial research of each country team. In the fall of 2015, all 16 teams are publishing stand-alone reports describing in greater detail their research into national DDPs. In addition, a new synthesis report provides a cross-cutting analysis of the aggregate results.

2 Is limiting global warming to 2°C achievable?

Deep decarbonization of today's highest emitting economies is technically achievable and can accomodate expected economic and population growth. Each country team produced multiple technically feasible pathways that resulted in deep decarbonization of their economies. Across all scenarios, by the year 2050 energy-related CO_2 emissions for the 16 DDPP countries were reduced to 9.8-11.9 Gt CO_2, or 48-57% below 2010 levels (Figure 1). These scenarios take into account expected population growth of 17% on average across the DDPP countries during the 2010-2050 period, and also accommodate aggregate GDP growth of 250%—an average rate of 3.1% per year—during the period. In the most ambitious set of scenarios, average per capita emissions in 2050 were reduced to 2.1 t CO_2/person across countries, while average emissions

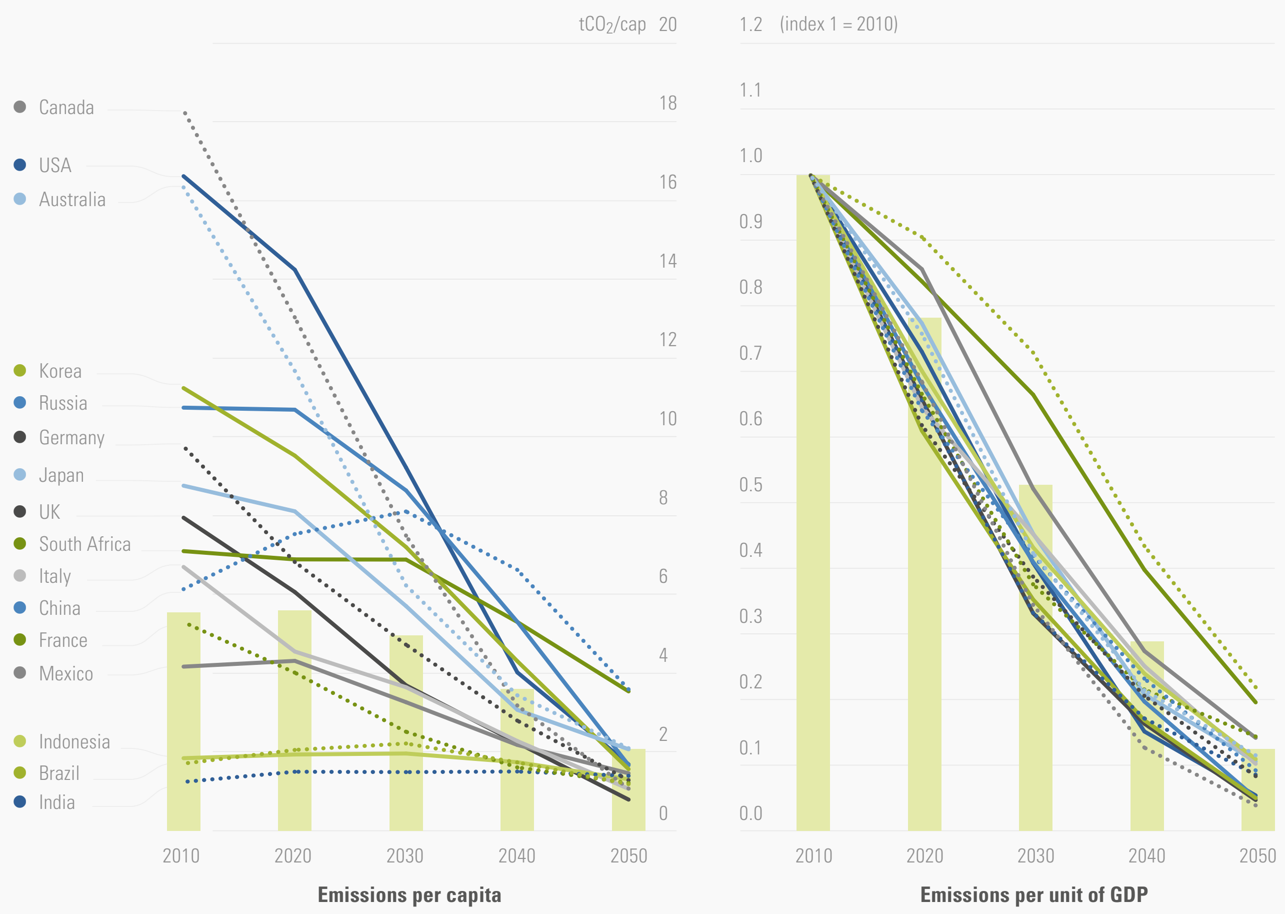
Figure 1. Emissions trajectories for energy CO_2, 2010-2050, showing most ambitious reduction scenarios for all DDPP countries. 2050 aggregate emissions are 57% below 2010 levels.



per unit of GDP were reduced 87% relative to 2010, with a range of 80-96% across countries (Figure 2). This order of magnitude decrease in carbon intensity of GDP shows the scenarios to be truly transformative. The clustering of carbon intensity trajectories shows similar levels of ambition across DDPP countries even while absolute emissions trajectories reflect different stages of economic development.

These results do not represent an upper limit on emissions reduction potential for the 16 countries analyzed. In the first phase of the DDPP, the research teams have focused primarily on understanding technical options and enabling conditions for deep decarbonization by mid-century within their countries, but did not necesssarily design their pathways to minimize cumulative emissions. However, the analysis has already revealed opportunities for deeper reductions and earlier timing of the low-carbon transition. These opportunities will be explored further during the next phase of DDPP research.

Figure 2. (L) Energy-related CO_2 emissions per capita for DDPP countries, (R) Energy-related CO_2 emissions per unit of GDP for DDPP countries 2010 to 2050, indexed to 2010.



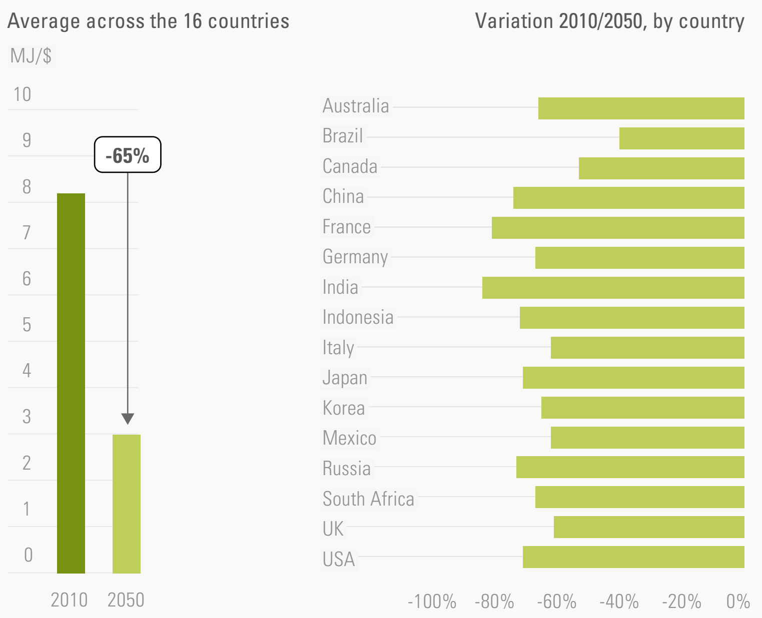
DDPP cumulative emissions are not inconsistent with the 2°C limit, in comparison to an IPCC benchmark. However, since only 16 countries were covered by the DDPP analysis, demonstrating that staying within 2°C is likely will require understanding the decarbonization opportunities in non-DDPP countries, and may well require deeper emissions reductions than in the current pathways in the DDPP countries. The DDPP scenarios result in cumulative 2011-2050 emissions of 805 to 847 Gt CO_2 from energy during 2010-2050. A context for assessing these emissions levels is found in the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), which defines ranges of CO_2 emissions associated with different likelihoods of limiting global warming to 2°C (Table 1). The difference between these benchmark values and DDPP cumulative emissions must allow for emissions from sources that were not analyzed, including land use and industrial process emissions, and most notably energy CO_2 from non-DDPP countries. Many of these are low-income, low-emissions countries for which deep decarbonization has not been explored in this analysis. It is not implausible that non-DDPP countries can achieve their economic development objectives while following emissions pathways that, in combination with DDPP cumulative emissions, result in total global emissions in the probability range of "as likely as not" for limiting warming to 2°C. Explicit analysis of non-DDPP countries will be required to characterize these emission pathways and their enabling conditions. Deeper emission reductions in DDPP countries will also increase the likelihood of staying below 2°C.

Table 1. Comparison of DDPP emission levels to IPCC benchmarks for different likelihoods of limiting global warming to 2°C, as a function of cumulative and 2050 emissions levels

	Likelihood of staying below 2°C during the 21st century (IPCC benchmark)		DDPP emissions (energy-related CO_2 for DDPP countries)
	Likely	As likely as not	
Cumulative CO_2 emissions to 2050 ($GtCO_2$)	550* 1300*	1130* 1530*	805** 847**
CO_2 emissions in 2050 relative to 2010	-72% -41%	-55% -25%	-57% -48%

* (2011-2050) ** (2010-2050)

Figure 3. (L) Average energy intensity of GDP for DDPP countries as a whole, 2010 and 2050. (R) Changes in energy intensity, 2010 to 2050, for individual DDPP countries.



All deep decarbonization pathways incorporate "three pillars" of energy system transformation: energy efficiency and conservation, decarbonizing electricity and fuels, and switching end uses to low-carbon supplies. These measures were all implemented using technologies that are commercially available or expected to be in the time frame of the analysis. The DDPs show multiple ways of implementing the three pillars, with country-specific strategies, technology mixes, and sequences of action. However, because of the interactive effects between them—for example, using low-carbon electricity in combination with the electrification of vehicles—deep decarbonization cannot be achieved if any of the pillars is absent or implemented at insufficient scale.

Energy efficiency reduced the energy intensity of GDP by an average of 65%, with nearly all countries making their economies two to four times more energy efficient in 2050 than in 2010 (Figure 3). This was accomplished through measures such as improving vehicle fuel economy, better building design and construction materials, and more efficient appliances and industrial processes and machinery, along with conservation measures such as urban design to encourage walking and bicyling.

In all DDPs, electricity becomes nearly carbon free by 2050, with average emissions per kWh reduced by a factor of 15 below the 2010 value (Figure 4). This was accomplished by progressively replacing most uncontrolled fossil fuel-based electricity generation with varying mixes of renewable energy such as wind, solar, geothermal, and hydropower; nuclear power; and fossil fuel generation with carbon capture and storage. In addition, liquid and gas fuel supplies were decarbonized using biomass fuels with low embedded carbon emissions and synthetic fuels such as hydrogen produced from decarbonized electricity.

The dominant trend in final energy consumption is to replace coal and petroleum with electricity and lower carbon fuels, including a coal to natural gas shift in some DDPs. Much of the direct combustion of fossil fuels in end-use equipment such as automobiles, hot water heaters, and industrial boilers is replaced by decarbonized electricity, which more than doubles the share of electricity in final energy consumption in 2050, to more than 40% (Figure 5).

Figure 4. (L) Average carbon intensity of electricity for DDPP countries as a whole, 2010 and 2050. (R) Carbon intensity of electricity in 2050, for individual DDPP countries.

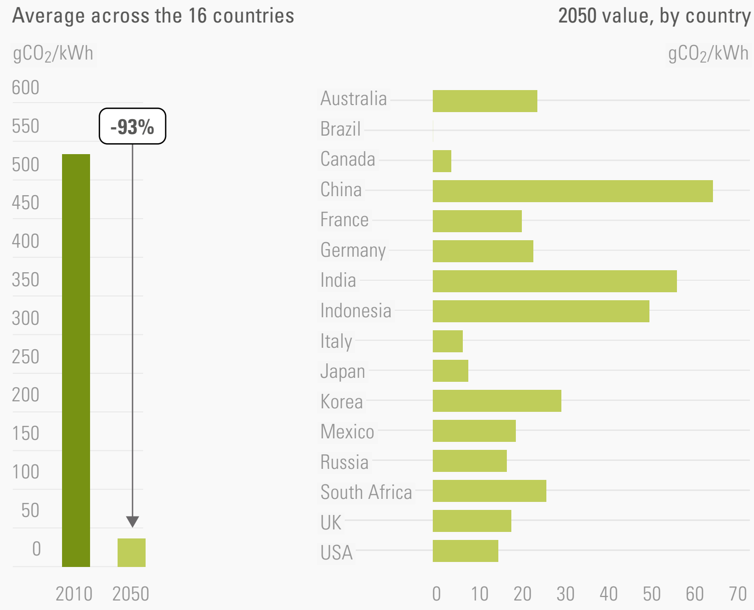
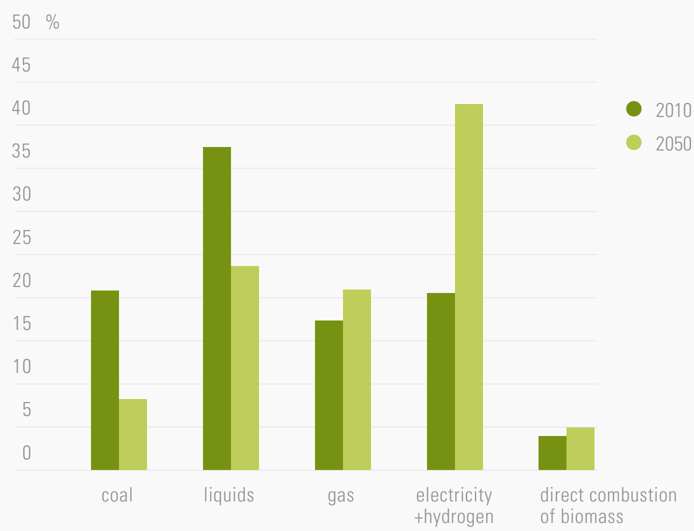


Figure 5. Share of different fuel types in final energy consumption.



3 Is deep decarbonization compatible with development and economic growth?

Deep decarbonization accomodates the energy services needed to meet countries' economic growth targets and social priorities. In the DDPs, the energy systems were designed to support all the energy services needed to meet national objectives, including expanded access to energy in developing countries. Economies continue to transport passengers and ship freight, provide similar or better housing and public amenities, and support high levels of industrial and commercial activity. The lowest income countries assumed the GDP growth rates needed to meet their development objectives, and per capita energy consumption increased with the population's access to energy services and higher living standards. The scale of infrastructure required to support these services is indicated by cumulative technology deployments over time aggregated across all the DDPs. For example, by 2050 the DDPs show a cumulative deployment of 3,800 GW of solar electricity generation and 4,100 gigawatts of wind, along with 1.2 billion electric, fuel cell, and plug-in hybrid passenger vehicles and 250 million alternative fuel freight vehicles.

DDPs show that deep decarbonization can support sustainable development and has many potential benefits, The most fundamental benefit is avoiding dangerous climate change. Unabated climate change threatens to undermine well-being in all countries, with the most vulnerable populations being the most at risk; in developing countries it jeopardizes many development goals. On the other hand, the DDPs show that, if enabling conditions are met, the infrastructure transformation required for deep decarbonization can be done in a way that provides multiple economic and environmental benefits and opportunities for raising living standards.

For these benefits to be fully realized by developing countries, low-carbon technologies must be affordable and energy planning must take social priorities into account. This is illustrated by the South Africa DDP, which shows that it is possible to deeply decarbonize while improving income distribution, alleviating poverty, and reducing unemployment. India's DDPs are also structured around the question of how deep decarbonization can support sustainable development.

The aggressive energy efficiency required for deep decarbonization is a key strategy for reducing energy poverty and improving energy access. Energy efficiency reduces the cost of energy supply, thereby lowering household energy costs, which are often a large share of household expenses for the poor. With supply costs reduced, households can afford to increase their utilization of energy services. The importance of energy efficiency as a strategy for addressing energy poverty was highlighted not only in developing countries DDPs but also in those for the UK, France and Germany.

Reduction of uncontrolled fossil fuel emissions has significant public health benefits, as seen in the China and India cases, since fossil fuel combustion is the major source of air pollution. In the China DDP, deep decarbonization resulted in reductions of 42-79% of primary air pollutants (e.g., SO2, NO¬x, PM2.5, VOCs, and NH3), sufficient to allow major cities to meet air quality standards.

Reducing fossil fuel demand can increase the energy security of energy-importing countries, and reduce their exposure to volatile international fuel prices, as seen in the Italy and Japan DDPs, while diversification of energy supplies also has economic benefits for resource exporting countries such as Russia.

4 Is deep decarbonization affordable?

Deep decarbonization is essentially the process of improving infrastructure over time by replacing inefficient and carbon-intensive technologies with efficient and low-carbon technologies that provide the same (or better) energy services. In developing economies with rapid population growth, this means avoiding investments in carbon-intensive technologies and 'leap-frogging' the development patterns of the past century. At the global scale, this will require the deployment of vast amounts of new equipment based on clean technologies ranging from LED lighting to electric heat pumps, from hydrogen production to solar electricity generation. Achieving the required level of consumer adoption of these technologies will require an ongoing process of technology improvement and cost reductions in which policy will play a pivotal role.

Under deep decarbonization, the scale of investment in low-carbon technologies will be orders of magnitude higher than current levels, creating major economic opportunities for forward-looking countries and businesses (Table 2). With money to be made, global finance can and will provide the necessary investment, provided adequate long term signals are in place to manage risk and maintain the value of the invested capital over time. Because it emphasizes end-use efficiency (which is enabled by many types of technologies) and low-carbon energy sources (which can be more widely distributed),

Table 2 Annual investment in key low-carbon technologies and their share of GDP
for DDPP countries

		2020	2030	2040	2050
Annual investments in the 16 DDPP scenarios (Billion US $)	Low-carbon power generation	270	514	701	844
	Low-carbon fuel production	57	117	124	127
	Low-carbon transport vehicles (passenger+freight)	157	333	626	911
	Total	484	963	1452	1882
Annual investments in low-carbon technologies as a share of GDP (%)		0.8%	1.2%	1.3%	1.3%

a deeply decarbonized world is characterized by less concentration of energy investments (i.e. in fossil fuel industries) and potentially a more prominent role for decentralized investment decisions by consumers. This calls for incentives to guide energy investment decisions towards low-carbon solutions especially in cases of high capital costs offset by lower operating costs, and in early stages of deployment before economies of scale have been achieved.

Energy investment under deep decarbonization does not represent a large increase in the toal energy investment required in the absence of climate policy, but a shift in investment away from fossil fuels toward low-carbon technologies. The gross investment requirement for low-carbon technologies in the DDPs constitute 1-2% of GDP for the DDPP countries, or 6-7% of total annual investment activity in these economies, which constitutes on average about one-quarter of GDP (Table 2). When done with foresight, the economic story of energy sector decarbonization is primarily one of investment displacement, in which investment in the energy sector transitions away from fossil fuel extraction as demand decreases, and towards low-carbon technologies.

The net cost of supplying and using energy under deep decarbonization typically includes higher costs for efficient and low-carbon equipment relative to conventional equipment, offset by fossil fuel and total energy savings. This is illustrated by U.S. case, in which the net cost of supplying and using energy for a deeply decarbonized scenario in 2050 is equivalent to about 1% of GDP in that year (Figure 6).

Modest increases in capital costs do not necessarily translate to increased final energy costs because of efficiency and conservation measures. This is illustrated by the case of household energy and transport costs in the Australia DDP, in which net energy costs fall in absolute terms due to energy savings. Energy costs fall even further as a share of average household income as GDP grows.

Deep decarbonization in developing countries can be accelerated by large global markets for low-carbon technologies. Deep decarbonization in developing countries is limited by the rate at which efficient and low-carbon technologies are adopted. Because of the relatively high capital cost of many of these technologies, developing country DDPs generally assume later adoption, and lower penetration rates, than in industrialized countries. In the meantime, they are building durable infrastructure that locks in fossil fuel consumption. A potential solution to reducing cumulative emissions from developing countries is for high income countries to take the lead in developing, deploying, and buying down the cost of low-carbon technologies, so that they become affordable earlier in developing countries relative to the cost of conventional technologies. Where initial markets for these technologies are in developing countries, for example concentrating solar power in South Africa, high-income countries can assist in local technology development and manufacturing. This can accelerate uptake, stimulate economic development, expand markets and promote international trade in low-carbon technologies, while avoiding a situation in which developing countries become net importers of low-carbon technologies.

International agreement to cooperate in deep decarbonization offers the promise of rapidly expanding markets and potentially dramatic cost declines in many key low-carbon technologies. Historical experience has shown that technology costs tend to decrease as a function of cumulative production,

Figure 6. Net energy system cost in the United States.

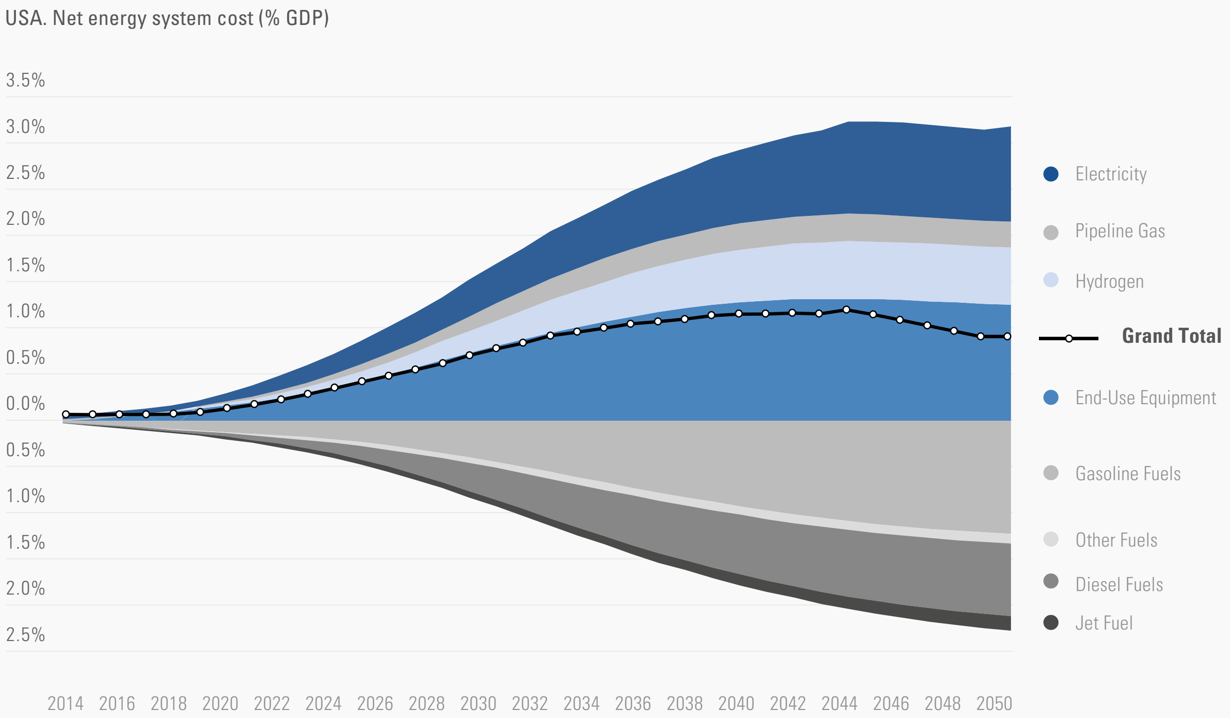


Figure 7. Average energy and personal transport costs per household in Australian DDP, 2012-2050.

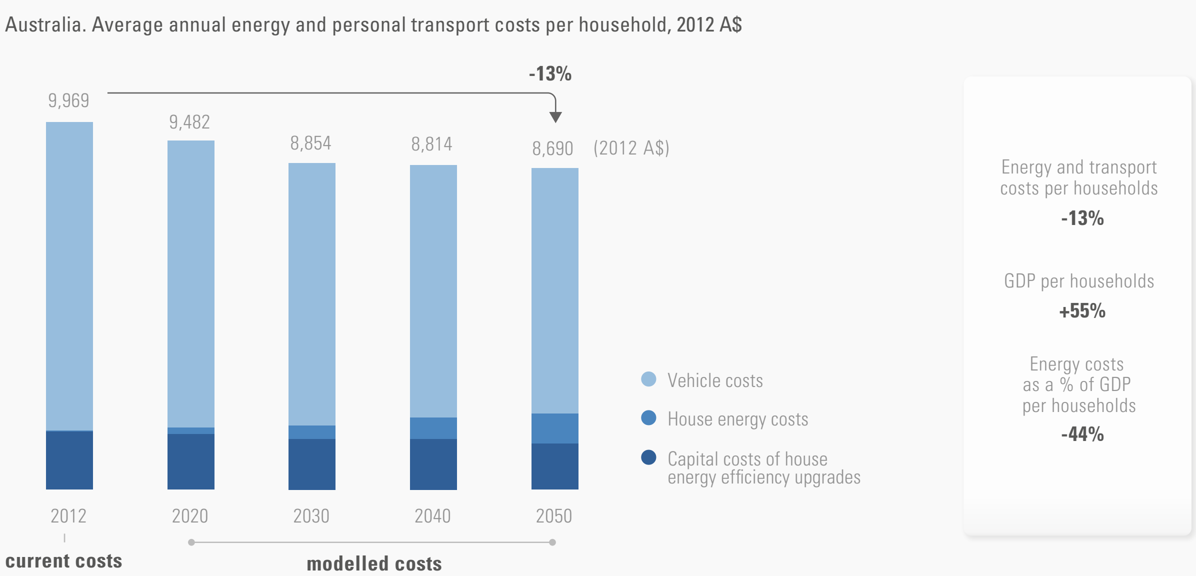
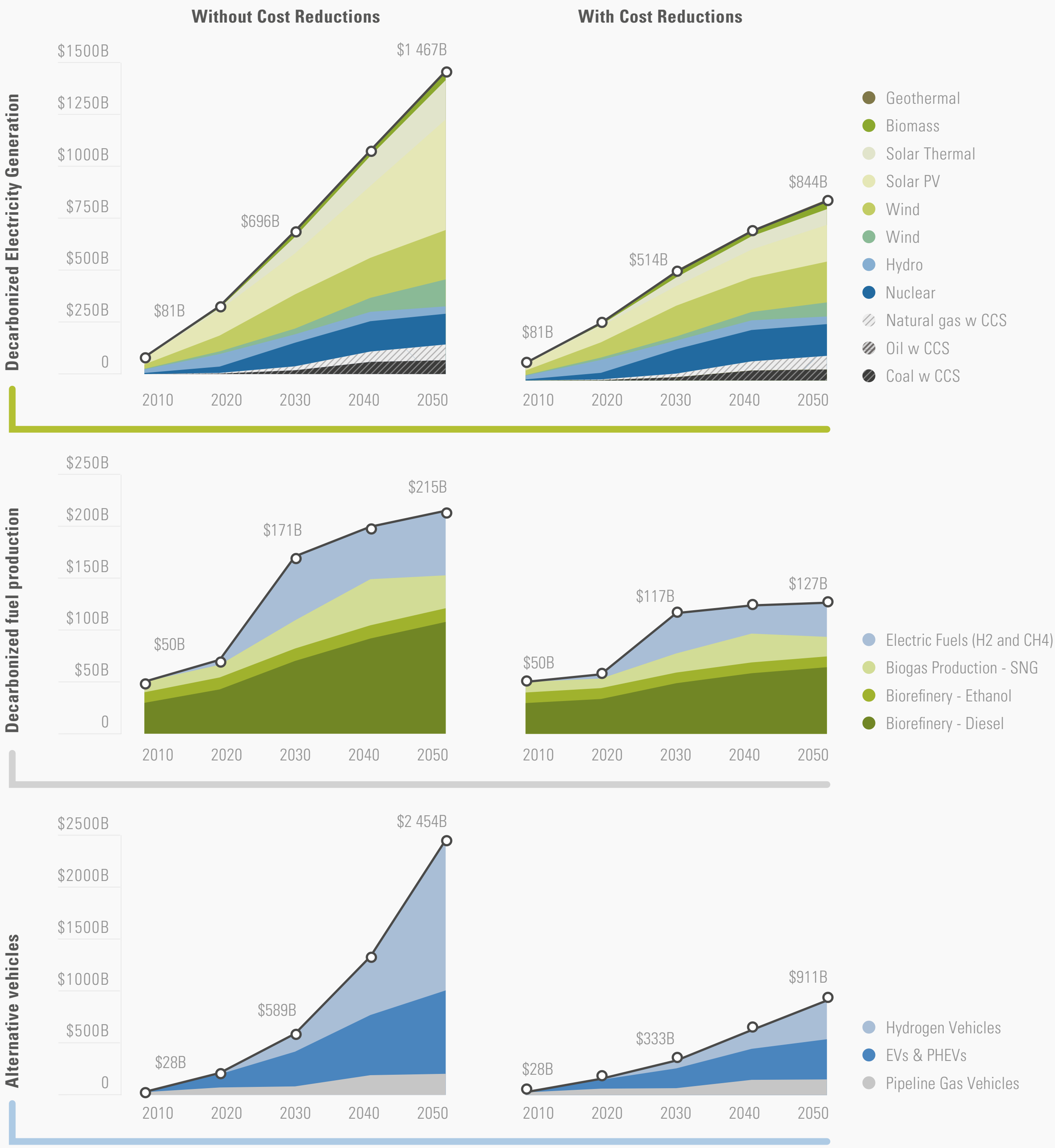


Figure 8. Annual investment requirements with vs without technological learning

(Left side, top to bottom) Annual investment requirements for decarbonized electricity generation, decarbonized fuel production, and alternative vehicles without technological learning. (Right side, top to bottom) Annual investment requirements for the same technologies with cost reductions due to technological learning taken into account.



as technologies mature and capture economies of scale, and learn more efficient production methods from experience. Applying historically-based assumptions about technological learning to key low-carbon technologies for power generation, fuel production, and transportation shows dramatic reductions in the cost of these technologies can be expected at the scale of production required by the country DDPs, relative to the cost without learning (Figure 8). Those savings illustrate how international cooperation in developing markets for low-carbon technologies can reduce cost for all countries relative to a go-it-alone approach, while providing large markets for technology providers and large incentives for further innovation. Mobilizing investment in the development and widespread deployment of low-carbon technologies—from research and development, to early-stage deployment, to full-commercialization—is the key to realizing cost declines along the pathway to deep decarbonization.

5 Why are deep decarbonization pathways essential for climate policy?

DDPs are needed for increasing the ambition of country commitments to reduce their GHG emissions under the UNFCCC. In advance of COP-21, countries are submitting Intended Nationally Defined Contributions (INDCs), which contain national commitments to emissions reductions, typically in a medium-term time frame (e.g., 2025 or 2030). By describing the full extent of the transformation required over a longer time frame, DDPs provide a unique context for understanding the ambition of current INDCs, and the further measures that deep decarbonization will entail. While DDPs are best seen as roadmaps of options and enabling conditions, they can nonetheless play a critical role in increasing the ambition of future national commitments, and provide long-term benchmarks for measuring short-term progress.

DDPs are needed for staying within carbon budgets and avoiding dead ends. Though 2050 may seem far away, the operational lifetimes of much of the infrastructure and equipment that drive CO_2 emissions—power plants, buildings, industrial boilers, heavy duty vehicles—are long compared to the time remaining between now and mid-century (Figure 9). DDPs support current policy and investment decisions by making the long-term emissions consequences of these decisions explicit. DDPs can help avoid lock-in to "dead end" investments that produce incremental emissions reductions in the short term, but are not compatible with deep decarbonization in the long term, posing the risk of early retirement of equipment or failure to meet emissions targets.

DDPs are needed to coordinate policy and investment across jurisdictions, sectors, and levels of government. By providing a transparent and concrete understanding of what a low-carbon transition entails—scope and timing of infrastructure changes, technology options, investment requirements, RD&D needs, market potential—DDPs and the informed policy choices they enable can help align public and private sector interests and expectations. Since substantial parts of the energy system are under private or sub-national control in many countries, DDPs can provide a framework for coordination of policy and investment between sectors, across jurisdictions, and between jurisdictional levels (e.g. federal, provincial, local).

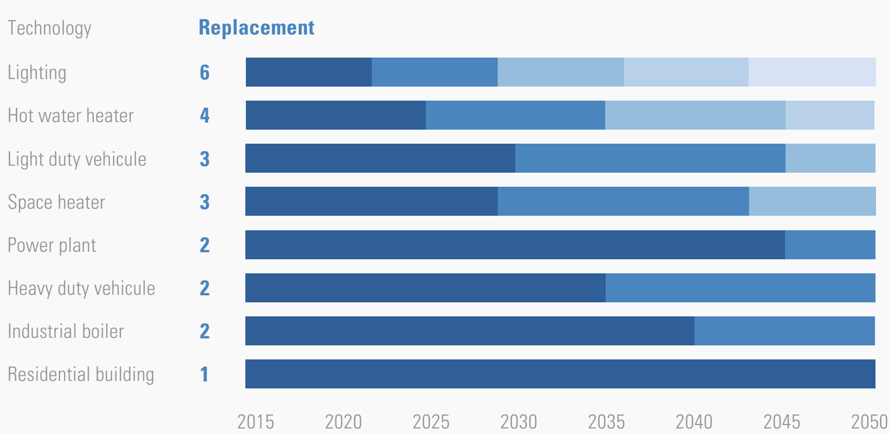
DDPs are needed for private-sector decision-making. DDPs will help businesses and investors understand the implications of deep decarbonization for their operations, helping them to identify market opportunities, develop investment and technology strategies, and plan for a smooth transition to a low-carbon economy. DDPs can provide a framework for stakeholder discussion of policy proposals, and identify potential areas for public-private partnerships.

DDPs are needed to inform long-term technology roadmaps. Our report underscores the importance of accelerating the development and diffusion of low-carbon technologies. Success will require public-private partnerships on Research Development, Demonstration and Deployment (RDD&D) organized using long-term technology roadmaps. DDPs provide a framework for aligning these roadmaps and partnerships with the objectives of deep decarbonization.

DDPs provide a framework for understanding how deep decarbonization can work in harmony with other sustainable development priorities. Having DDPs as a public point of reference can help countries ensure that the energy transformation and other decarbonization measures (e.g. land use) also support long-term goals such as energy access, employment opportuntities, environmental protection, and public health.

DDPs clarify the enabling conditions for developing countries to incorporate deep decarbonization into their development strategies, including the kinds of support needed from the international community. Some potential consequences of a deep decarbonization strategy, such as foregone revenues from fossil-fuel exploitation, add to the

Figure 9. Typical lifetimes and opportunities for replacement of some important energy supply and end-use equipment and infrastructure.



economic challenges of developing countries. DDPs are an essential vehicle for understanding how international cooperation can help mitigate these challenges and enable low-carbon development.

DDPs will increase trust in the international climate policy process. DDPs represent a transparent approach to understanding the long-term policy challenges, technology needs, and cost structures of deep decarbonization in different countries. This can do much to change the tenor of the international climate discourse, and place greater focus on opportunity-seeking and collective problem-solving. In contrast to a "black box" approach, DDPs are about credible and transparent data and analysis, making long-term national aspirations and the underlying assumptions that inform them clear to other countries. An open approach of this kind can lead to greater trust—including trust in the credibility of INDCs—and help to identify areas for policy cooperation, joint RD&D, market development, and mutual assistance.

The DDPP itself demonstrates the value of transparent, long-term pathways. When the project began in late 2013, most DDPP countries had never developed pathways consistent with 2°C, nor were they actively considering this question. The initial results of the DDPP have changed this, demonstrating that taking actions consistent with 2°C is possible and that there are different road maps for doing so in every country. As understanding of the value of the approach grows, more country-level discussions on deep decarbonization are taking place. Long-term pathways are increasingly understood in the research and policy communities as a framework for cumulative and collective problem solving, which can be presented and discussed with key constituencies and revised and improved over time. As the DDPP experience demonstrates, this approach can lead to a shared understanding of what staying within 2°C will require, what problems will arise, and what some of the options are for addressing them, including international cooperation. The DDPP has created a collegial environment for learning across and within countries, and the sharing of state of the art methods, data, and information.

6 What's new and what's next?

What is new in the recent work of the DDPP? The 2015 Synthesis Report expands and deepens the analysis of the 2014 report, building off the new work by the country resarch teams. All 16 teams are issuing stand-alone reports on deep decarbonization in their countries. These reports include new pathways that increase the robustness of the analysis by demonstrating multiple technical options for reaching deep decarbonization goals. Many of the new country pathways reach deeper emissions reductions than those reported in 2014, and all describe in more detail how deep decarbonization can be made consistent with national development objectives. For developing countries, the reports clarify the enabling conditions, including the support needed from the international community, that will allow them to fully incorporate deep decarbonization into their development strategies. The 2015 Synthesis Report synthesizes the findings of the country reports, and describes new cross-cutting analyses. These include analyses of aggregate annual and cumulative emissions and their relation to the 2°C limit, and the aggregate investment requirements and their implications for global markets and cost reductions.

What's next for the DDPP? Moving forward, the DDPP is looking to expand its network, deepen the DDPs already developed, and provide new public tools to allow greater participation in, and dialogue on, deep decarbonization.

- The DDPP is already in discussion with research teams from other countries wishing to join the project, and welcomes others to contact us. Our ambition is to support the development of DDPs for every interested country. To this end we are developing a freely-licensed, open-source Pathways model that can be used by any country, subnational government, NGO, or business.
- A priority area for expanded country coverage is in low-income countries, where much of the world's economic and population growth over the decades ahead is expected to take place. A better understanding of the deep decarbonization potential and enabling conditions in these countries is essential for determining what is required to stay within 2°C.
- The next phase of the DDPP's analysis will focus on identifying options to reduce cumulative emissions pathways, and further exploring how global cooperation on low-carbon technologies can accelerate low-carbon transitions in both industrialized and developing countries.
- The DDPP will support national stakeholder discussions—with government, business, and civil society—around deep decarbonization strategies, how different pathways fit with national priorities, and how they can be communicated and improved.
- In support of stakeholder discussions within and across countries, the DDPP is developing a web-based portal for the display and analysis of decarbonization scenarios from many sources and analytical exercises (not only the DDPP) in order to provide a platform for communicating and comparing different approaches to the low-carbon transition.

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