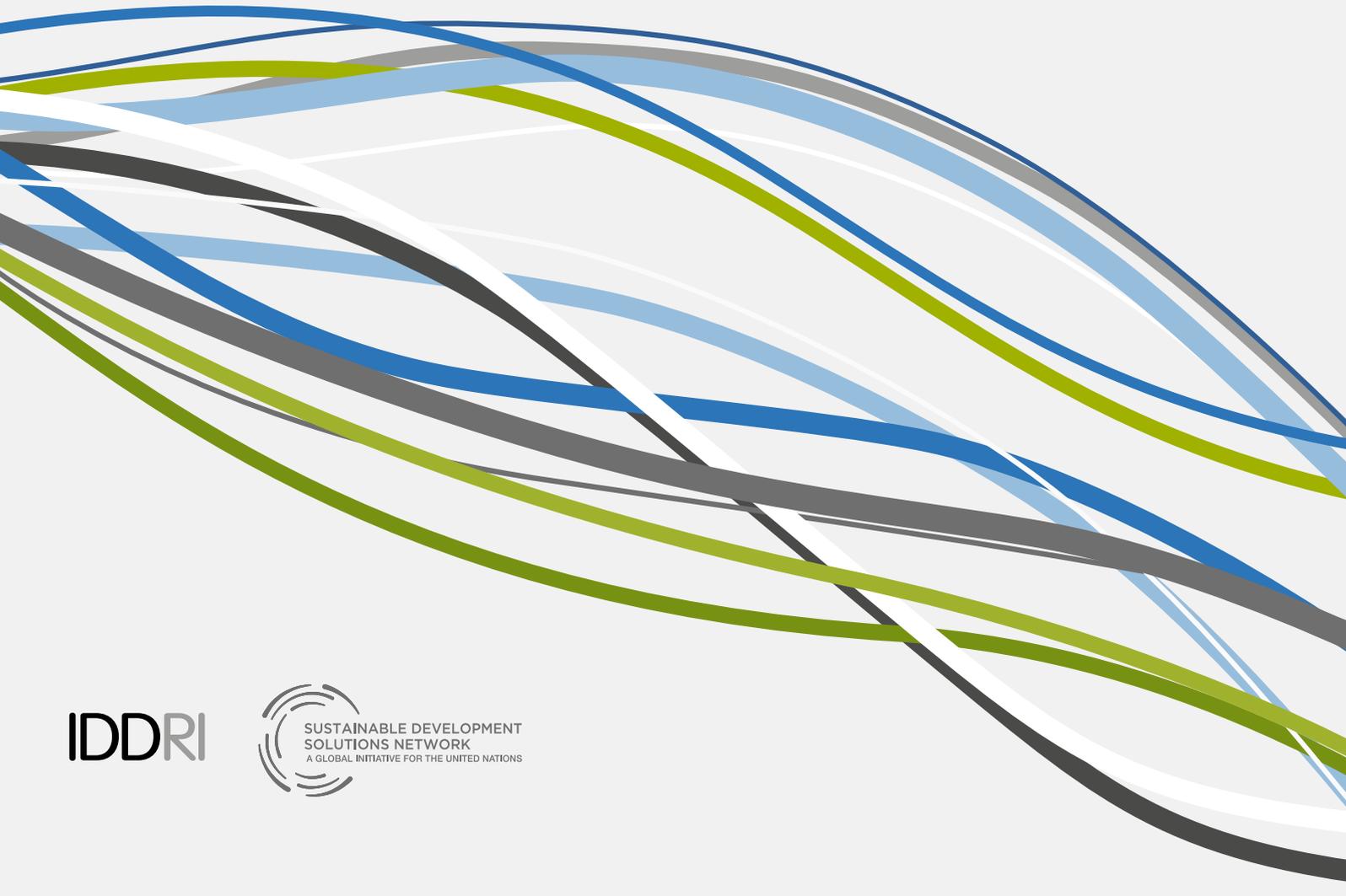




DEEP
DECARBONIZATION
PATHWAYS
PROJECT

2015 report

pathways to
deep decarbonization



IDDRI



SUSTAINABLE DEVELOPMENT
SOLUTIONS NETWORK
A GLOBAL INITIATIVE FOR THE UNITED NATIONS

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IDDRI

The Institute for Sustainable Development and International Relations (IDDRI) is a non-profit policy research institute based in Paris. Its objective is to determine and share the keys for analyzing and understanding strategic issues linked to sustainable development from a global perspective. IDDRI helps stakeholders in deliberating on global governance of the major issues of common interest: action to attenuate climate change, to protect biodiversity, to enhance food security and to manage urbanization, and also takes part in efforts to reframe development pathways.



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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This report was written by a group of independent experts who have not been nominated by their governments. Any views expressed in this report do not necessarily reflect the views of any government or organization, agency or program of the United Nations.

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pathways to deep decarbonization

The executive summary of this Synthesis Report is available at:

http://deepdecarbonization.org/wp-content/uploads/2015/06/DDPP_EXESUM.pdf

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Acronyms

2°C	2 degrees Celsius	RDD&D	research, development, demonstration, and diffusion
2Ws	2-Wheelers	sqm	square meter
3Ws	3-Wheelers	SNG	synthetic natural gas
4Ws	4-Wheelers	SO₂	sulphur dioxide
AR5	Fifth Assessment Report	tce	tons of coal equivalent
BAU	Business-As-Usual	tCO₂	tons of CO ₂
BECCS	bioenergy with CCS	toe	tons of oil equivalent
BIPV	building-integrated photovoltaics	tkm	ton-kilometer
cap	capita	TPES	total primary energy supply
CCS	carbon capture and sequestration	TWh	terawatt-hours
CO₂	carbon dioxide	UK	United Kingdom
CO₂e	carbon dioxide equivalent	UN	United Nations
COP-21	21 st Conference of the Parties	UNFCCC	United Nations Framework Convention on Climate Change
DDPP	Deep Decarbonization Pathways Project	US	United States
DDPs	Deep Decarbonization Pathways	WGIII	Working Group 3
EJ	exajoule		
gCO₂	grams of carbon dioxide		
GDP	Gross Domestic Product		
GHG	greenhouse gas		
GJ	Gigajoules		
Gt	gigatons		
GW	gigawatts		
HDVs	Heavy-Duty Vehicles		
INDCs	Intended Nationally Determined Contributions		
IPCC	Intergovernmental Panel on Climate Change		
kWh	kilowatt-hour		
LDVs	Light-Duty Vehicles		
LNG	liquefied natural gas		
MJ	Megajoules		
MtCO₂	Million tons of carbon dioxide		
Mtoe	Million tons of oil equivalent		
MWh	megawatt		
NGO	non-government organization		
PM_{2,5}	Particulate Matter up to 2.5 micrometers in size		
pkm	passenger-kilometer		
PPP	purchasing power parity		
PV	photovoltaic		
R&D	Research and Development		

1 What is the DDPP?

Purpose: The Deep Decarbonization Pathways Project (DDPP) is a collaborative global research initiative seeking to understand how individual countries can transition, on a technological, socio-economic and policy “pathway”, to a low-carbon economy consistent with the internationally agreed goal of limiting anthropogenic warming to less than 2 degrees Celsius (2°C). Achieving this goal requires that the world cut global net emissions of greenhouse gases (GHG) so that they approach zero between 2050 and 2075, consistent with the Intergovernmental Panel on Climate Change (IPCC)¹ 2014 findings that to ensure a better-than-even chance of remaining below a 2°C temperature rise, global annual emissions will need to be reduced 42%–57% by 2050 (relative to 2010), and 73%–107% by 2100. This will entail, more than any other factor, the profound transformation of energy systems through steeply reducing carbon intensity in all sectors of the economy. We call this transition “deep decarbonization” and our products, Deep Decarbonization Pathways (DDPs).

Organization: The DDPP, which was formed in October 2013, consists of domestic research teams from 16 countries representing 74% of current global GHG emissions: Australia, Brazil, Canada, China, France, Germany India, Indone-

sia, Italy, Japan, Mexico, Russia, South Africa, South Korea, the United Kingdom and the United States. The teams consist of scholars from leading research institutions acting independently and who do not necessarily represent the official positions of national governments. The DDPP is convened by the Sustainable Development Solutions Network (SDSN) and the Institute for Sustainable Development and International Relations (IDDRI), coordinated by a joint secretariat of these organizations.

Approach: The DDPP fills a gap in the climate policy dialogue by providing, in the form of deep decarbonization pathways (DDPs), a clear and tangible understanding of what will be required for countries to reduce emissions, consistent with the 2°C limit. The research teams developed these DDPs as blueprints for change, sector by sector and over time, for each country’s physical infrastructure—such as power plants, passenger and commercial vehicle fleets, buildings and industrial equipment—to inform decision makers about the technological and cost requirements of different options for meeting the emissions reduction goal. DDPs are not forecasts but “backcasts,” a term for the process of defining a desirable future and working backwards to identify the policies and programs needed to

¹ See Table SPM.1 in the WGIII summary for policymakers, available at: http://www.ipcc.ch/pdf/assessment-report/ar5/wg3/ipcc_wg3_ar5_summary-for-policymakers.pdf

reach that future from the present. DDPs begin with an emissions target in 2050 and determine the steps required to get there. In many countries, the DDP analysis was an iterative process in which researchers gradually increased the depth of emission reductions the countries could achieve by adjusting the assumptions they considered. Country teams autonomously defined their targets, chose their analytical methods and incorporated into their scenarios national aspirations for development and economic growth, taking into account national circumstances such as existing infrastructure and natural resource endowments. At the same time, the DDPP is highly collaborative. Country teams transparently shared methods, modelling tools, data and results.

Results: The DDPP issued a report on the first phase of its work, preliminary findings on technically feasible pathways, at the UN Climate Summit in September 2014, at the invitation of Secretary General Ban Ki-moon. This report summarized each country team's initial research. In the fall of 2015, all 16 teams published stand-alone reports describing in greater detail their research into national DDPs. This 2015 Synthesis Report provides a cross-cutting analysis of the aggregate results, complementing the executive summary published in September 2015. All reports and results are available on the DDPP website: www.deepdecarbonization.org.

What is new in this iteration of the DDPP?

Since the 2014 DDPP Synthesis Report, all 16 research teams have issued new reports analyzing the deep decarbonization of their countries' energy systems, the focus of the cross-cutting analysis developed in this report. Some of the individual country analyses consider sources of carbon emissions other than energy, or other greenhouse gases, according to their importance in their national emissions profile. The

2015 country reports include new pathways, demonstrating that there are additional technical options for reaching deep decarbonization goals, increasing the robustness of their analysis. For some countries, the 2015 reports demonstrate more ambition, reaching deeper emissions reductions than those reported in 2014. The country reports also delve more deeply into how national priorities intersect with deep decarbonization, and describe their policy packages accordingly. For developing countries, the reports clarify the enabling conditions, including support from the international community, for them to fully incorporate deep decarbonization into their development strategies. This 2015 Synthesis Report analyzes aggregate annual and cumulative emissions; their relation to the 2°C limit; investment requirements in aggregate; and how to reduce, through engaging global markets, the cost of the technology that will be necessary.

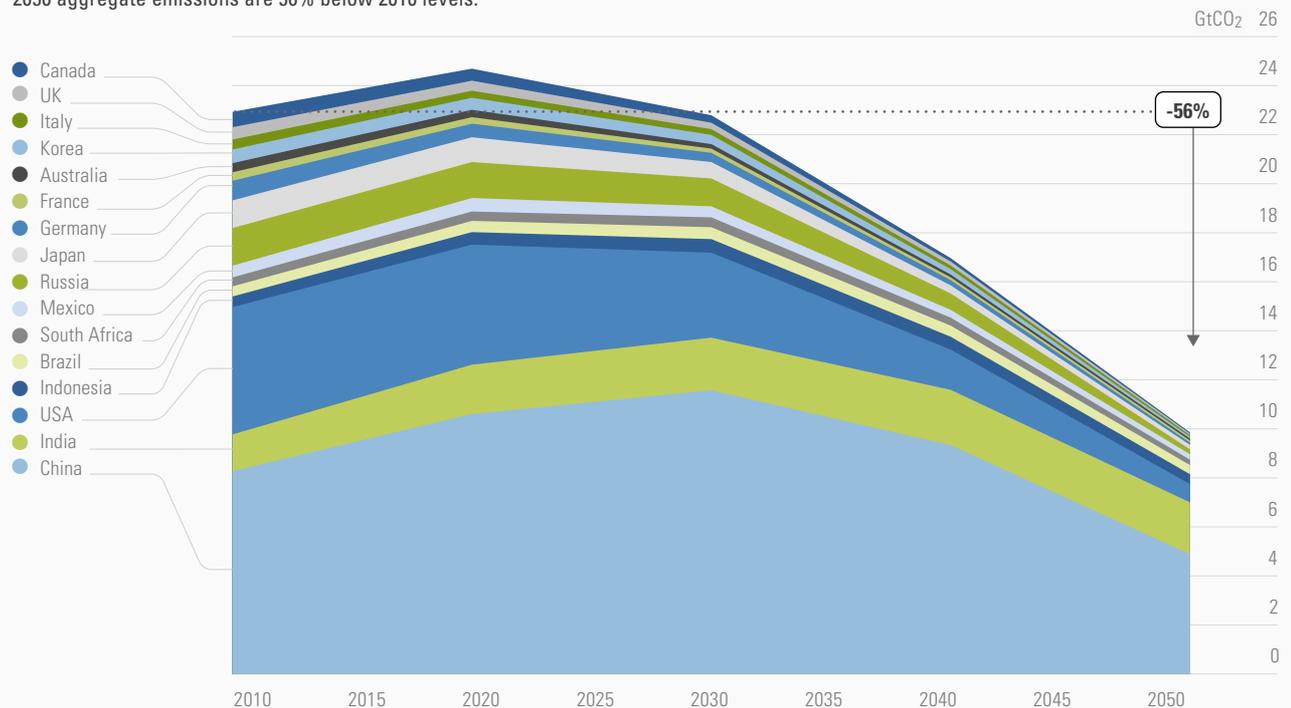
2 Is Limiting Global Warming to 2°C Achievable?

2.1 Deep decarbonization is technically feasible

Deep decarbonization of today's highest emitting economies can be achieved while accommodating economic and population growth. Each country team produced several technically feasible DDPs—pathways to the successful deep decarbonization of their economies. National economies at different stages of development and different national circumstances follow different types of emission profiles (see

further discussion below) but, in aggregate across the 16 DDPP countries, by 2050 energy-related CO₂ emissions were reduced under the modeled scenarios to 9.9 - 12.1 Gt CO₂, or 46%-56% below 2010 levels (Figure 1). The scenarios took into account country-specific forecasts of population evolution adopted in the DDPP pathways, that in aggregate lead to expected population growth of 17% from 2010–2050 across the 16 countries, consistently with the UN medium fertility scenario.² The scenarios accommodated cumulative aggregate GDP growth of 250%—a

Figure 1. Emissions trajectories for energy CO₂, 2010-2050, showing most ambitious reduction scenarios for all DDPP countries. 2050 aggregate emissions are 56% below 2010 levels.



² Although some of the country population assumptions were not directly obtained from UN forecasts, the global aggregate is similar with those projections.

global average rate of 3.1% per year through 2050. Considering the most ambitious of the modeled scenarios in each country lead to reduced average per capita emissions in 2050 of 2.1 tCO₂ per capita across the 16 countries, with average emissions per unit of GDP reduced 87%, relative to 2010.

Every national Deep Decarbonization Pathway involves the drastic decoupling of emissions from economic (GDP) and population growth by 2050. The characteristics of the 16 DDPP countries that most directly determine approaches to deep decarbonization, including their level of economic development and the initial carbon intensity of their energy systems, are diverse.

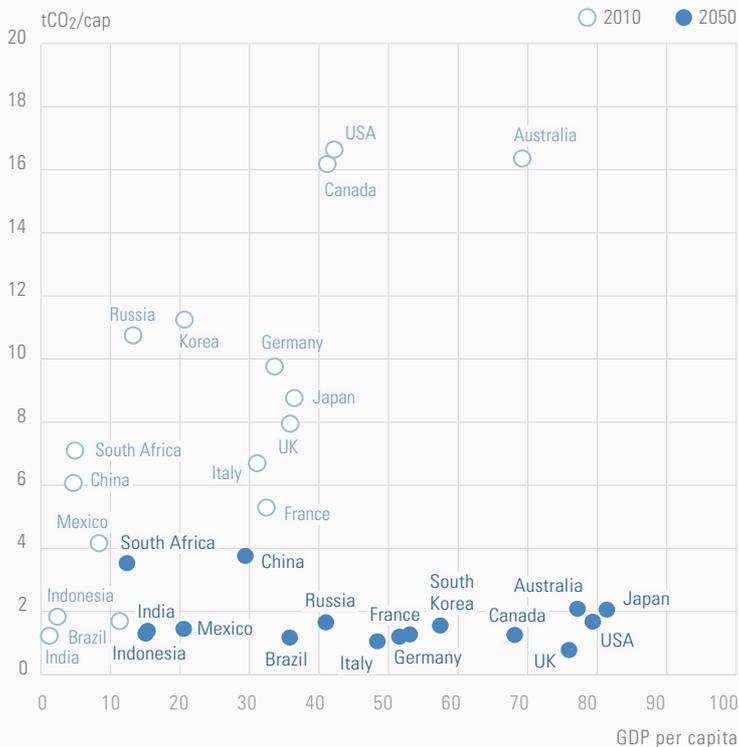
Figure 2 illustrates each country's initial (2010) and post-decarbonization (2050) standing along these two dimensions, as quantified by GDP per capita (horizontal axis) and energy-related CO₂ emissions per capita (vertical axis).

All pathways start with country teams defining socioeconomic goals and national circumstances and assessing their core socio-economic assumptions accordingly (see more extensive discussion in Section 3), as illustrated by the assumptions on GDP growth rates displayed in Figure 3.

The set of the 16 most ambitious pathways dramatically reduce emissions intensity, measured by per unit of GDP (reduced by 87% in aggregate) or per capita (reduced by 62% in aggregate), holding population and GDP growth at the levels noted above. Reductions in the carbon intensity of GDP range from 80% to 96% across the 16 countries (Figure 4b). The clustering of carbon-intensity trajectories shows that, under the modeled scenarios, all DDPP countries undergo true transformations, even as their absolute emissions trajectories reflect different stages of economic development. Most of the ambitious pathways achieve 2050 energy-related emission levels at or below 2 tCO₂ per capita, with many near 1.5 tCO₂ per capita (Figure 4a)³. Although all countries dramatically reduce in emissions per unit of GDP, the figures highlight three very distinct types of per capita emissions profiles:

- Fast and profound declines in developed economies with moderate GDP growth rates.
- Peak, plateau and decline trajectories in emerging economies.
- Stabilization of emissions in low-income and lower-middle income countries (India and Indonesia in our DDPP sample).

Figure 2. GDP and energy-related emissions per capita across the 16 countries



Australia's GDP per capita increases by 56% between 2012 and 2050 in local currency. The small increase observed in the graph is due to fluctuations in the exchange rate between Australian and US dollars⁴

3 China and South Africa display higher emissions per capita in 2050 (around 3.5tCO₂), although experiencing similar levels of decoupling of emissions and GDP as in other countries. This result can be understood in light of two shared traits: (1) a very carbon-intensive initial energy system and (2) the need for fast enough short-term economic growth to satisfy their development priorities.

Figure 3. Average annual GDP growth rate 2010-2050

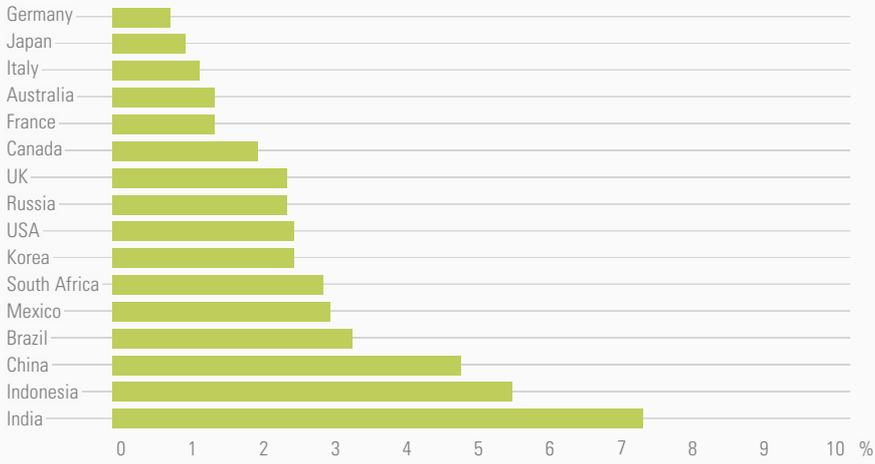
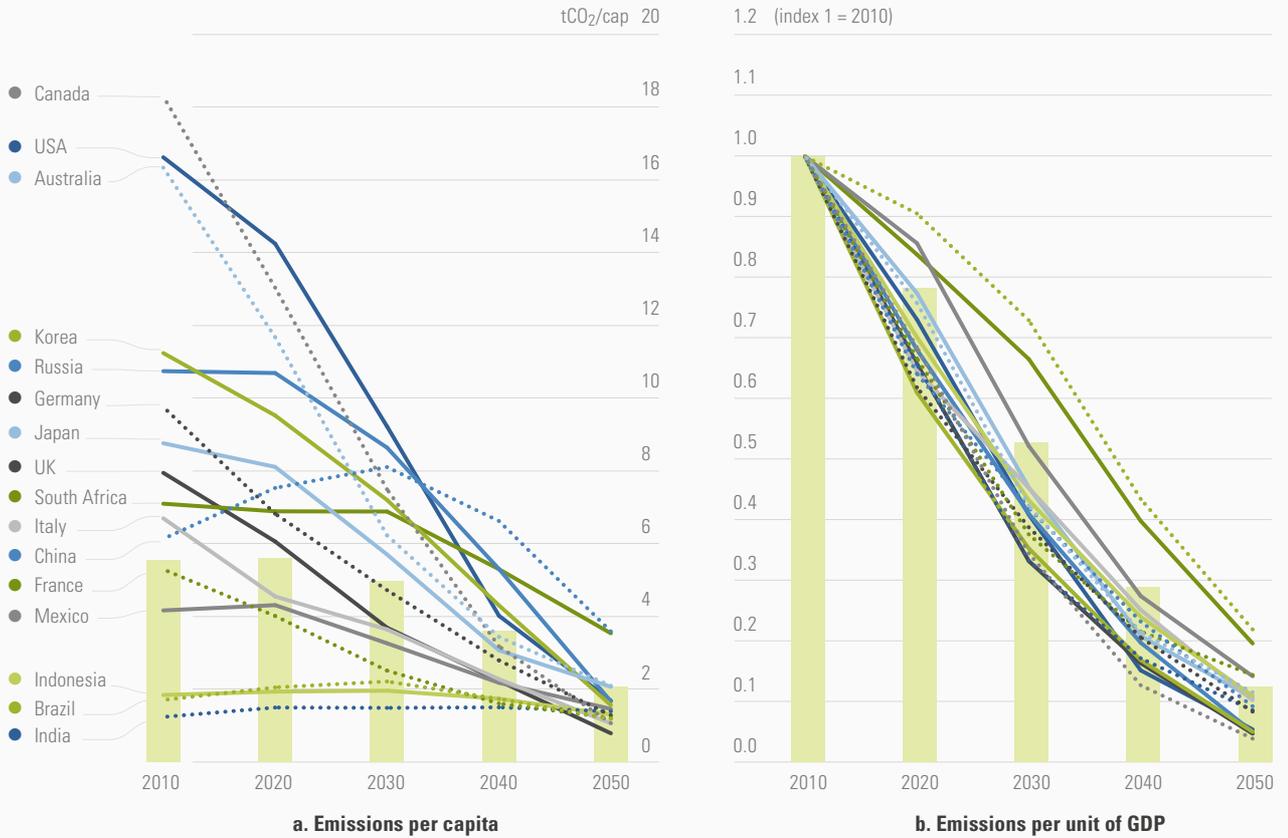


Figure 4. (L) Energy-related CO2 emissions per capita for DDPP countries, (R) Energy-related CO2 emissions per unit of GDP for DDPP countries 2010 to 2050, indexed to 2010.



2.2 Deep Decarbonization of the energy system Rests on Three Pillars

All pathways incorporate, at scale, efficiency and conservation, decarbonization of fuels and electricity, and the switch to low-carbon energy.

Following the decomposition $\text{CO}_2/\text{GDP} = \text{CO}_2/\text{Energy} * \text{Energy}/\text{GDP}$, reducing the carbon intensity of GDP (CO_2/GDP) is the result of decreasing the energy intensity of GDP (Energy/GDP) and the carbon intensity of energy ($\text{CO}_2/\text{Energy}$). Reducing the energy intensity of GDP can be achieved through energy efficiency and conservation (pillar one of deep decarbonization is energy efficiency and conservation). Reducing the carbon intensity of energy comes about through a combination of decarbonizing electricity and fuels (pillar two is decarbonizing electricity and fuels) and switching to low-carbon sources in most energy end-uses (pillar three is switching to low- and eventually zero-carbon sources).

The three pillars of energy system transformation

- **Energy efficiency and conservation:** Lowering the energy consumed per unit of GDP (energy intensity) by technically improving products and processes, including waste reduction and structural and behavioral changes. Examples in transport include improving vehicle technologies, smart urban design and optimizing logistical chains; in buildings, improving end-use equipment, architectural design, building practices and construction materials; in manufacturing, improving equipment, production processes, material efficiency and the re-use of waste heat.
- **Decarbonizing electricity and fuels:** Reducing the carbon content of all transformed energies: electricity, heat, liquids and gases. In the power sector, replacing uncontrolled fossil

fuel-based generation with renewable energy (e.g., hydro, wind, solar and geothermal), nuclear power and/or fossil fuels with carbon capture and storage (CCS). For on-site and in-vehicle combustion, decarbonizing liquid and gas fuels through the diffusion of biomass fuel and/or synthetic fuels (e.g. hydrogen) produced through low-carbon processes.

- **Switching energy end-uses to lower-carbon, and eventually zero-carbon, energy carriers (e.g. electricity, hydrogen and biofuels):** Initially, for example, shifting from coal to natural gas; in the longer run, shifting to decarbonized energy carriers, e.g. electrification of space and water heating and cooling; adoption of electric, biofuel or hydrogen vehicles; and industry directly using biofuels, hydrogen or synthetic natural gas (syngas).

In all DDPs, the pillars interact; deep decarbonization is only achieved when the pillars are implemented at sufficient scale.

All pathways incorporate these three pillars in an interactive way. For example, energy efficiency and conservation (pillar 1) reduces potential electricity demand and therefore facilitates the decarbonization of electricity (pillar 2) by limiting the need for deployment of low-carbon generation. Deep decarbonization of electricity and fuels (pillar 2) is a necessary condition to make some fuel switching options (pillar 3) actually beneficial from a decarbonization point of view, like in the example of electric use in industrial or transport activities. And fuel switching (pillar 3) can support energy efficiency (pillar 1) when the associated options are more energy efficient, like electric vehicles compared to thermal combustion engines. This highlights that deep decarbonization cannot be achieved if any of these pillars is implemented at insufficient scale. In all the DDPs, the decarbonizing measures that were considered rely on technologies already commercially available, or are expected to be within

the time frame of the analysis, given the current stage of research and development (R&D). The DDPs show that there are multiple ways to implement the three pillars, with country-specific strategies, technology mixes and sequences of action. These are detailed in [individual country reports](#). The modeled scenarios demonstrated that through energy efficiency, pillar one, a country can reduce the energy intensity of its GDP by an average of 64% (2.5%/yr from now to 2050). Nearly all the modeled countries' economies become 2–4 times more energy efficient in 2050, compared to 2010. This is accomplished through measures such as improving vehicle fuel economy, building design and construction materials, the efficiency of appliances, industrial processes and machinery, along with conservation measures such as urban design that encourages walking and bicycling.

In all the DDPs modeled, decarbonization (pillar two) and fuel switching (pillar three) are implemented. Electricity becomes nearly carbon-free by 2050, with average carbon intensity across the countries reduced by a factor of 15 below its 2010 value (Figure 6).⁴ This is accomplished by replacing most uncontrolled fossil fuel-based electricity generation with varying mixes of renewable energy (wind, solar, geothermal and hydropower) nuclear power, or fossil-fuel generation with CCS. In addition, liquid and gas fuel supplies are decarbonized using biomass fuels with low- or net zero carbon emissions (e.g. ethanol and diesel based on switchgrass or algae), hydrogen produced from decarbonized electricity, or synthetic natural gas produced using electrolyzed hydrogen and captured CO₂. Overall, the most significant trend in final energy consumption is the replacement of coal by natural gas and eventually, of all fossil fuels by electricity and other zero-carbon energy carri-

Figure 5. (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.

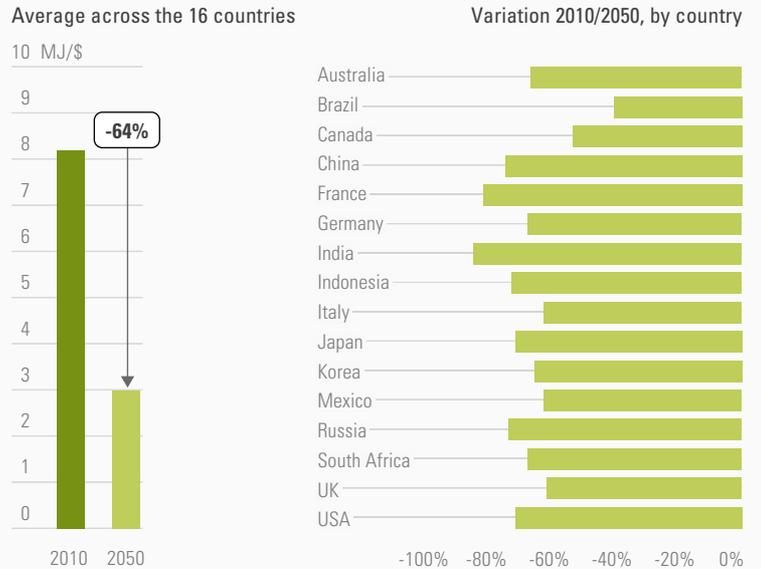
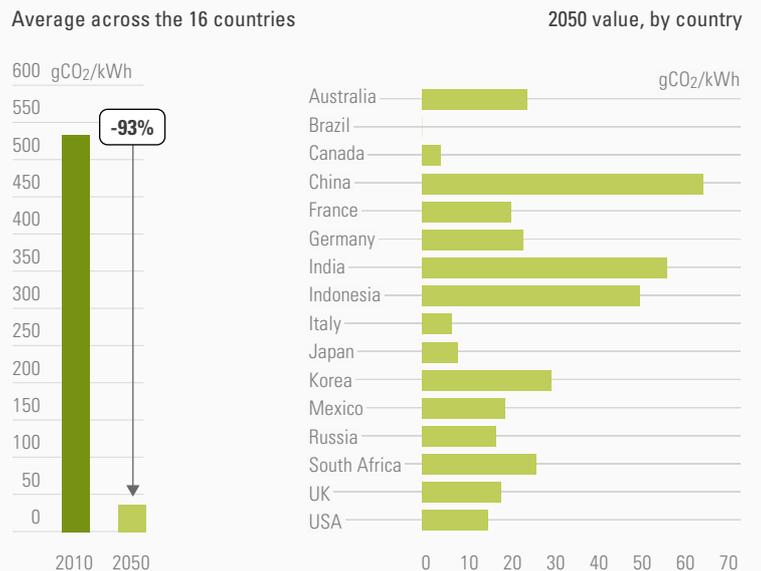


Figure 6. (L) Average carbon intensity of electricity for DDPP countries as a whole, 2010 and 2050. (R) Carbon intensity of electricity in 2050, for individual DDPP countries.



⁴ Only the UK DDPs considered BECCS (bioenergy with CCS), in contrast to many of the IPCC AR5 scenarios that are (2°C) compatible (Fuss et al, 2014). Adding bioenergy with CCS to other country DDPs would make hitting the targets easier. <http://www.nature.com/nclimate/journal/v4/n10/full/nclimate2392.html>

ers. Much of the direct fossil fuel combustion in end-use equipment, such as automobiles, building heating and cooling and industrial boilers, is replaced by decarbonized electricity. The share of electricity in final energy consumption finally doubles to more than 40% (Figure 7).

Figure 7. Share of different fuel types in final energy consumption

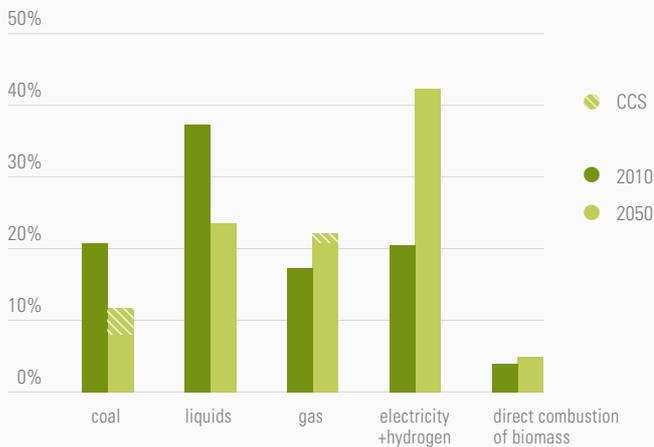
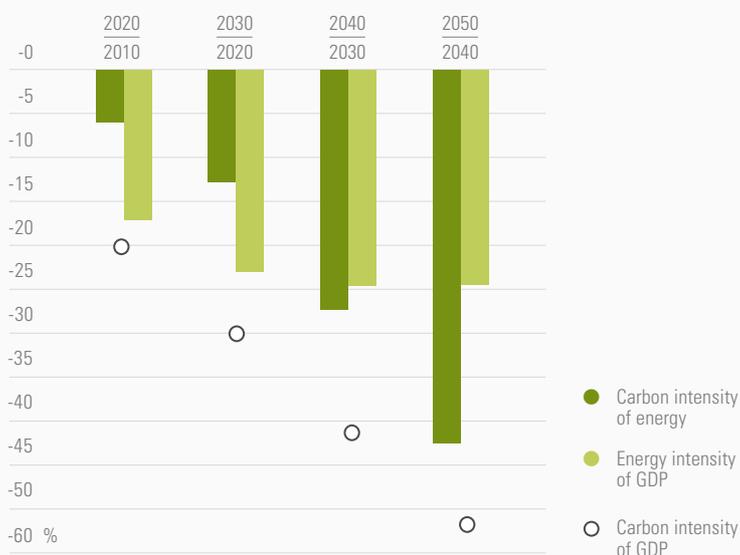


Figure 8. Time profile of the drivers of decarbonization, by decade



The three pillars' contribution to decarbonization changes with time

A time profile analysis of the decarbonization process reveals a continuous acceleration in the reduction of carbon intensity of GDP, with decadal reductions starting at 20% below 2010 levels in 2020, reaching 57% below 2040 levels in 2050. The relative contribution of each pillar to reducing energy intensity and decarbonizing the energy system changes each decade. Reducing energy intensity (pillar one) provides a contribution to decarbonization that remains rather flat across decades: it begins at 17% in the first decade (2020 reduction compared to 2010 levels) and rises to 27% in the last decade (2050 reduction compared to 2040 levels). It is the dominant pillar until 2030. Many energy efficiency and conservation actions can be implemented quickly, thanks to the immediacy of operations improvements and the near-term renewal of short-lived equipment such as lighting, appliances and private vehicles, for which performance standards can influence most of the stock turnover within a decade.

Decarbonization of energy, combining pillars two and three, on the other hand, makes only a modest contribution in the early years, but becomes the dominant driver of decarbonization after 2030 (Figure 8).

Decarbonization of energy carriers is a longer-term proposition. Decarbonizing electricity, biofuels, hydrogen and syngas (pillar 2) as well as ensuring the large-scale fuel switch in end-uses (pillar 3) requires reorganizing and upgrading the country's supply and transmission infrastructure, reorienting consumption by end-users, and in some cases (e.g. syngas and CCS), innovating, prototyping and commercializing new technologies. Energy systems are characterized by a slow turnover of infrastructure and operating equipment (e.g. coal plants typically last half a century) and long lead times for the development and diffusion of new technologies. Their

complete decarbonization can only be achieved over a longer time horizon than was modeled (i.e. 2050–2075). Over the long term, technical innovations can continually improve short-lived equipment, while efforts to improve long-lived infrastructure, such as buildings and power plants, come to fruition.

Most country scenarios follow a trajectory similar to the aggregate.

The three pillars' contribution to decarbonization changes with sectors

The relative contribution of the three pillars to decarbonization differs by sector.

In aggregate, the rate of emissions reduction varies widely by end-use sectors. The models find buildings and passenger transport achieve a steady decrease in emissions, with emissions falling 70% lower in 2050 than 2010. Industry and freight transport lag; industry attains a 50% reduction by 2050 and freight transport, only a 20% reduction by 2050 (Figure 10). As a result, industry and freight transport's share of total emissions grows during the period modeled. Industry emits 57% of total emissions in 2050; freight transport 17% of total emissions in 2050 (Figure 11). An important conclusion is that deep emissions reduction in industry and freight transportation will pose the greatest challenge, and require intensive efforts in research, innovation, demonstration and commercialization.

Figure 9. Equipment infrastructure : replacement opportunities between 2015 and 2050

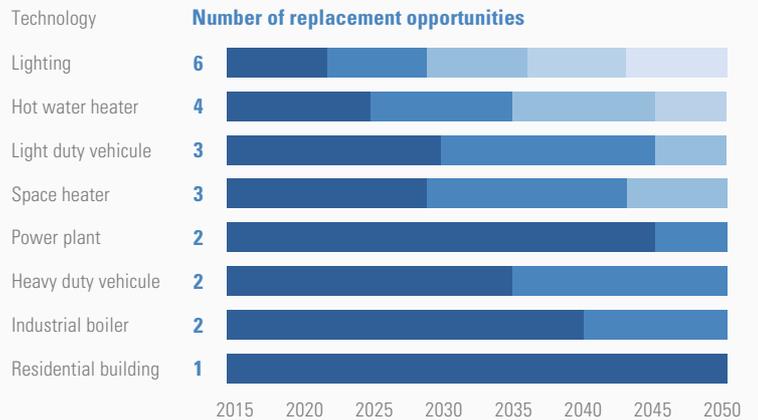


Figure 10. Sectoral emissions, aggregate across 16 countries

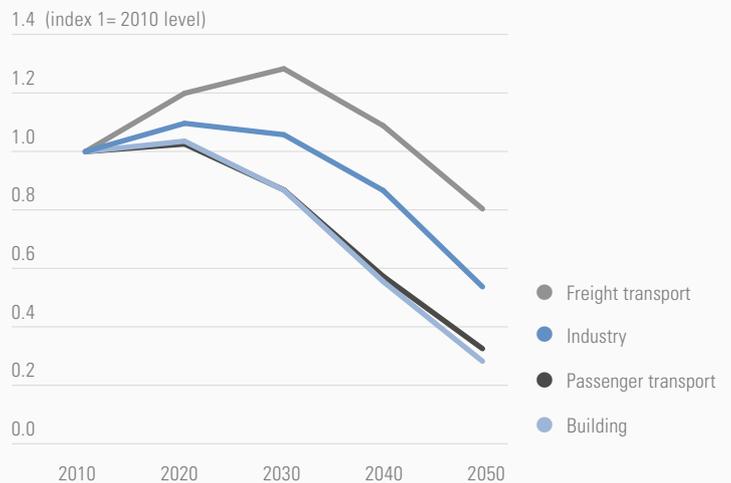


Figure 11. Share of sectoral emissions in total energy-related emissions, aggregate across 16 countries



To investigate more in-depth the drivers of emission reduction by sector, we decompose them along the three pillars.

Figure 12. Variation of energy intensity in end-use sectors 2010/2050 aggregate across 16 countries

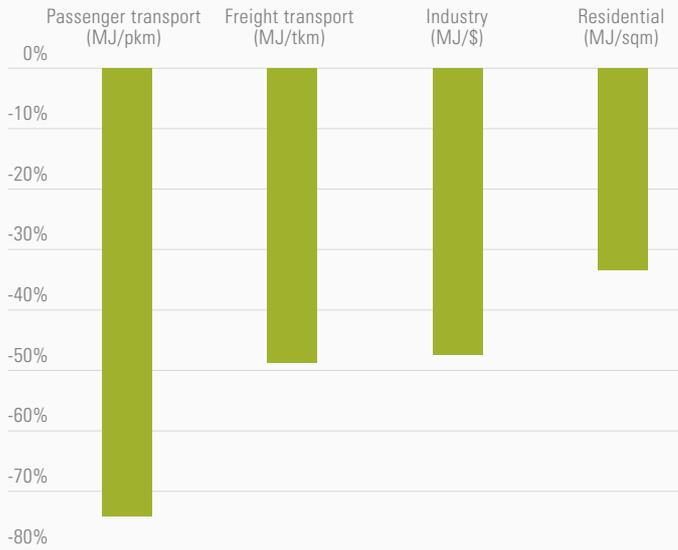
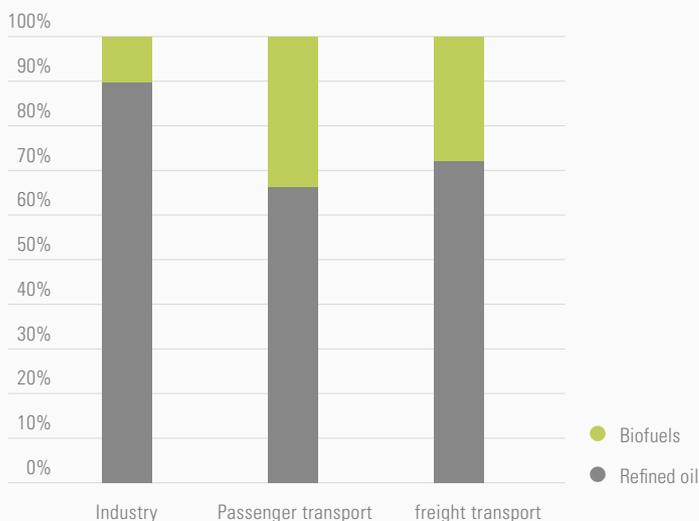


Figure 13. Sources of liquids in 2050 across end-use sectors aggregate across 16 countries



Pillar 1: Energy efficiency and conservation

The results for reducing energy intensity, rather than cutting emissions, are quite different (Figure 12). Notably, transport (freight and passenger) achieves the greatest reduction in energy intensity in aggregate by 2050 due to the combined force of improved vehicle efficiency and the modal shift from private towards public transport. The effect is particularly pronounced in passenger transport, because of the fast turnover rate of the private vehicle fleet and efficiency prospects for the gasoline internal combustion engine. The effect in freight transport is less pronounced because modal shifts require reorganizing underlying production and distribution processes and networks. Industry achieves almost a 50% aggregate reduction in energy intensity by 2050, the result of increased efficiency in industrial processes and a slower growth rate in more carbon-intensive sub-sectors (cement, steel). These effects do not necessarily imply an absolute reduction in the production of energy-intensive materials. Finally, the reduction in energy intensity in the residential building sector is the lowest, partly because homes are already relatively efficient from the start; partly because of an increased demand for energy services, particularly in developing countries; and finally because the focus of effort in the residential building sector switches to the second pillar, electrification with decarbonized electricity.

Pillar 2: Decarbonizing electricity and fuels

The decarbonization of electricity does not vary by sector, because all sectors draw their electricity from the grid. But other energy carriers follow very different trends by sector, as seen in the penetration rates of biofuels (Figure 13). Notably, the models show biofuels playing a prominent role in transport, where their adoption is an efficient decarbonization strategy. Liquids are the dominant end-use fuels in the transport sector, and remain so even well into decarbonization

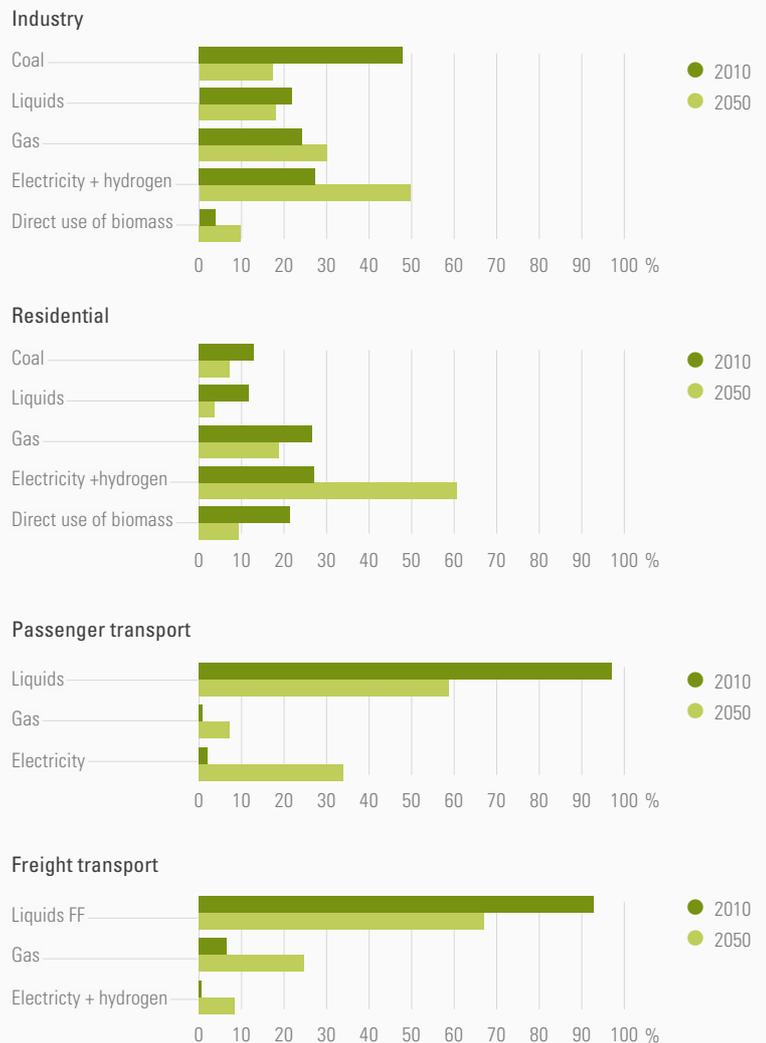
scenarios because of a limited ability in transport to switch from liquids. In industry, however, liquids are more marginal in the energy mix and can be substituted. For the industrial sector in many cases, changing the composition of liquid fuel is not the preferred option for decarbonizing because fuel switching (to natural gas or decarbonized electricity) would prove easier.⁵

Pillar 3: Fuel switching to low-carbon energy carriers

The mix of energy sources used by sector, and how their relative shares evolve under deep decarbonization, varies by sectoral characteristics (Figure 14). Switching to decarbonized electricity dominates in all stationary energy end-use applications that do not require very high temperatures, such as residences, commercial and institutional buildings (e.g. through air source heat pumps) and light manufacturing. There is also a significant opportunity for the electrification of short-distance passenger and—to a lesser extent—light- and medium-duty daily “return-to-base” freight transport activities. For long-range, heavy-duty and aviation transport, however, biofuels, hydrogen or syn-gas are essential because liquids provide the range and extended heavy-duty pulling power required, which batteries lack. Finally, in heavy industry, the pathways show that substantial process heat requirements limit the potential for fuel switching towards low-carbon sources. A shift from coal to natural gas plays an important role because CSS can eventually be considered and therefore allow for keeping fossils in the final energy mix. Changing the energy source of industrial processes to electricity or hydrogen made with renewables is another possibility, but generally considered to a limited extent in the modeling analysis, because

of the limited time frame, only through 2050. Indeed, this option requires first a deep decarbonization of these energy carriers and then a deployment of electricity-based equipment and infrastructure, both processes taking time given inertia associated to these transformations.

Figure 14. Share of final energy aggregate across 16 countries



⁵ The residential building sector is not discussed here, because the composition of fuels used in this activity is not tracked in the scenarios.

2.3 Deep Decarbonization Pathways are country-specific

The deep decarbonization of each country's energy system requires that it craft its own distinct set of strategies, appropriate for its initial level of development and economy-wide carbon intensity, giving emphasis to national priorities and taking account of social preferences for some technological options over others. Such country differences are evident in the 16 country DDPs. The detailed country reports provide a comprehensive illustration of all country-specific assumptions and analytical results (www.deepdecarbonization.org). In this aggregated analysis, countries have been grouped into different categories according to their current level of economic development, as measured by GDP per capita in 2010, and their current levels of energy-related CO₂ emissions, to identify similarities and differences that help explain their different approaches and strategies for carbon mitigation (Table 1).

Countries with low emissions and moderate income

The country group of Brazil, India, Indonesia and Mexico all emit below 5 tCO₂ per capita and had less than \$12,000 per capita GDP in 2010. Given that currently a large fraction of their populations lack access to basic energy services, and the shared goal of expanding such access, countries

in this group would be expected to increase their emissions dramatically in the coming decades, absent significant policy and technical change. In contrast, our models of these countries' Deep Decarbonization Pathways show a common pattern: moderate increases in emissions until about 2020, followed by a prolonged plateau or decline through 2050. Owing to population growth, per capita emissions also increase until 2020, but then decrease or feature a moderate increase until 2050, to levels similar or below per capita emissions in 2010.

Energy-demand sectors do not display important absolute emission reductions in the Deep Decarbonization Pathways of these countries. However, this does not mean that efforts to improve energy efficiency are not important. On the contrary, it is crucial that countries undergoing rapid economic development deploy all available solutions to limit the increase of emissions associated with improving and accelerating their population's access to energy services. This is particularly true in the building sector, where energy use increases to provide for basic comfort needs such as heating and cooling. This is also true in the transportation sector, as transport expands to satisfy rising mobility needs (see case studies 1 [PDF](#) and 2 [PDF](#) of the on-line supplementary material for specific analyses in Mexico and Brazil). On the other hand, the industrial sector achieves significant reductions in carbon intensity thanks to a gradual shift towards light industrial sub-sectors which are less energy

Table 1. Country groupings according to their 2010 levels of per capita income and per capita emissions

	Moderate 2010 levels of income (\$1,160 PPP < GDP per capita < \$12,000 PPP)	High 2010 levels of income (GDP per capita > \$12,000 PPP)
Low 2010 per capita emissions (1.2–5 tCO ₂)	Brazil, India, Indonesia, Mexico	-
Medium 2010 per capita emissions (5–12 tCO ₂)	China, Russia, South Africa	France, Germany, Italy, Japan, Korea, United Kingdom
High 2010 per capita emissions (>12 tCO ₂)	-	Australia, Canada, USA

intensive, and efficiency improvements due to the diffusion of modern industrial processes and equipment.

The final energy consumption profile of this country group illustrates that their energy systems are still developing. On average, per capita final energy consumption in this group grows two-fold between 2010 and 2050, and fossil energy continues to increase even on a Deep Decarbonization Pathway, typically doubling in absolute terms by 2050. However, electricity increases even faster and the share of electricity doubles over the same period, with decarbonized sources making up more than half of final energy by 2050. Decarbonization of electricity poses a particularly important challenge in the DDPs of these countries, given their need to quickly develop new capacities to support steeply increasing in energy needs, in parallel with enhanced population access to the grid and advanced services. Country-specific deployment challenges define the mitigation strategies, necessary but different in each case (see case studies 3 [PDF](#) and 4 [PDF](#) of the on-line supplementary material on the example of hydropower in Indonesia and Brazil).

Countries with medium emissions and moderate income

This group includes countries above 5 tCO₂ per capita and less than \$12,000 per capita GDP in 2010, e.g. China, Russia, and South Africa. Contrary to the previous country group, technological and structural changes, largely in the industrial sector, are strong contributors to emission reductions on the demand side (see case study 5 [PDF](#) of the on-line supplementary material on the example of industry in China). On the supply side, a significant level of decarbonization takes place among energy carriers, notably electricity, becoming a crucial driver of decarbonization because of all three countries' initially high carbon intensity of electricity generation.

The DDP results for South Africa and China project emissions peaking around 2030, then rapidly decrease up to 2050 to levels approximately 40% lower than in 2010.

Unlike the countries analyzed in the previous section (where final consumption increases over the entire pathway period), here energy consumption peaks between 2030 and 2040 in all scenarios modeled. Final fossil consumption levels are roughly equivalent in 2050 to 2010. The share of electricity in final demand reaches in aggregate about 33%, up from less than 20% in 2010.

When comparing national scenarios for this group, we observe that fossil fuels without CCS are completely phased out by 2050 in the scenarios that consider the least efforts on demand side; in the scenarios where the greatest efforts are implemented of the demand-side, fossil fuels without CCS, although reduced to a large extent by 2050, can maintain a small role in the power mix during the transition period. This illustrates the “consumption reduction versus supply decarbonization” trade-off: lowering demand offers some margin of flexibility on the supply side.

Countries with medium emissions and high income

This country group includes France, Germany, Italy, Japan, Korea and the United Kingdom, all countries below 12 tCO₂ per capita and GDP per capita above \$12,000 in 2010. This is the group where demand-side action has the most powerful decarbonization potential, through end-user efficiency and fuel switching in all sectors (see case studies 6 [PDF](#), 7 [PDF](#), 8 [PDF](#), 9 [PDF](#) and 10 [PDF](#) of the on-line supplementary material on the buildings sector in France, the passenger and freight transport in the UK and the industrial sector in Italy). Although the contexts are different, these countries experience a common trend culminating in 2050: emissions reductions that fall to 80% below 2010 levels. Common trends in all the DDPs of these countries include sig-

nificant decreases in final energy consumption, a significant reduction of the share of fossil fuels in the final energy mix and a steep expansion of electricity's share in the final energy mix, from one-fourth today to almost half of final energy consumption in 2050, on average. Today, the electricity sector in this group of countries is already more advanced in decarbonization than any of the other groups, with an

average carbon intensity of electricity of about 400 gCO₂/kWh in 2010. By 2050, coal is virtually eliminated from power generation, while natural gas, typically with CCS, still plays a role. In all cases, the average carbon content of electricity falls to less than 25 gCO₂/kWh in 2050, but the pathways to achieving those reductions differ across the countries. Case studies 10, 11, and 12 of the on-line supplementary material discuss

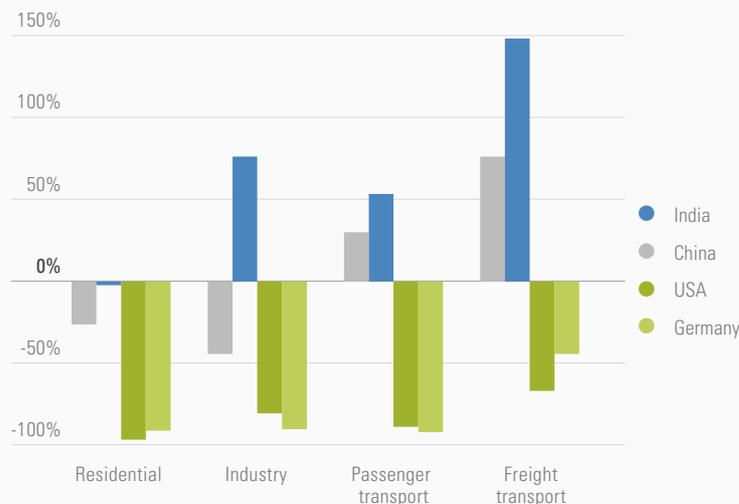
Box 1. National trends in sectoral emission reductions: A comparison of China, India, the USA and Germany

How, and by how much, each sector of a country's economy reduces emissions depends heavily on national circumstances, particularly the country's level of development and initial carbon intensity. It is instructive to compare emissions reductions in China, India, the USA and Germany because they are representative of the four country groups in table 1. Figure B1 illustrates the changes in sectoral emissions between 2010 and 2050 for each country. Industrialized

countries (Germany and the USA, in this example) follow a pathway of deep reductions in absolute emissions in all sectors, thanks to extensive efforts in energy efficiency and fuel switching. Developing countries (China and India, in this example) also implement efficiency and fuel switching measures across all sectors, but the growth in energy services required by their economic development (increasing access to basic services in the residential sector, increased personal

mobility for passenger transport, increased industrial production and associated transport) erodes or eliminates net emission reductions. This 'development effect' is particularly prominent in India.

Figure B1. National trends of sectoral emission reductions – a comparison China, India, USA, and Germany



the models' scenarios for power decarbonization in three contexts: in Germany, where the focus is squarely on renewables; in Japan, where the potential for CCS potential is the main driver; and in the UK, where the model shows renewables, CCS and nuclear can all contribute to different extents, depending on the energy system configuration and the techno-economic characteristics that prevail during the decarbonization period.

Countries with high emissions and high income

This country group includes all countries with emissions above 12 tCO₂ per capita and per capita GDP above \$12,000 in 2010: Australia, Canada and the USA. The scenarios modeled show they experience steady economic and population growth through 2050. Technological change on the demand side plays a crucial role in decarbonization, particularly in the transport sector (see case study 13  PDF of the on-line supplementary material on the example of industry in China).

Compared to other high-income countries, reductions in final energy demand are much less significant in this group in absolute terms (falling to 10% below 2010 levels in 2050, versus 40% below 2010 levels for the previous group), but are more important in per capita terms (42% below 2010 levels in 2050 for this group versus 33% for the previous group). The share of electricity in total energy use increases for high-income high-emitters, to about 56% in 2050 versus 2010 (compared with about 46%

for the high-income medium emitters, the previous group). Coal disappears from final demand here and the share of oil shrinks, replaced in the transport sector by natural gas, electricity, bio-fuels, hydrogen and syngas. The power sector is almost fully decarbonized in 2050 in all cases, but with very different mixes depending on the country and the scenario. (see case study 14  PDF of the on-line supplementary material on the example of the US)

2.4 DDPP cumulative emissions and the 2°C limit

Perhaps the most significant motivation for this DDPP study is to understand precisely how individual countries can avoid increasing global warming above the 2°C limit, beyond which, according to the accumulated scientific evidence, which has been politically recognized, the risk increases significantly of catastrophic climate system feedbacks.⁶

Scientific analysis has documented a strong relationship between temperature increases and cumulative emissions over time, as summarized in the 2014 IPCC report⁷: "Multiple lines of evidence indicate a strong, consistent, almost linear relationship between cumulative CO₂ emissions and projected global temperature change to the year 2100 [...] Any given level of warming is associated with a range of cumulative CO₂ emissions. [...]"⁸ Given uncertainties,

⁶ This understanding became part of negotiations at the Copenhagen Climate Change Summit, the 15th Conference of Parties (COP 15), was formally adopted at COP 16 in Cancun in 2010, and has served as the benchmark for global ambition in climate negotiations since then, exemplified by a June 2015 G7 communique where all G7 members committed to 2°C compliant decarbonization by 2050, and full decarbonization by 2100 (see Leaders' Declaration, G7 Summit, 7–8 June 2015. https://sustainabledevelopment.un.org/content/documents/7320LEADERS%20STATEMENT_FINAL_CLEAN.pdf [Accessed 26.08.15])

⁷ See section SPM 2.1 of the summary for of the Synthesis Report, available at http://www.ipcc.ch/pdf/assessment-report/ar5/syr/AR5_SYR_FINAL_SPM.pdf

⁸ Another important statement from IPCC is that "quantification of this range of CO₂ emissions requires taking into account non-CO₂ drivers". CO₂ is not the only important anthropogenic greenhouse gas influencing climate change; notably, methane (CH₄), nitrous oxide (N₂O) and fluorinated gases represent 16%, 6% and 2% of the total anthropogenic emissions in 2010.

IPCC (2014) provides ranges of cumulative emissions between 2010 and 2050 corresponding to different likelihoods⁹ to keep the temperature increase below the 2°C limit (Table 2).

The purpose of this section is to position our DDPP scenarios, which amount to a range of energy-related emissions of 805–847 GtCO₂, with respect to these benchmarks. Although the IPCC ranges of cumulative emissions correspond to all CO₂ emissions, the DDPP analysis does not cover all sources of CO₂ emissions because it is focused on energy-related emissions and includes only 16 countries.¹⁰ The approach developed in this section is to discuss orders of magnitude by making assumptions on the sources not covered in our analysis, i.e. non-DDPP energy-related

CO₂ emissions, bunker fuels (for international transport), land-use and process emissions (see details in Box 2).

Table 3 summarizes the findings of these assessments. They show that the ranges of global emissions derived from the DPP analysis fits within the “as likely as not” likelihood for being consistent with 2°C. This indicates that the deep decarbonization pathways discussed in this report demonstrate an important step forward towards the 2°C limit, albeit at significant probability of exceeding. This demonstrates that additional emission reductions would have to be considered in DDPP countries in order to increase the likelihood to meet the 2°C limit.

Two important remarks must be made on this assessment, which pave the way for future research.

First, a more precise assessment whether DDPP analysis is compatible with staying within 2°C limit will require understanding the emissions and decarbonization opportunities in non-DDPP countries. Many of these are low-income, low-emissions countries for which deep decarbonization raises the most uncertainties, notably because the emission trajectories must be analyzed in the light of their development priorities. Although extrapolation from India can give a first order estimate, explicit analysis of decarbonization pathways in these countries and their country specific enabling conditions are needed.

Table 2. World emission profiles corresponding to different likelihoods to reach the 2°C limit *

Cumulative CO ₂ emissions (GtCO ₂) 2010–2050**	Likelihood of staying below 2°C over the century
586–1336	Likely (>66%)
1166–1566	About as likely as not (33%–66%)

* See Table SPM.1 in the WGIII summary for policymakers, available at: http://www.ipcc.ch/pdf/assessment-report/ar5/wg3/ipcc_wg3_ar5_summary-for-policymakers.pdf

** Note: the ranges given by IPCC cover the period 2011–2050. The ranges indicated here are for the period 2010–2050 and have been calculated by adding 36GtCO₂, corresponding to the estimate of total CO₂ emissions for the year 2010.

Table 3. Summarizes the findings of these assessments

	Methodology of assessment	Emission source	Minimum	Maximum
Energy-related emissions	Explicitly assessed in DDPP	DDPP countries	805	847
	Extrapolated from DDPP	Non-DDPP European countries	44.5	44.5
	Extrapolated from DDPP	Non-DDPP high- and upper-middle-income countries	178	238
	Extrapolated from DDPP	non-DDPP low-income and lower-middle income countries	127	175
	Exogenous	Bunker fuels	47	47
Non-energy CO ₂ emissions	Exogenous	AFOLU	-54	164
	Exogenous	Process	39	39
TOTAL			1185	1555

⁹ Given the important number of uncertainties associated with climate analysis, the results of the IPCC are expressed in terms of the probability of an event or outcome to occur. A standardized terminology is used, according to which “likely” and “about as likely as not” correspond to probabilities in the range of 66–100%, and 33–66%, respectively.

¹⁰ Some DDPP modeling teams addressed non-CO₂ pollutants and/or non-energy CO₂ emissions but others did not. As a result this synthesis is focused on energy-related CO₂. For more information on other pollutants, please refer to the individual country reports.

Box 2. Assumptions on CO₂ emissions not covered in DDPP

a) Energy-related CO₂ emissions in non-DDPP countries

These emissions represent 26% of energy-related CO₂ emissions in 2010. Non-DDPP countries are very heterogeneous and we distinguish three groups

1. non-DDPP European countries

The 24 non-DDPP European countries are assumed to follow, on average, an 80% reduction compared to 1990 levels, consistent with the lower range of official European targets and with the emission reductions reached by the four European countries of the DDPP sample. A simple linear interpolation between 1,81 Gt¹ in 2010 level and 410 Mt in 2050 (corresponding to the 80% target relative to 1990 level) gives a cumulative energy-related emissions of 44,5 GtCO₂ in total for the 24 non-DDPP European countries.

2. Non-DDPP high- and upper-middle-income countries

The DDPP sample includes a set of high- and upper-middle-income countries featuring a wide variety of national circumstances. We use evaluations of cumulative emissions resulting from the DDPP analysis to plausibly represent the deep decarbonization emission pathways followed in the non-DDPP high- and upper-middle-income countries. The purpose here is not to assess the emissions trajectories exactly (which would require detailed country-level analysis), but to give an order of magnitude estimate of the cumulative emissions.

To this aim, we use the ratio of cumulative emissions over 2010–2050 to the initial level in 2010 as a unit-less indicator. We adopt as

a benchmark the value of this ratio from the deep decarbonization pathways in the middle-income countries from the DDPP sample (Brazil, China, Mexico, South Africa), which reaches between 35:1 and 47:1² in the current DDPP pathways.

Given the 2010 level of 5.07 GtCO₂ for the non-DDPP high- and upper-middle-income countries, the range of cumulative emissions obtained using these ratios is estimated at 178 to 238 GtCO₂ over 2010–2050.

3. non-DDPP low-income and lower-middle income countries

For these countries, we use India as the benchmark. Because India is a higher carbon intensity low income country, our estimates for these countries will contain a bias towards more rather than less emissions. We assume convergence of these countries' 2050 emissions per capita towards levels reached in the Indian DDPP scenarios (1.4 - 2.1 tCO₂/cap). This represents a significant catch-up compared to today's level since these countries have a very low intensity of emissions in 2010, around ~0.85 tCO₂/cap compared to India's current level of 1.24 tCO₂/cap. Under this assumption, and using UN population estimates (according to which these countries (except India and Indonesia) grow from 1.8 billion to 3.44 billion between 2010 and 2050), the group of non-DDPP low-income and lower-middle income countries emits cumulative emissions between 127 GtCO₂ and 175 GtCO₂ 2010-2050.³

b) Emissions from bunker fuels

Given the national scale of the analysis, these emissions are not considered in the

DDPP. To make an estimate, we refer to the 450 scenario in the 2011 World Energy Outlook⁴, which gives forecasts for these emissions over 2010-2035. Extrapolating these trends linearly to 2050, we obtain cumulative emissions of around 46.8 GtCO₂.

c) Net emissions from AFOLU

For AFOLU, we start with a range of estimates for 2010 CO₂ emissions between 3.3 GtCO₂ (medium estimate) and 6.2 GtCO₂ (upper-end of the range)⁵. We then assume a linear decrease towards 2050 emission levels as assessed by the IPCC in (IPCC 2014, SYR, figure 4.1), i.e. between +2 GtCO₂ and -6GtCO₂.⁶ This leads to a range of cumulative CO₂ emissions over 2010-2050 for scenarios in line with the 2°C limit between -54 GtCO₂ and +164 GtCO₂

d) Industrial process emissions

For industrial process CO₂ emissions, we refer to the 450 scenario in the 2011 World Energy Outlook⁴, which estimates an industrial trajectory compatible with the 2°C limit, with emissions at 1.4 Gt in 2009, 1.0 Gt in 2020, and 0.8 Gt in 2035. Extrapolating a constant value between 2035 and 2050, this leads to a cumulative sum of 37 GtCO₂ emitted between 2010 and 2050.

1 All energy-related emission data for non-DDPP countries in 2010 are taken from the US Energy Information Administration available at; <http://www.eia.gov/cfapps/ipdbproject/iedindex3.cfm?tid=90&pid=44&aid=8>
 2 The DDPP scenarios in industrialized countries correspond to much lower values of this ratio, between 22 and 28, as a measure of stringent decreases of absolute emissions.
 3 Note that these values are larger than those obtained with an assessment based on the ratio approach outlined for the previous group of countries in an attempt to capture cumulative emission pathways. Indeed, Indian ratios are 55:1 – 71:1. If applied to non-DDPP low-income and lower-middle income countries, this would

lead to a range of cumulative emissions of 121-158 GtCO₂. As a conservative assessment we keep the higher values for our assessment.
 4 https://www.iea.org/publications/freepublications/publication/WE02011_WEB.pdf
 5 See page 45 of the Synthesis Report of the 2014 IPCC report, available at http://www.ipcc.ch/pdf/assessment-report/ar5/syr/SYR_AR5_FINAL_full.pdf
 6 See Figure SPM.7 in the WGIII summary for policymakers, available at: http://www.ipcc.ch/pdf/assessment-report/ar5/wg3/ipcc_wg3_ar5_summary-for-policymakers.pdf

Second, the existing pathways do not assume any breakthroughs in key technologies, but rather look at what technologies we know today could achieve. Much progress is likely to be seen in coming decades, as has been seen with solar photovoltaic (PV) and batteries in the last decade. Also, the current pathways mostly exclude opportunities linked to behaviour change. This means that additional cuts are possible and that the current results do not represent an upper limit on emissions reduction potential for all

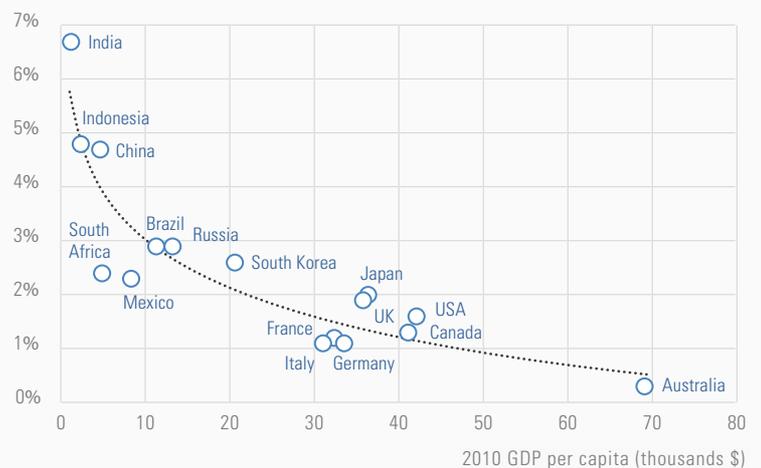
the 16 countries analyzed. In the first phase of the DDPP, the research teams have focused primarily on understanding technical options and enabling conditions for deep decarbonization by mid-century within their countries, but did not necessarily design their pathways to minimize cumulative emissions.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

3 Is deep decarbonization compatible with development and economic growth?

Deep Decarbonization Pathways accommodate the expansion of energy services needed to meet countries' economic growth targets and social priorities. The DDPs decarbonize 16 national energy systems in a context of economic growth and development. These pathways were designed to ensure that crucial domestic socio-economic objectives are met in each country and, notably, that energy services through 2050 would meet national objectives, allow citizens of developing countries expanded access to energy, and enable economies to continue transporting passengers, shipping freight, providing similar or better housing and public amenities, and support high levels of industrial and commercial activity.

As illustrated in **Figure 15**, all 16 DDPs assume continued economic growth to 2050, but at different rates according to initial level of development. For low and middle-income countries, which start from a lower GDP per capita and therefore have room for catch-up growth, faster GDP growth is assumed at rates necessary to meet their development objectives. In parallel, the per capita energy consumption in these countries increases. As illustrated in **Figure 16**, average energy consumption per capita declines in absolute terms in high-income countries, where energy efficiency improvements outweigh population and GDP growth. In low and middle-income countries, on the other hand, energy consumption increases in absolute terms as a result of population's growing access to energy services and higher living standards. However,

Figure 15. Growth rate of GDP per capita, 2010-2050



Australia's GDP per capita increases by 56% between 2012 and 2050 in local currency. The small increase observed in the graph is due to fluctuations in the exchange rate between Australian and US dollars"

Figure 16. Average annual rate of change of final energy per capita, 2010-2050

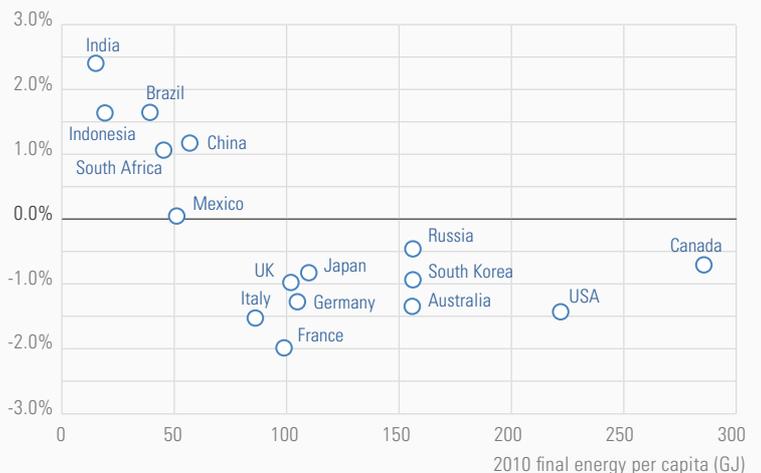
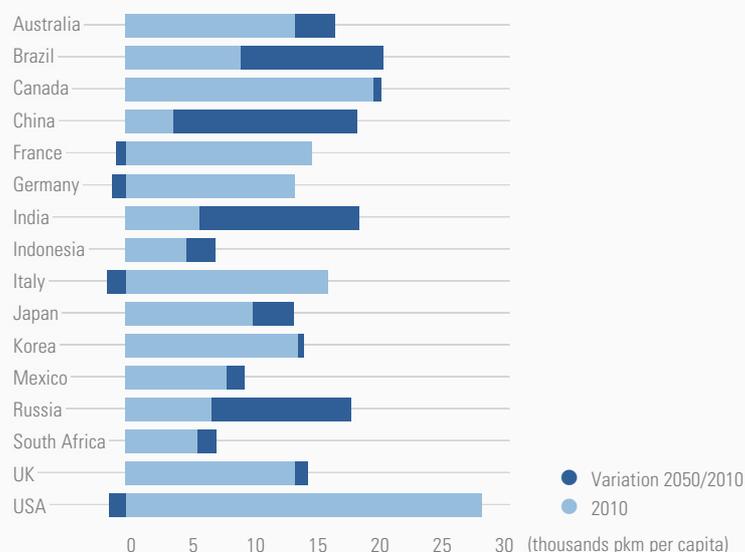


Figure 17. Passenger mobility



this increase is lower than it would otherwise be because of improvements in energy efficiency. Finally, there is a notable convergence of activity levels across the 16 DDPs. This can be seen in passenger mobility, measured by passenger km per capita, as shown in [Figure 17](#).

DDPs show that deep decarbonization supports sustainable development and is compatible with many economic and social benefits. The most fundamental benefit is avoiding dangerous climate change. Unabated, climate change threatens well-being in all countries, with the most vulnerable populations most at risk; in developing countries it jeopardizes many development goals. 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. These include improved air quality (see, case studies 15 [PDF](#) and 16 [PDF](#) of the on-line sup-

plementary material on the example of China and India), enhanced energy security (case studies 17 [PDF](#) and 18 [PDF](#) of the on-line supplementary material on the example of Japan and India), addressing energy poverty (see, case studies 19 [PDF](#), 20 [PDF](#) and 21 [PDF](#) of the on-line supplementary material on the example of UK, France and South Africa improved employment, reduction in basic poverty and improved income distribution (case study 22 [PDF](#) of the on-line supplementary material on the example of South Africa). and good macroeconomic performance (case studies 23 [PDF](#) and 24 [PDF](#) of the on-line supplementary material on the example of France and Brazil). For all countries to fully realize these benefits, low-carbon technologies must be made affordable and energy planning must treat social priorities as paramount.

One case in point, South Africa, has experienced persistent and very high levels of income poverty, inequality and unemployment. In 2011, 46% of the population was living below the poverty line, the income share of the bottom 40% was 7%, the Gini coefficient had deteriorated from 59 to 64 since 1993, and in 2015 the employed population over 15 years of age was only 40%, down from 45% in 1995. Deeper analysis by the South African team linked this to persistent challenges with improving educational outcomes in the post-apartheid era, resulting in a skill deficit affecting the functioning of the economy.

Labor skills shortages are a binding limit on what sectors can grow and on economic growth overall, and have important impacts on decarbonization strategy notably because the coal industry is a major current contributor to the South African economy and employer of the less-skilled. Restructuring the economy away from coal mining would mean retraining this workforce to keep it employed in a decarbonized world; because of difficulties raising general skill levels, work must be found for them in other low-skill, low-GHG intensive occupations.

Two illustrative alternative economic pathways modeled for South Africa illustrate how improvement of development indicators and decarbonization can be achieved. One economic pathway centers on changing the structure of the economy, promoting sectors that are less GHG intensive and can absorb lower-skill labor. The other pathway (high-skills) assumes success in improving the education system, allowing low-GHG sectors that require higher-skilled labour to grow.¹¹ Linking these economic pathways with the energy system, the South African DDPP analysis shows that there can be significant improvements in both the carbon and socio-economic indicators. Under a GHG budget of 14Gt for South Africa, the unemployment rate drops from 25% in 2015 to between 12% (economic structure pathway) and 18% (high skills), and the percentage of low-income households drops from 49% in 2010 to 18% in 2050. Whilst these are not ideal, they represent significant improvements.

India's DDPs are also structured around the question of how deep decarbonization can support sustainable development (case study 25 [PDF](#) of the on-line supplementary material). In India's

Figure 18. South Africa. Unemployment rate over time as calculated from the quantity of labour demanded in the e-SAGE CGE model

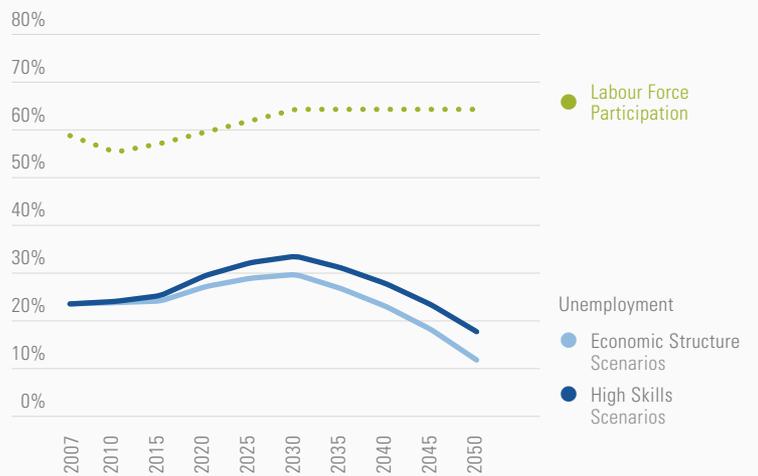
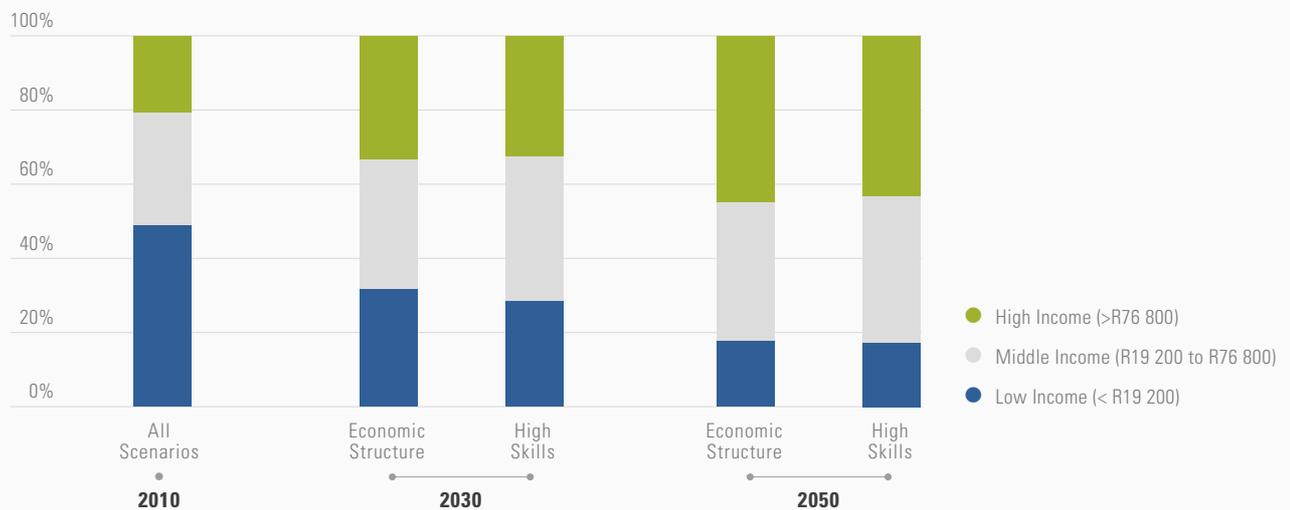


Figure 19. South Africa. The percentage of the population in the low, middle and high income groups as defined by SATIM



¹¹ These are illustrative; in actuality, combined elements of these and other factors are possible. The objective was to illustrate interesting features of what might be possible.

case, fundamental transitions in demography, income, urbanization and industrialization are expected to alter the drivers of future greenhouse gas emissions. These multiple transitions bring opportunities and challenges regarding the twin goals of development and decarbonization. The scale and diversity of India's resource endowments, its institutions and socio-economic dynamics, frustrate any attempt to find a 'one-size-fits-all' solution package, and suggest instead a scan of the entire policy spectrum to holistically address the national and sub-national goals of economic development, environmental integrity and social justice. India's National Action Plan on Climate Change (NAPCC)¹² envisions addressing the varying objectives simultaneously by adopting national policies (on inclusive growth, smart urbanization, balanced regional development, sustainable mobility and building codes, to name a few) aiming at structural and behavioral shifts that will alter market dynamics towards lowering material-use intensity and environmental damages.

The Indian DDPP analysis considers two pathways resting on distinct approaches to the policy package for deep decarbonization by 2050. The Conventional Scenario modeled envisions deep decarbonization as a commitment to apply a global carbon-price trajectory consistent with the 2°C limit, while other socioeconomic policies are not coordinated with decarbonization. The 'Sustainable Scenario,' in contrast, entrenches deep decarbonization within the mix of national Sustainable Development Goals. In an integrated approach across diverse sectors, geographical scales and dimensions of sustainable development, this scenario considers a multitude of local, bottom-up and sectoral policies and measures targeting various objectives like Sustainable Development Goals, share of renewable energy, air quality, energy access

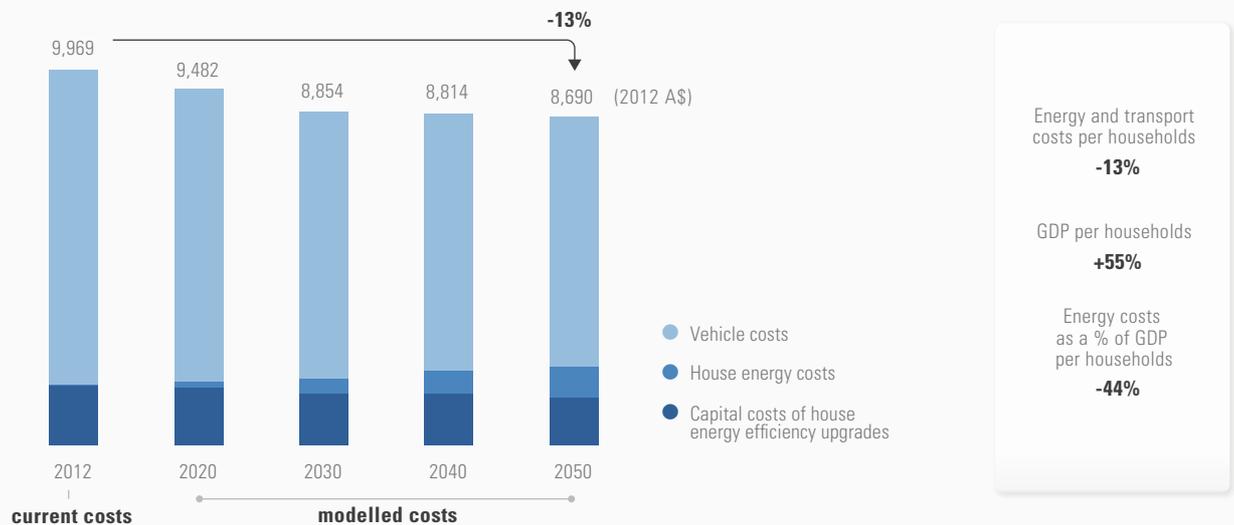
and energy efficiency, waste reduction, dematerialization and resources conservation. The prominent measures include the choice of urban form, investment in low-carbon infrastructure, energy-efficient building codes, fuel-economy standards, air quality standards, waste recovery mandates, water conservation policies, regional agreements for sharing rivers and infrastructures and the wise use of common property resources. The Conventional Scenario overlooks these opportunities. A carbon price alone cannot motivate all these objectives to the same degree, i.e. most don't have costs that a carbon price could influence.

The aggressive pursuit of 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 consumption, 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 those modeled for the UK, France and Germany. Despite concerns that climate change could increase energy costs, the UK scenarios showed strong synergies between tackling fuel poverty and reducing CO₂ emissions by taking action on energy efficiency (see case study 19  PDF of the on-line supplementary material). DDP analysis shows that carefully designed and targeted energy efficiency policy interventions can offset higher energy costs. Analysis also highlighted the need for careful policy design, to ensure that passing through costs to energy bills does not unduly burden low-income households. In the UK, the DDPP analysis illustrated that, if policies

¹² <http://www.moef.nic.in/ccd-napcc>

Figure 20. Australia. Average annual energy and personal transport costs per household, 2012 A\$



are effectively designed to deliver the 2030 level of emission reductions required under deep decarbonization, decarbonization also slashes the number of fuel-poor households from 2.86 million in 2013 to 1.18 million by 2030.

The Australian DDP also achieves substantial emissions reductions while reducing the net cost of energy to households (case study 26 [PDF](#) of the on-line supplementary material). It pursues ambitious energy efficiency and the decarbonizing of energy use in residential buildings and personal transport. The result is the cost of energy and transport for households falling by 13%, as shown in figure 21 below, despite higher capital costs and electricity prices. As income is expected to increase more than 50% over this period, this cost cutting represent a near-halving of the costs of energy and transport, as a proportion of household income.

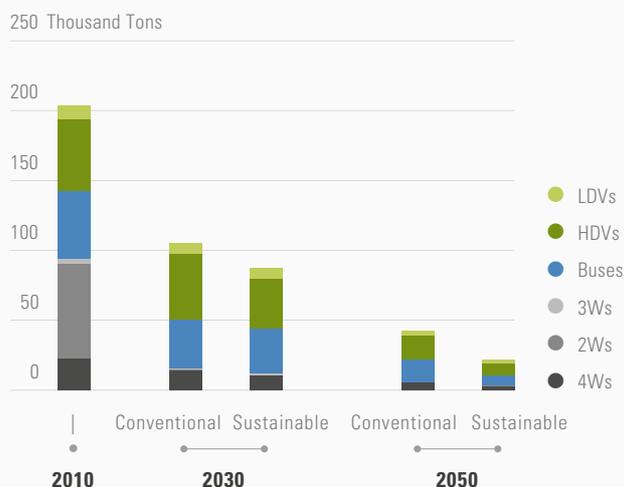
Reducing uncontrolled fossil fuel emissions has significant public health benefits. The potential scale of these benefits can be seen in the cases of China and India, where fossil fuel

combustion is the major source of the important air pollution heavily affecting population's health. In the China DDP, deep decarbonization reduced primary air pollutants (SO₂, NO_x, PM_{2.5}, VOCs and NH₃) by 42%–79%, allowing major cities to meet WHO air quality standards (case study 15 [PDF](#) of the on-line supplementary material).

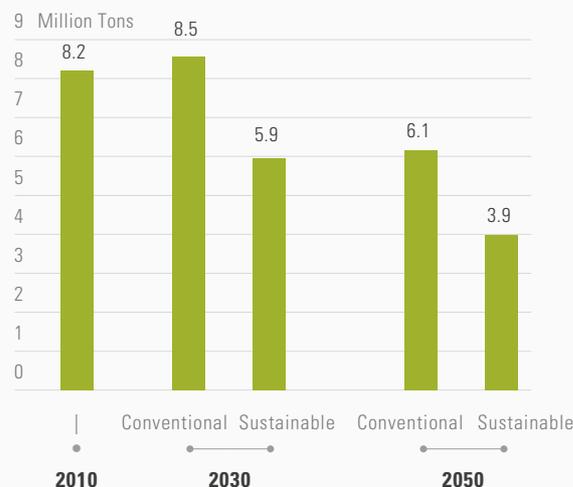
The Indian DDP analysis shows that while the Conventional Scenario reduces CO₂ emissions, the Sustainable Scenario achieves the same reduction with better air quality by aligning sustainable development with deep decarbonization actions case study 16 [PDF](#) of the on-line supplementary material. The approach of the Conventional Scenario to air pollution focuses on expensive end-of-the-pipe technology and fuel-related interventions like catalytic converters in vehicles or desulfurization equipment for industrial coal combustion. The levers of air pollution control in the Indian Sustainable Scenario are very different. They reduce end-use demand and shift consumption to cleaner modes and technologies, raising the clean-energy fraction of the energy supply mix.

Figure 21. India. Air quality, PM_{2.5} and SO₂ Emissions

PM_{2.5} Emissions from Road Transport



SO₂ Emissions

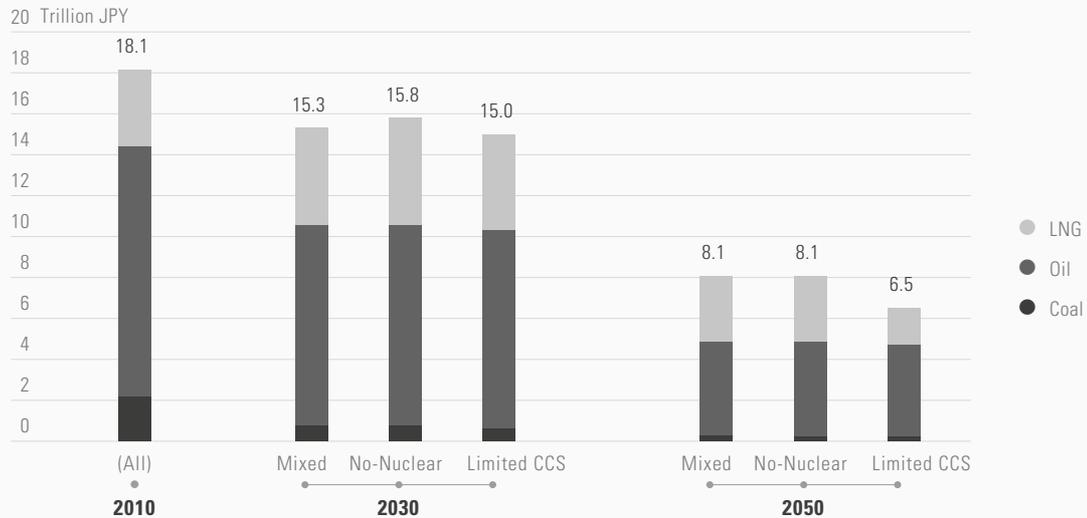


For instance, most PM_{2.5} comes from transport. The key mitigation actions in road transport include improving urban design and planning to reduce travel, investments in infrastructure that facilitate a modal shift to public transport and non-motorized transport, and support for alternate technology innovation (e.g. electric vehicles and energy storage). Implementing targeted measures to reduce travel demand can potentially slice demand in half in 2050 in the Sustainable Scenario, compared to the Conventional Scenario, translating into reduced energy demand and lower travel times. In addition, market based incentives for cleaner, low-carbon fuels like natural gas and biofuels deliver sizable CO₂ emissions mitigation as well as reductions in PM_{2.5} (Figure 21). SO₂, on the other hand, comes mainly from coal combustion in industry and electricity generation. Conventional SO₂ emissions mitigation typically takes one of two paths: direct flue gas cleaning or shifting towards lower sulfur sources. In the Sustainable Scenario, advanced technologies, dematerialization,

recycling and sustainable behavior reduce the necessity for heat-intensive primary material processing in the first place (Figure 21).

Reducing fossil fuel demand can increase the energy security of energy-importing countries; diversification can benefit resource exporters. The benefits to importers can be seen clearly in the Italian and Japanese DDPs (case studies 27 [PDF](#) and 17 [PDF](#) of the on-line supplementary material). In all the DDP scenarios examined for Japan, dependency on imported fossil fuels is reduced substantially by 2050, compared to 2010. This is achieved thanks to a reduction in energy demand plus deployment of non-fossil options, notably renewable energy on the supply side. Nuclear power supply is also drastically reduced from its 2010 level under all the DDP scenarios considered. In 2050, under every DDP scenario for Japan, fossil fuel consumption falls by approximately 60% compared to 2010. Fossil fuel import costs fall below 2010 levels by 2030 and decrease further in 2050. In one of three scenarios

Figure 22. Japan. Fuel import costs in DDPP scenarios



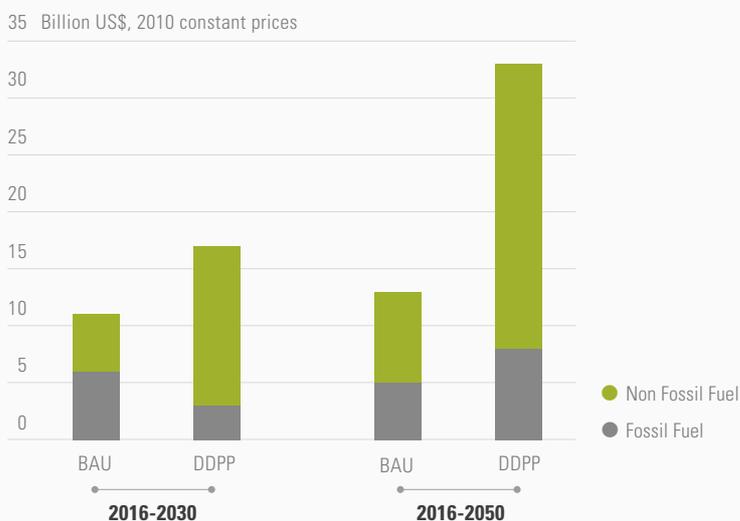
modeled, called the Limited CCS Scenario, fuel import costs in 2050 are lowest because additional renewable energies are deployed in place of fossil fuel, mainly in the electricity sector. In a framework in which decarbonization efforts are shared by all countries, a Deep Decarbonization Pathway can produce positive macroeconomic effects for trade balances. The outcome, depending on the sector, is either increased net exports or lower net imports. The trade impact is particularly pronounced as energy dependence is lowered, when countries' reliance on domestic renewable energy sources reduces their fossil fuel imports. In the three decarbonization pathways considered for Italy, renewable energy sources account for 60%–70% of the energy mix and imports of primary fossil fuels fall 55%–76%, while imports from energy-intensive industries as a whole would decrease 7%–13%. The trade balance for energy-intensive products remains negative, but is reduced in all the decarbonization scenarios. The most important trade-deficit reductions for energy-intensive industries come

from non-metallic minerals, chemicals, petrochemicals, iron and steel.

The Russian economy currently relies heavily on the export of natural resources (case study 28 [PDF](#) of the on-line supplementary material). Primary energy contributes about 70% of Russia's total export revenue (when minerals and metals are included, this percentage goes up to 90%). Russia's abundance of natural resources provides tremendous benefits and opportunities, but also creates risks, seen clearly in the current economic slowdown that has followed the fall in oil prices. DDP modeling shows resource-exporting countries including Russia reap economic benefits from the diversification of energy supplies. The growth in investments, the 'quality' shift in investments, plus the positive energy-bill savings, will result in 2050 in at least a 1% overall increase in Russia's GDP and a net gain in jobs of more than 3%, with higher demand for skilled labor.

Decarbonization is fully consistent with Russia's official, long-term goals of modernization

Figure 23. Russia. Average annual investment in energy over different time periods



and reducing the economy's dependence on energy and raw materials exports. Deep decarbonization leading to a 25% carbon emissions reduction by mid-2030 (versus 2010) would require an additional cumulative investment of \$200-\$250 billion (in constant 2010 dollars, depending on the decarbonization strategy). The deep decarbonization scenarios considered in the Russian analysis assume that as greater demand for energy innovation unfolds, significant investments are made in energy efficiency and clean-energy technologies, spurring large-scale economic impacts. In addition, deep decarbonization permits a net reduction of \$30-\$50 billion in total energy expenditures at the country level by 2030. Decarbonization demands more efficient resource utilization and the decarbonization of electricity generation.

Figure 23 compares the investment structure under current business-as-usual policies (BAU) and under a DDP scenario. The DDP scenario requires investing about 60% more in the power industry by 2030, and investing more than 2.5 times more by 2050 than BAU, with a signif-

icant shift towards non-fossil generation. Notably, this higher level of investment will not increase electric generation costs because of fuel savings and the longer lifespan of some generation capacities (such as hydro- and nuclear power plants). Sectors besides power generation will have to invest in energy efficiency and fuel switching as well; this shift assumes higher demand for industrial manufactured products and information and communication technology products and services, which are more labor intensive and have greater long-term growth potential. This can stimulate more research and development (R&D), greatly strengthen Russia's position in the global competition for investment, provide incentives for modernization and unlock opportunities for cooperation in the field of clean energy.

4 Is Deep Decarbonization Affordable?

Deployment at the scales analyzed by the country teams offers huge promise for catalyzing necessary cost reductions.

Deep decarbonization is essentially the process of replacing inefficient, carbon-intensive technologies with efficient, low-carbon technologies that provide the same (or better) energy services. The scale of infrastructure required to support

deep decarbonization is indicated by cumulative technology deployments over time, aggregated across all the DDPPs (Table 4). For example, by 2050 the DDPPs show a cumulative deployment of 3,800 GW of solar electricity generation and 4,100 GW of wind, along with 1.2 billion electric, fuel cell and plug-in passenger vehicles and 250 million alternative fuel freight vehicles.

Table 4. Cumulative production of decarbonized units, all DDPP countries*

Technology		2010	2020	2030	2040	2050
Electric Generation Capacity						
Coal w/ CCS	GW	0	3	36	160	362
Fuel Oil w/CCS	GW	0	0	1	1	2
Natural gas w/ CCS	GW	0	12	93	342	798
Nuclear	GW	2	53	259	632	1053
Hydropower	GW	8	190	425	624	813
Wind-Onshore	GW	13	315	1064	2174	3511
Wind-Offshore	GW	1	29	100	268	616
Solar PV	GW	11	275	823	1752	3254
Solar Thermal	GW	0	10	90	294	598
Biomass	GW	1	26	105	221	370
Geothermal	GW	0	4	27	61	97
Fuel Production Capacity						
Hydrogen Production - Steam Reformation	EJ	0	0	0	0	1
Hydrogen Production - Electrolysis	EJ	0	1	5	13	20
Power-to-Gas Production	EJ	0	0	1	2	4
Biorefinery - Ethanol	EJ	0	2	4	7	9
Biorefinery - Diesel	EJ	0	4	10	18	28
Biogas Production - SNG	EJ	0	4	10	20	32
Alternative vehicles						
Electric Vehicle	Million	0	32	134	333	650
Plug-in Hybrid Electric Vehicle	Million	0	12	75	206	375
Hydrogen Fuel Cell Vehicle	Million	0	3	31	102	221
Compressed Pipeline Gas Vehicle	Million	1	12	27	64	121
Liquefied Pipeline Gas Vehicle	Million	0	5	16	25	34
Hydrogen Fuel Cell Vehicle	Million	0	0	4	27	104

* The values in this table represent total number of units produced over the period, and exclude retirement of worn-out units.

This analysis assumes a world committed to decarbonization, where key technologies are in demand, and cost declines are driven by global uptake. As technology costs decline, deep decarbonization starts to provide its own momentum: lower costs encourage deployment, which can encourage even lower costs. **The “tipping point” in this process is when costs decline at a rate and speed sufficient to drive their global deployment based solely on their favorable economics,** e.g. when wind or solar becomes cheaper than coal (and eventually natural gas) for generating electricity. History has shown that technology costs tend to decrease as a function of cumulative production, 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 that 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. Those savings illustrate how international cooperation in developing markets for low-carbon technologies can reduce costs 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 R&D to early-stage deployment to full-commercialization—is the key to realizing cost declines along the Deep Decarbonization Pathway, as shown in [figure 24](#).

Large investments in deep decarbonization via low-carbon technology deployment are likely to benefit all decarbonizing nations by helping to drive costs down. These results show those benefits. Once sufficient momentum has been achieved, cost lowering dynamics can become self-reinforcing, with lower prices stim-

ulating deployment and deployment stimulating lower costs. The global markets' demonstrated ability to catalyze cost reductions—as seen in the precipitous declines in solar PV costs to date—can stimulate greater ambition by policymakers to pursue a bootstrapping process of setting ambitious targets, aggressively deploying low-carbon technologies, and realizing cost declines, all further positioning deep decarbonization as the new normal in the energy economy.

Deep decarbonization in developing countries can be accelerated by global markets for low-carbon technologies. Deep decarbonization in developing countries is limited by the rate at which countries adopt efficient, low-carbon technologies. 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 might build inadequate durable infrastructure, locking 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 they become affordable earlier in developing countries, relative to the cost of conventional technologies. In cases where developing countries are the initial markets for these technologies, for example concentrating solar power in South Africa (see case study 29 [PDF](#) of the on-line supplementary material), 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.

Figure 24. 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.

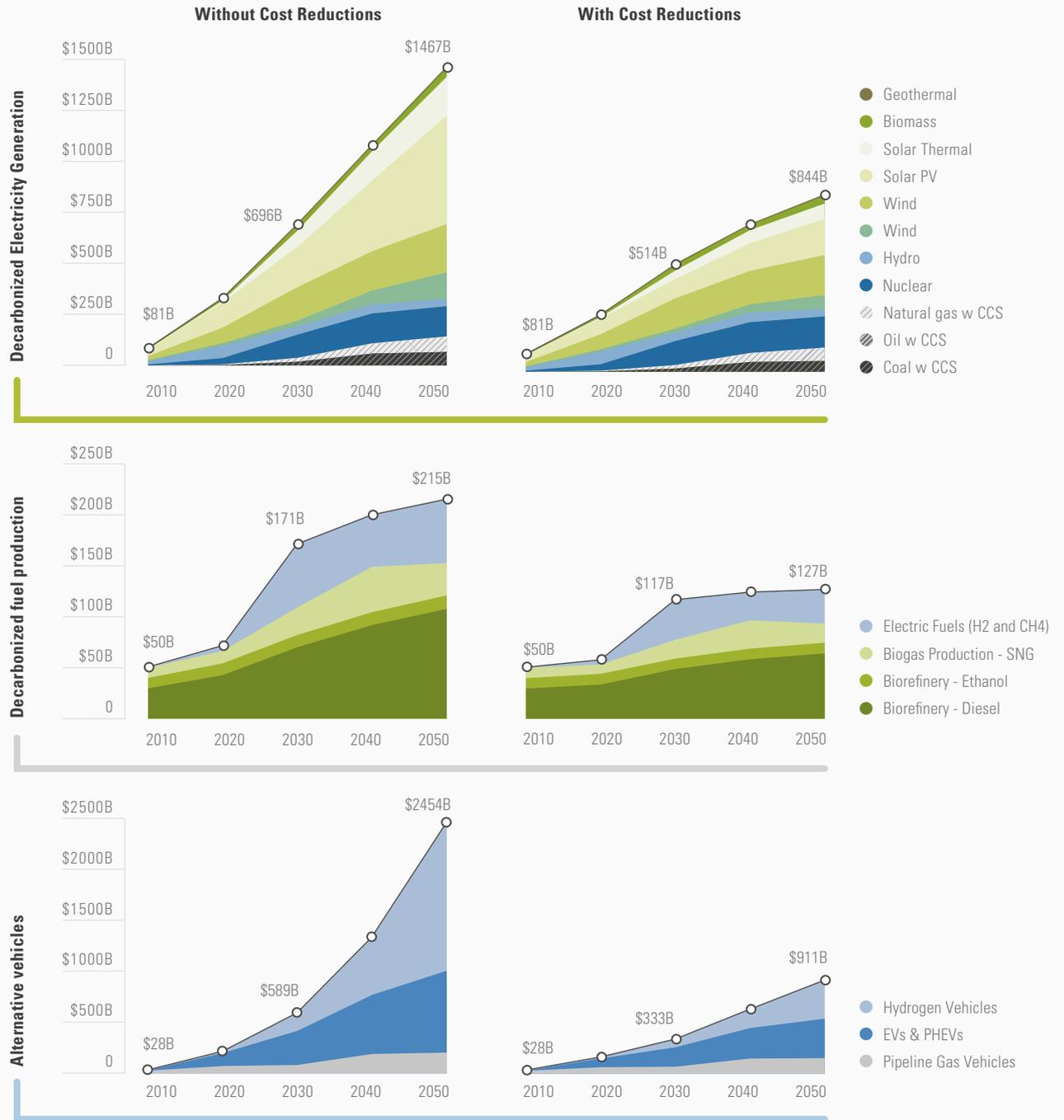


Table 5. Annual investment in key low carbon technologies and their share of GDP for DDPP countries.

		2020	2030	2040	2050
Annual investments in the 16 DDPP scenarios (B\$)	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 (Billion US \$)	484	963	1452	1882
Annual investments in low-carbon technologies as a share of GDP (%)		0,8%	1,2%	1.3%	1.3%

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 5). With money to be made, global finance can and will provide the necessary investment, provided adequate long-term decarbonization policy 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), 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 where high initial capital costs are offset by lower operating costs, and in early stages of deployment before economies of scale and learning effects have been achieved.

Energy investment under deep decarbonization requires only a modest increase in the gross energy investment required in the absence of climate policy, but a major shift in investment away from fossil fuels toward low-carbon technologies. The gross

investment requirement for low-carbon technologies in the DDPPs must rise to an average 1.2–1.3% of GDP for the DDPP countries (up from their much lower level today). This represents 6%–7% of total annual investment activity in these economies, which typically consumes about one-quarter of GDP, so that the aggregate low-carbon investment requirements appear manageable. This is even truer if taking into account the precipitous decline of annual global fossil fuel supply investments in a world pursuing deep decarbonization and reducing fossil fuel demand, compared to the business-as-usual scenario which foresees around \$1 trillion of investments per year in fossil energy over the next decade (according to the New Policies Scenarios of the World Energy Investment Outlook)¹³. In some country DDPPs, such as for Australia, no additional capital was required as a proportion of GDP, it was all transitioned away from fossil fuel oriented investment (see case study 30  PDF of the on-line supplementary material).

The net cost of deep decarbonization is substantially lower after accounting for reduced operating costs. 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 the US case, in which the

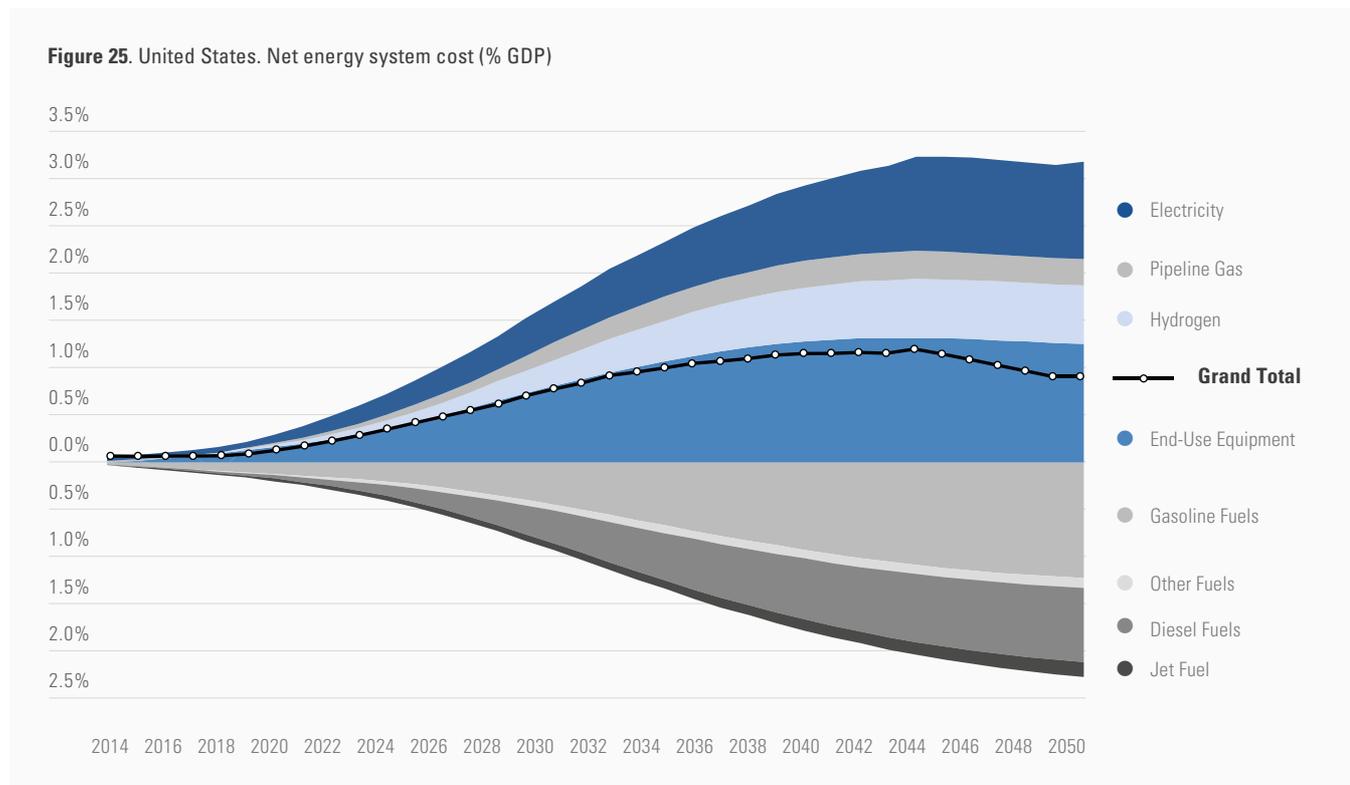
¹³ <https://www.iea.org/publications/freepublications/publication/WEIO2014.pdf>

net cost of supplying and using energy for a deeply decarbonized scenario in 2050 is equivalent to about 1% of GDP in that year. The principal impact of deep decarbonization on the energy economy is not an overall increase in spending, but a fundamental shift in the direction of that spending. Instead of consumers and businesses continuing to expend vast sums on refined fossil fuels at the pump, spending is directed toward investment in low-carbon technologies on both the supply and demand sides of the energy system. **Figure 25** shows the levelized cost impacts of these changes compared to a reference fossil fuel-based future (For more details, see case study 31 [PDF](#) of the on-line supplementary material)

Another factor that reduces the net cost of deep decarbonization is greater energy efficiency and conservation (see case

study 32 [PDF](#) of the on-line supplementary material). This is illustrated by the case of household energy and transport costs in the Australian DDP, in which net energy costs fall in absolute terms due to energy savings and lower operating costs. Energy costs fall even further as a share of average household income as GDP grows case study 26 [PDF](#) of the on-line supplementary material).

The decarbonization of the energy system decentralizes the standard energy system investment model. Deep decarbonization requires transformational, rather than marginal, changes in energy production and consumption systems. This, in turn, requires that capital would flow to low-carbon technologies—principally in the areas of decarbonized supply infrastructure (generation and fuel production) and end-use equipment (energy efficiency and



fuel switching to decarbonized energy carriers). This is associated with a change in the nature of investors. Energy supply investment is currently concentrated in a limited number of fossil-fuel producing regions, under large state-owned enterprises or multi-national corporations with access to deep and liquid capital markets and proven business models.

Creating a favorable policy and regulatory framework to reduce the risk associated with the upfront, lumpy, and illiquid nature of decarbonization investments is a key role for policymakers. This shift in investment results in major new market opportunities for technologies in the areas of decarbonized power generation (renewables, nuclear, and CCS); decarbonized fuel production (advanced biofuels, hydrogen electrolysis, and synthetic methane); and alternative fuel vehicles (powered by electricity, liquid biofuels, hydrogen, and synthetic decarbonized pipeline gas). Ensuring that capital is available to all parts of this new energy economy—businesses engaged in early stage R&D, developers wishing to build a new solar PV power plant, utilities financing new infrastructure to support electrification, and consumers wishing to purchase heat pumps or an electric vehicle—is a key challenge to making the transformation happen.

Implementing a low net-cost energy transformation will require that policymakers establish investment market rules and institutions

to direct investments towards low-carbon options. Indeed, the challenge is not so much the availability of global capital but its availability in the low-carbon sectors, adequate to support the deep decarbonization transformation. This means:

- encouraging adequate allocation of capital, in particular to those actors without access to deep and liquid pools of capital (households, low-carbon SMEs, etc.) for example, through mechanisms that amortize solar panels and heat pumps through property taxes instead of personal borrowing;
- providing a consistent regulatory environment, including a planning framework commensurate with the timescale of large fixed-capital investments;
- offering appropriate incentives to encourage the adoption of key technologies; and
- developing mechanisms to manage any inequitable distributional impacts.

5 Why are deep decarbonization pathways essential for climate policy?

Deep decarbonization pathways (DDPs) can increase the ambitiousness of country commitments to reducing their GHG emissions under the UNFCCC. In advance of COP-21, countries have submitted Intended Nationally Defined Contributions (INDCs), which contain national commitments to emissions reductions, typically medium-term (e.g. to 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 what further measures deep decarbonization will entail. While DDPs are best seen as roadmaps of options and enabling conditions, they can also play a critical role in increasing the ambitiousness of national commitments in the future. DDPs can also provide long-term benchmarks for measuring short-term progress. DDPs are needed so that countries, and the firms and households that compose them, stay within their carbon budgets and avoid dead ends. Though 2050 may seem far away, the operational lifetimes of much of the infrastructure and equipment that drive CO₂ emissions—power plants, buildings, industrial boilers and heavy-duty vehicles—are longer. DDPs support current policy and investment decisions by making the long-term emissions consequences of infrastructure- and equipment-investment 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. In other words, if new,

long-lived infrastructure is not low-carbon, that infrastructure will become an obstacle to deep decarbonization in the long run and will need to be abandoned and replaced at great additional cost to reach mitigation targets. The US analysis (see US report [PDF](#)) demonstrates that with appropriate foresight and early actions, DDPs can help countries avoid the need for costly early replacement of major infrastructure—for example, fossil-fuel power plants that are decommissioned early; fossil-fuel vehicles scrapped before the end of their useful lives; or costly retrofits for homes, businesses, and industries still using fossil fuels. For shorter-lived equipment, adoption rates for low-carbon options can ramp up more gradually, but they must comprise the bulk of new sales to drive innovation and to ensure that they dominate the stock by 2050 (e.g. by 2035 for cars, with the understanding that nearly all cars last less than 15 years). Anticipating and addressing barriers to the near-term adoption of low-carbon infrastructure should be the focus of near-term policy action.

DDPs help design resilient, adaptive policies in a context of long horizons with large uncertainties (see case study 33 [PDF](#) of the on-line supplementary material). Deep decarbonization is marked by strong technological uncertainties and inertias, making sequential decision-making necessary to take advantage of continual learning. Policy design and dynamic management plays an important role in this context, making the transformation more robust,

(i.e. suited to very different economic or technological environments, domestic and international) and resilient (able to swiftly recover their balance and functionality in the event of surprises). The policies and measures that deserve to be prioritized are those:

- that are common to all pathways (e.g. electrification using decarbonized electricity);
- for which near-term action is required to make gradual deployment at scale possible over the course of the transition (e.g. efficiency); and
- which preserve future freedom of choice by encouraging the extended use of existing facilities and/or systems (e.g. re-use of natural gas networks to transmit renewable syngas or a portion of hydrogen).

“Surprises” can also affect the efficiency of domestic policies. One French very low energy demand DDP scenario features an ambitious building energy efficiency retrofitting program (600,000 buildings per year). This program may not fulfill its objective (because of financing constraints, an insufficiently skilled workforce, or transaction costs), necessitating adjustment of the policy package at some point, e.g. acceleration of the decarbonization of energy with different policy focuses and instruments.

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 also provide a framework for stakeholders to discuss policy proposals and identify potential areas for public-private partnerships.

Investors can work with the businesses they invest in to identify and mitigate their carbon exposure, and support the development of new technologies through investing in early-stage R&D.

DDPs provide a necessary analytical tool, a long-term road map, to guide today's policies and investments in low-emission technologies. All DDPs rely on technologies that are currently available or will become available in the near future, given reasonable assumptions, but they also show that the development and diffusion of low-emission technologies must be accelerated. Many of these technologies are already commercially available, but deep decarbonization requires an orders-of-magnitude increase in their rate of deployment, standardization of their use, and associated decreases in their costs. In addition, several critical low-emission technologies (e.g. CCS, energy storage, grid management, advanced vehicles and biofuels) are still in the R&D phase. Developing new technologies involves long time lags and can require complex private-public partnerships.

DDPs show that greater international cooperation on research, development, demonstration and diffusion (RDD&D) is necessary for widespread uptake of low-emission technologies in all countries before mid-century. Our analysis demonstrates that deep decarbonization requires a large number of low-carbon technologies to become reliable, cost-competitive and widely available in all countries. Many of these technologies are already commercially available, but deep decarbonization requires a scale-up of their diffusion, generalization of their use, and decrease in their costs through economies of scale. A few key technologies still in the R&D phase are needed globally, and the rate and range of technological diffusion required in the DDPs is only possible if coordinated RDD&D leads to “learning-by-researching” and “learning-by doing” effects. The deployment of CCS in electricity generation illustrates this point. Several country DDPs consider this technology critical for deep decarbonization, but it is only commercially available as a prototype. To

achieve deep decarbonization, CCS must experience a demonstration phase over the next 10 years, and then enter the market at scale during the late 2020's (Figure 26). To enable this rapid deployment, the cost-competitiveness of CCS must improve significantly over time (Figure 27). In the absence of carbon prices and global cooperation on RDD&D, it is difficult to see how the necessary technological improvements and cost reductions can be achieved at the required pace and to see it installed at the needed magnitude (about 25 GW per annum by 2030, across the 16 countries).

International cooperation on technology development and diffusion is particularly important, because absent climate policy, developing countries are expected to build many new fossil-fuel power plants between 2010 and 2050. Deep decarbonization remains feasible even if the deployment of CCS is more disappointing than assumed, but would require rapid and substantial RDD&D technology and policy adjustments to push alternatives (renewables, nuclear or efficiency). For CCS, as for other decarbonization technologies, coordination of global R&D efforts would accelerate the demonstration and testing phase, and more quickly reveal if the technology has promise or if other measures must be pursued.

The DDPP analysis underscores the importance of international cooperation to maximize the size of the global market for low-carbon technologies. Building worldwide markets for these technologies is the greatest opportunity for maximizing innovation and minimizing costs. Historically, the biggest advances in low-carbon technologies have occurred in richer countries. These countries have the financial resources to shift their own investments from high- to low-carbon technologies, thereby bringing down costs for everyone else—as has occurred with the interaction of mainly German

demand and Chinese supply of solar PV cells. Developed countries have a leading role to play in the development and diffusion of the broad portfolio of global low-carbon technologies. This requires clear and coordinated policies and measures to align and focus efforts by technol-

Figure 26. Annual deployment of CCS in the power generation sector across the 16 DDPP countries

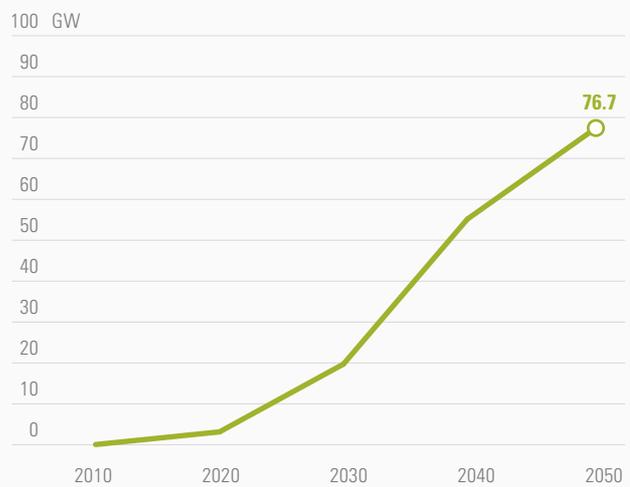
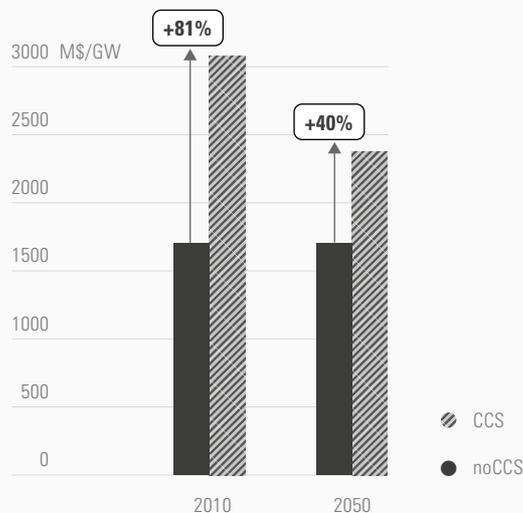


Figure 27. Investment cost in coal-fired power plants, CCS vs. noCCS



ogy development firms, for example by avoiding the emergence of multiple technology standards (e.g. for electric car chargers or distributed two-way transmission equipment), which would create fragmented markets and delay the learning process.

DDPs provide a framework for understanding how deep decarbonization can work in harmony with other sustainable development priorities.

Having DDPs as a focus for public policies 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 opportunities, environmental protection and public health. DDPs concretely investigate the synergies that occur when national sustainable development and decarbonization policies are aligned, and analyze how economic, social and energy policies can and need to be coordinated on a long-term basis for achieving desired outcomes. For example, the Chinese DDPP analysis suggests that deep decarbonization is instrumental in reducing local air pollution while maintaining fast growth over the coming decades (see case study 15 [PDF](#) of the on-line supplementary material) In India's case, fundamental changes in demography, income, urbanization and industrialization are expected to alter the key drivers of future GHG emissions. These multiple transition vectors bring opportunities and risks to the twin challenges of development and decarbonization. The Indian DDP shows that a policy response that focuses on carbon alone could cost five times as much per tonne abated as one that coordinates with other social goals (see case study 25 [PDF](#) of the on-line supplementary material) The South African DDPs also show that deep decarbonization can be compatible with significant reductions of unemployment and inequalities (see case study 22 [PDF](#) of the on-line supplementary material)

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 and 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 coordinating policy and investment between sectors, across jurisdictions, and between jurisdictional levels (federal, provincial, local). Decarbonization might require institutional reforms to implement innovative policy approaches, such as enhanced cooperation between different levels of political governance, the participation of broad groups of stakeholders, and public private partnerships on decarbonization technology RDD&D (see case studies 34 [PDF](#), 35 [PDF](#) and 36 [PDF](#) of the on-line supplementary material for discussions in the UK, Australian and German examples).

The pathways to national transformation are based on comprehensive policy packages.

The DDP policy packages combine sectoral and economy-wide measures, economic incentives and regulations of different forms. They have been designed by each country research team to fit each nation's specific context. In general, along with other country-specific policies, implementing each national DDP will likely require some mix of the following:

- Regulations and information for less price-sensitive sectors, particularly with respect to buildings and transport efficiency (e.g. building codes, performance standards).
- Carbon pricing for price-sensitive sectors, and to incentivize technology innovation.
- Policies that support innovation (e.g. R&D, prototyping, and commercialization support,

such as municipalities purchasing decarbonized vehicle fleets).

- Policies that support infrastructure change (e.g. municipal land use planning, property taxation reform, and transit charges).

The Canadian DDPP (see case study 37  of the on-line supplementary material) for example, relies on an integrated combination of policies and measures to reach deep decarbonization, the main elements of which are:

1. Best-in-class mandatory energy and GHG intensity regulations requiring the use of zero- or near-zero emission technologies in the buildings, transport, and electricity sectors¹⁴, applied to all new installations and retrofits:
 - In buildings, regulations trend down to require net-zero-energy residential buildings after 2025, and commercial buildings after 2035. This is enabled by highly efficient building shells, electric space and water heaters with heat pumps, solar water heaters, and eventually, building solar PV as costs fall. Another option is identifying opportunities for community-scale heating by mapping energy demand.
 - In transport, regulations for personal vehicles and light freight are set on a rolling, five-year schedule. This is because there are many technologies available and innovation allows them to change rapidly. Examples include improvements in efficiency, electrification, use of biofuels, hydrogen fuels and mode shifting. The long-term goal is for all new personal vehicles to run on decarbonized energy by the early 2030s. Heavy freight vehicles with fewer options (i.e. rail-based mode shifting, efficiency, biofuels and hydrogen) would be on a schedule to decarbonize by 2040.
2. Mandatory 99% controls for all landfill and industrial methane sources (landfill, pipe-

lines, etc.). Any remaining emissions would be charged as per the following policy.

3. A hybrid carbon-pricing policy, differentiated between heavy industries and the rest of the economy:
 - A tradable GHG performance standard for heavy industry (including electricity), evolving from 25% reductions compared to 2005 in 2020 to 90% by 2050, using output-based allocations to address competitiveness concerns. If more feasible, an absolute cap-and-trade system could be implemented instead with similar effects.
 - A flexible carbon price, either a carbon tax or an upstream cap-and-trade covering the rest of the economy, rising to CDN \$50 by 2020 and then reaching CDN \$350 through \$10 annual increments to 2050. The funds are returned to consumers, half through lower personal income taxes and half through lower corporate income taxes. The charge would be flexible and benchmarked against technological progress.
4. A land-use policy package that values the net carbon flows of large parcels of land. The policy would provide standardized valuation and accounting for net carbon flows on agricultural, forested, brownfield and wild private lands. Government lands would be managed including net carbon flows in the mandate.

There is no unique or 'optimal' policy package—ambitious emission reductions in a given country can be reached through very different policies. The choice of policy instruments depends on societal preferences, political economy concerns and institutional considerations. In the UK analysis, all scenarios feature the same 32% reduction of CO₂ emissions between 2020 and 2030 but the combination of measures dif-

¹⁴ The best mix of regulations and pricing for electricity will depend on the region and circumstance.

fers widely. One scenario's policy incentives favor the near-term diffusion of nuclear and wind; another works to steadily reduce energy demand, supported by building retrofitting programs to limit residential demand and car tax incentives and locally-based measures to control demand for cars. In both scenarios, carbon pricing obviously plays a role, but to a more limited extent than under yet another scenario where it is the dominant instrument - the carbon price reaches twice the level it does in the other two cases.

DDPs provide a framework for determining how to coordinate policies across a broad range of sectors.

As demonstrated in Section 4, the extra investments required for deep decarbonization are relatively modest compared to the total volume of global investments. This shows that low-carbon investment is not so much an issue of capital availability as one of how to redirect existing investment in fossil fuel supply and demand towards a low-carbon energy system. One of the main challenges lies in the expectations and attitude of financial institutions towards long-term investments, given their natural preference for liquid assets. This behavior raises specific barriers for low-carbon projects, which usually feature positive net present values but can be seen as more risky than business-as-usual investments due to their higher upfront costs, the lack of data on their financial performance and most critically, a lack of consistent and predictable carbon prices (among other investment payback determinants).

Carbon pricing is an important component of all the DDPP policy packages.

The policy tools for carbon pricing include economy-wide and sectoral cap-and-trade systems or taxation, with a wide range of revenue recycling options for both. The recycling method (e.g. reduced taxes or direct financing of emission reduction programs) can have a huge effect on the performance of price instruments. Regulatory standards can also

be designed to work in much the same way as implicit carbon prices (e.g. inter-company, tradable vehicle fuel efficiency standards).

Given that decarbonization relies on the right choices by millions of decentralized actors, effective economy-wide carbon pricing is a crucial tool to coordinate these decentralized choices. Effective economy-wide carbon pricing provides three benefits: (i) a long-term, emissions-reduction signal; (ii) a natural instrument to minimize total costs by matching the environmental objective to the last necessary abated tonne of CO₂ through marginal abatement signals; and (iii) an incentive for research and innovation. Through the long-term price signal it provides, carbon pricing also reduces the uncertainties associated with low-carbon capital investments.

The different DDPs use a broad range of policy tools, and underscore that the appropriate mechanisms and their design features need to be determined by national circumstances, complementary policy objectives (e.g. promoting energy access), policy preferences (e.g. preference for market-based mechanisms over taxation), as well as specific sector needs. As we underscore throughout this report, carbon pricing and other policy tools need to place particular importance on creating incentives and adequate financing for the long-term development of low-emission technologies.

The role of carbon pricing must be thought of in light of national circumstances; it is an especially efficient policy instrument in mature market economies.

The efficiency and policy-relevance of economic signals, and of carbon prices in particular, depends largely upon the maturity of market-based economic systems. In mature market economic systems, where the institutional, infrastructural and socioeconomic frameworks are reasonably stable, economic instruments can efficiently play the role of providing a signal that economic agents can fully integrate into their deci-

sion-making processes; this is largely the case in developed countries. In the less-mature market systems of developing countries, where markets are incomplete because of the strong role of informal exchanges, institutions' instability and poor information availability, economic signals may be swamped in a myriad of contradictory signals and incentives. In this case, a carbon price would still be part of the policy package, but probably as a secondary tool limited to the mitigation potentials that can be tapped through market incentives. The core of decarbonization would, at least in a transition period, be triggered by a more complex set of policies and measures tailored to the abatement potential and development needs of the country in question.

Indeed, if used as the only incentive, carbon prices would need to be quite high to compensate for the capital-intensive nature of low-carbon energy supply and efficiency investments. But because high carbon prices would raise concerns regarding competitiveness, stranded assets, and distributional effects, other well-tailored financial instruments will be needed to unleash low-carbon investment opportunities that today are frozen. Climate finance in particular could provide an efficient bridge between long-term emissions reduction assets and short-term cash balances. It could reduce the investment risks of low-carbon projects by signaling to investors that reasonable returns are available with a reasonable degree of risk, and that the policy environment governing these returns will be reasonably predictable for the life of the investment.

DDPs clarify the enabling conditions for developing countries to incorporate deep decarbonization into their development strategies, including the type and volume of support needed from the international community. It is crucial that developing countries do not delay their participation in the process of technological innovation and adoption. To see

adoption, many technologies will require modifications and sales, support and maintenance services adapted to local conditions. Even if they initially have lower adoption rates, developing nations can represent a significant market share for low-carbon technologies and help resolve barriers to their eventual adoption.

This means that some potential consequences of a deep decarbonization strategy, such as the higher capital cost of many low-emission technologies or foregone revenues from fossil-fuel exploitation, add to the economic challenges of deep decarbonization (see case study 38 [PDF](#) of the on-line supplementary material in the Indonesian case) in developing countries. DDPs provide a framework for understanding how international cooperation can help mitigate these challenges and enable low-carbon development. In addition, some technologies that have the potential to play a critical role in decarbonizing energy systems are a perfect fit for certain emerging country contexts, such as biomass and solar based micro grids. Developing those markets will be crucial for ensuring greater uptake of those technologies. This, in turn, highlights the importance of adequate policy schemes to open large emerging markets to low-carbon technologies (as illustrated by the example of concentrated solar power with storage in South Africa (see case study 29 [PDF](#) of the on-line supplementary material in the South African case). The maturation of these markets provides an unprecedented opportunity for economic development via investment in innovation, technology leadership and manufacturing in developing countries.

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. They also provide a transparent framework to understand whether a country's

short-term policies are consistent with achieving the stated objective. 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 DDP project 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 a global 2°C limit, nor were they actively considering this question. The initial results of the DDPP demonstrated that taking actions consistent with the 2°C limit is possible and context-specific. 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 next for the DDPP?

The DDPP is looking to expand its network, further improve available DDPs, and provide new public tools to allow greater participation and dialogue on deep decarbonization.

Expand the DDPP network and coverage:

The DDPP is already in discussion with research teams from additional countries wishing to prepare national pathways, and encourages 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 to prepare DDPs. A priority is expanding coverage to low-income countries, where much of the world's economic and population growth is expected to take place in the decades ahead. A better understanding of the deep decarbonization potential and enabling conditions in these countries is essential to determine what will be required to stay within the 2°C limit.

Improve available DDPs: This report synthesizes the second iteration of the 16 national DDPs, which represent the only collection of national pathways consistent with the 2°C limit for all major GHG emitters. While much has been achieved, we are conscious of the limitations of the work done so far. The next phase will therefore focus on identifying options to: (i) further reduce estimated cumulative emissions; (ii) deepen engagement with governments, business, civil society and other stakeholders to review and improve available pathways and build greater public awareness of the feasibility and implications of deep decarbonization; and (iii) explore with interested partners how public-private cooperation on developing and diffusing

low-emission technologies can be accelerated to support deep decarbonization in both developed and developing countries.

Develop and disseminate tools in support of deep decarbonization.

In addition to disseminating a generic Pathways tool for deep decarbonization in early 2016, the DDPP maintains a [web-based portal](#) for the display and analysis of decarbonization pathways from the DDPP and other initiatives, to provide a platform for communicating and comparing different approaches to deep decarbonization for a diversity of stakeholders.

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