

pathways to
deep decarbonization

interim 2014 report

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The full report is available at deepdecarbonization.org.

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Pathways to Deep Decarbonization

INTERIM 2014 REPORT

July 8, 2014

Preface

The Deep Decarbonization Pathways Project (DDPP) is a collaborative initiative to understand and show how individual countries can transition to a low-carbon economy and how the world can meet the internationally agreed target of limiting the increase in global mean surface temperature to less than 2 degrees Celsius (°C). Achieving the 2°C limit will require that global net emissions of greenhouse gases (GHG) approach zero by the second half of the century. This will require a profound transformation of energy systems by mid-century through steep declines in carbon intensity in all sectors of the economy, a transition we call “deep decarbonization.”

Currently, the DDPP comprises 15 Country Research Teams composed of leading researchers and research institutions from countries representing 70% of global GHG emissions and different stages of development: Australia, Brazil, Canada, China, France, Germany, India, Indonesia, Japan, Mexico, Russia, South Africa, South Korea, the UK, and the USA. The Country Research Teams are acting independently of governments and do not necessarily reflect the positions or views of their national governments. Each DDPP Country Research Team is developing a “pathway” analysis for deep decarbonization. We expect the number of Country Research Teams to grow over the coming months and years.

Several Partner Organizations contribute to the analysis and outreach of the DDPP, including the German Development Institute (GDI), the International Energy Agency (IEA), the International Institute for Applied Systems Analysis (IIASA), and the World Business Council on Sustainable Development (WBCSD). We invite other organizations to become DDPP partners and contribute to practical problem solving for deep decarbonization.

The Sustainable Development Solutions Network (SDSN) and the Institute for Sustainable Development and International Relations (IDDRI) co-founded and lead the DDPP. The DDPP is an ongoing initiative that will issue periodic reports on deep decarbonization. The DDPP is issuing this interim 2014 report to the UN Secretary-General Ban Ki-moon in support of the Climate Leaders’ Summit at the United Nations on September 23, 2014. The interim 2014 report describes the DDPP’s approach to deep decarbonization at the country level and presents preliminary findings on technically feasible pathways to deep decarbonization.

As underscored throughout this report, the results of the DDPP analyses remain preliminary and incomplete. Additional country chapters¹ will be published in the coming weeks. The complete 2014 DDPP report will be issued ahead of the Climate Leaders’ Summit in September 2014. In the meantime, the DDPP welcomes comments and suggestions on this draft to be sent to info@unsdsn.org and iddri@iddri.org before August 15, 2014.

In the first half of 2015, the DDPP will issue a more comprehensive report to the French Government, host of the 21st Conference of the Parties (COP-21) of the United Nations Framework Convention on Climate Change (UNFCCC). The 2015 DDPP report will refine the analysis of the technical

¹ This interim 2014 DDPP report includes 12 country chapters. The remaining 3 (Brazil, India and Germany) will be put online at deepdecarbonization.org in the coming weeks and included in the complete 2014 report to be published in September.

decarbonization potential, exploring options for even deeper decarbonization, but also better taking into account existing infrastructure stocks. At this stage, we have not yet looked in detail at the issue of the costs and benefits of mitigation actions, nor considered the question of who should pay for these costs. The 2015 DDPP report will take a broader perspective, and go beyond technical feasibility, to analyze in further detail how the twin objectives of development and deep decarbonization can be met through integrated approaches, identify national and international financial requirements, and map out policy frameworks for implementation.

We hope that the Deep Decarbonization Pathways (DDPs) outlined in this report and the ongoing analytical work by the Country Research Teams will support discussions in every country on how to achieve deep decarbonization. Above all, we hope that the findings will be helpful to the Parties of the UN Framework Convention on Climate Change (UNFCCC) as they craft a strong agreement on climate change mitigation at the COP-21 in Paris in December 2015.

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² This interim 2014 DDPP report includes 12 country chapters. The remaining three chapters (Brazil, Germany, and India) will be made available online at deepdecarbonization.org in the coming weeks. The full set of 15 country chapters will be included in the full 2014 DDPP report to be published in September.

Acronyms

2DS 2°C scenario	HDV heavy duty vehicles
4DS 4°C scenario	IPCC Intergovernmental Panel on Climate Change
6DS 6°C Scenario	KPBY Kyoto Protocol
AR4 Fourth Assessment Report	kWh kilowatt-hour
AR5 Fifth Assessment Report	LNG liquefied natural gas
BAU Business-As-Usual	LULUCF land use, land-use change and forestry
BECCS bioenergy with CCS	MtCO₂ metric tons of carbon dioxide
BIPV building-integrated photovoltaics	Mtoe metric ton of oil equivalent
CCS carbon capture and sequestration	Mton metric ton
CHP combined heat and power	MWh megawatt
CLT coal-to-liquids	NDP National Development Plan
CNG compressed natural gas	NGO non-government organization
CO₂ carbon dioxide	NGP New Growth Path
CO₂e carbon dioxide equivalent	PE primary energy
COP-21 21st Conference of the Parties	PPM parts per million
CSP concentrated solar power	PPP purchasing power parity
DDPP Deep Decarbonization Pathways Project	PV photovoltaic
DDPs Deep Decarbonization Pathways	RDD&D research, development, demonstration, and diffusion
EDGAR Emissions Database for Global Atmospheric Research	RPS renewable portfolio standards
EJ exajoule	SNG synthetic natural gas
EOR enhanced oil recovery	T&D Transmission & Distribution
ETP Energy Technology Perspectives	tce tons of coal equivalent
ETS Emissions Trading Scheme	tCO₂ tons of CO ₂
EV electric vehicles	toe tons of oil equivalent
FE final energy	TPES total primary energy supply
FEC final energy consumption	TWh terawatt-hours
GCAM global integrated assessment model	UNFCCC United Nations Framework Convention on Climate Change
GDP Gross Domestic Product	WEO World Energy Outlook
GEA Global Energy Assessment	WG2 Working Group 2
GHG greenhouse gas	
Gt gigatons	
GW gigawatts	

Executive Summary

This interim 2014 report by the Deep Decarbonization Pathway Project (DDPP) summarizes preliminary findings of the pathways developed by the DDPP Country Research Teams with the objective of achieving emission reductions consistent with limiting global warming to less than 2°C. The DDPP is a knowledge network comprising 15 Country Research Teams and several Partner Organizations who develop and share methods, assumptions, and findings related to deep decarbonization. Each DDPP Country Research Team develops illustrative pathway analysis for the transition to a low-carbon economy, with the intent of taking into account national socio-economic conditions, development aspirations, infrastructure stocks, resource endowments, and other relevant factors. The interim 2014 report focuses on technically feasible pathways to deep decarbonization.

This executive summary starts with a short outline of key results from previous global studies (discussed in chapter I to IV) and then turns to what is new and special about the country-level approach of the DDPP (explained in chapter V). It summarizes the main preliminary findings from the Deep Decarbonization Pathways (DDPs) developed by the Country Research Teams (included in chapter VI) and draws some lessons for the international negotiations leading up to the 21st Conference of the Parties (COP-21) of the UN Framework Convention on Climate Change (UNFCCC) to be held in Paris in December 2015.

Climate change and sustainable development

The economic, social, and environmental risks of unabated climate change are immense. They threaten to roll back the fruits of decades of growth and development, undermine prosperity, and jeopardize countries' ability to achieve even the most basic socio-economic development goals in the future, including the eradication of poverty and continued economic growth. These risks affect all developed and developing countries alike.

Avoiding dangerous climate change and achieving sustainable development are inextricably linked. There is no prospect of winning the fight against climate change if countries fail on poverty eradication or if countries do not succeed in raising the living standards of their people. Addressing climate change requires deep emission reductions of all greenhouse gases (GHGs), including the deep decarbonization of energy systems. To be successful, this transition must ensure that socio-economic development needs are met within the constraints of very low emissions.

The results from previous global studies, including the Intergovernmental Panel on Climate Change (IPCC) Assessment Reports (AR), show that deeply reducing GHG emissions and achieving socio-economic development are not mutually exclusive. Robust economic growth and rising prosperity are consistent with the objective of deep decarbonization. They form two sides of the same coin and must be pursued together as part of sustainable development. The DDPs developed by the Country Research Teams assume continued, sometimes rapid, economic growth. The forthcoming report from the Global Commission on the New Climate Economy provides additional insights on how to pursue these twin objectives.

The carbon budget and emissions reduction trajectory to stay below 2°C

In 2010, all governments operationalized the objective of the UNFCCC to “prevent dangerous anthropogenic interference with the climate system” by adopting the target of keeping the global rise in mean surface temperature below 2°C compared with the pre-industrial average. They did this in recognition of the extreme risks to future human wellbeing resulting from a rise in temperature above 2°C. The latest scientific research analyzed by the IPCC Fifth Assessment Report (AR5) Working Group 2 (WG2) concludes that even an increase in global temperatures of 2°C constitutes a serious threat to human wellbeing. Keeping below 2°C of global warming is indispensable to maintain climate change within the boundaries of manageable risks and to our ability to adapt to climate change.

Limiting the increase in global mean temperature to less than 2°C imposes a tough constraint on cumulative GHG emissions, including CO₂ emissions, which are the largest single source (76%) of GHG emissions. To have a likely chance—defined as a probability higher than two-thirds—of staying within this limit, the level of cumulative CO₂ emissions from land use, fossil fuels, and industry must be in the range of 550-1300 billion tons (Gigatons or Gt) by mid-century. If one excludes a significant contribution from net negative emissions,³ the CO₂ budget to 2050 is 825 Gt. Staying within this CO₂ budget requires very near-term peaking and a sharp reduction in CO₂ emissions thereafter, especially in energy-related CO₂ emissions. The scenarios reviewed by the IPCC that give a likely chance of staying within the 2°C limit project CO₂ emissions from the burning of fossil fuels and industrial processes (“CO₂-energy emissions”) close to 11 Gt in 2050 on average (down from 34 Gt in 2011). The IEA Energy Technology Perspective (ETP) 2°C scenario (2DS), which gives only a 50% chance of staying within the 2°C limit, reaches 15 Gt CO₂-energy in 2050. Assuming a world population of 9.5 billion people by 2050—in line with the medium fertility forecast of the UN Population Division—this means that countries would need to converge close to a global average of CO₂-energy emissions per capita of 1.6 tons in 2050, which is a sharp decrease compared to today's global average of 5.2 tons, especially for developed countries with current emissions per capita much higher than today's global average.

Why the 2°C limit should be taken seriously

The world is not on track to stay within the 2°C limit. While awareness of climate change is rising, and a large and growing number of countries, cities, and corporations have pledged to reduce their GHG emissions, these pledges taken together are not sufficient to stay within the 2°C limit. The IPCC AR5 Working Group 3 (WG3) calculates that in the absence of additional commitments to reduce GHG emissions, the world is on a trajectory to an increase in global mean temperature of 3.7°C to 4.8°C compared to pre-industrial levels. When accounting for full climate uncertainty, this range extends from 2.5°C to 7.8°C by the end of the century.

The consequences of such a temperature rise would be catastrophic. A recent report prepared by the Potsdam Institute for Climate Impact Research (PIK) for the World Bank⁴ describes a dramatic

³ The sustainability of the large-scale deployment of some net negative emissions technologies, such as bioenergy with carbon capture and sequestration (BECCS), raises issues still under debate, in part due to the competition in land uses for energy and food purposes.

⁴ Schellnhuber, HJ, et al. *Turn down the heat: climate extremes, regional impacts, and the case for resilience - full report*. Washington DC; World Bank. June 2013.

picture of a 4°C warmer world, where climate and weather extremes would cause devastation and intense human suffering. It would have severe repercussions on human and physical systems and potentially unleash positive feedback mechanisms that further amplify the human drivers. The IPCC AR5 and a large number of other international and national assessments validate this finding. It is therefore vital that the world become much more serious about the implications of staying within the 2°C limit. Governments, businesses, and civil society must understand and operationalize the profound transformations required to reach this target.

We do not subscribe to the view held by some that the 2°C limit is impossible to achieve and that it should be weakened or dropped altogether. The science is clear that global warming beyond 2°C carries the risk of grave and irreversible harm to human wellbeing and development prospects in all countries. The political risks of jettisoning the 2°C limit are also significant. If the world fails to mobilize in support of the 2°C limit or if countries try to weaken it there will be no realistic prospect for the international community to agree to another quantitative target. Countries would find themselves on a slippery downward slope with no quantitative foothold to organize an international and coordinated response to climate change. The 2°C limit is an invaluable tool for international mobilization that must be preserved.

The latest scientific research indicates that keeping below the 2°C limit is challenging but feasible. Global studies—including the scenarios reviewed by the IPCC AR5 WG3, the IEA World Energy Outlook (WEO) and Energy Technology Perspectives (ETP) reports, and the Global Energy Assessment (GEA) led by the Institute of Applied Systems Analysis (IIASA)—show that reducing global GHG emissions to a level consistent with the 2°C limit is still within reach. Clearly, though, the window of opportunity is closing fast. Countries therefore need to act quickly and in a determined and coordinated manner to keep the 2°C limit within reach.

Operationalizing the global 2°C limit

Very few countries have looked seriously at the operational implications of staying within the 2°C limit. All large emitting countries now have quantified targets to reduce their GHG emissions by the year 2020. But these targets—which sometimes are yet to be backed by detailed policy actions and implementation plans—are collectively insufficient to put countries on a trajectory consistent with the long-term global objective of deep decarbonization. In fact most 2020 emissions reductions targets were framed as a deviation from Business-As-Usual (BAU) trends, reductions in the carbon intensity of GDP, or relatively modest decrease in absolute GHG emissions compared to a base year. By and large national targets are not derived from an assessment of what will be needed to stay within the 2°C limit.

Only an internationally coordinated, goal-oriented approach to operationalizing the 2°C limit will allow humanity to avoid dangerous climate change. As this interim DDPP report and many other analyses make clear, staying within 2°C will require deep transformations of energy and production systems, industry, agriculture, land use, and other dimensions of human development. It will require profound changes in the prevailing socio-economic development frameworks. Many of the technologies that will need to underpin these transformations are available, but many others are not

ready for large scale deployment.. Making critical low-carbon technologies commercially available and affordable, enabling countries to pursue long-term transformations, will require long-term international cooperation and trust. One important purpose of the DDPP is to lay out an analytical approach to operationalizing the 2°C limit that can underpin a goal-oriented international response to mitigating climate change, taking into account country-specific socio-economic conditions and development aspirations.

The need for country-level Deep Decarbonization Pathways (DDPs) to 2050

The DDPP aims to help countries think through how to pursue their national development priorities while achieving the deep decarbonization of energy systems by mid-century consistent with the 2°C limit. Following the launch of the DDPP in October 2013, the DDPP Country Research Teams have collaborated to identify key principles and requirements for successful DDPs. A broad consensus has emerged on the role of DDPs and criteria for success.

Staying within the 2°C limit requires that countries develop long-term pathways to deep decarbonization to explore options and develop a long-term strategy. The nature and magnitude of the decarbonization challenge are such that there is no quick and easy fix. Deep decarbonization will not happen overnight, and there is no silver bullet. Deep decarbonization is not about modest and incremental change or small deviations from BAU. In particular, it requires major changes to countries' energy and production systems that need to be pursued over the long-term. Decisions made today with regards to, say, power generation and transport infrastructure, will have a long-term impact on future GHG emissions, which must be mapped out carefully and understood quantitatively.

The DDPs developed by the Country Research Teams “backcast” from the global goal of limiting the rise in temperature below 2°C to explore the transformations for deep decarbonization required to reach the goal. We use the term “backcasting,” to describe a process where the future GHG emission target is set, and then the changes needed to achieve that target are determined. Backcasting is not to be confused with rigid, central planning. A process of deep decarbonization must be adaptive, as strategies and pathways will have to be continually revised and updated based on new results from climate science, technological innovation, and lessons learnt from implementation.

The DDPP follows a two-stage approach to problem solving. The first, which is the focus of this report, is to identify technically feasible DDPs for achieving the objective of limiting the rise in global temperatures below 2°C. At this stage, we have not looked in detail at the issue of costs and benefits, not considered the question of who should pay for them. In a second—later—stage we will refine the analysis of the technical potential, exploring the options for even deeper decarbonization pathways, and better taking into account infrastructure stocks. We will also take a broader perspective, beyond technical feasibility, by quantifying costs and benefits, estimating national and international finance requirements, mapping out domestic and global policy frameworks, and considering in more detail how the twin objectives of development and deep decarbonization can be met. These issues will be described in the 2015 DDPP report. But technically feasible DDPs are a vital first step towards achieving the 2°C limit, by illuminating the scale and nature of technological and structural changes required and their related investment needs.

The technical DDPs developed by the Country Research Teams rest on a number of national and global policy assumptions that will be investigated in more detail in the 2015 DDPP report. These policy assumptions include:

- All countries take strong, early, and coordinated actions to achieve deep decarbonization.
- All countries adopt adequate nationally appropriate policies, regulations, and incentives.
- Financial flows are re-directed from high-carbon to low-carbon portfolios and projects.
- Financial support is provided to countries that appropriately require financial assistance to implement mitigation policies and finance low-carbon investments.

The DDPs developed by the Country Research Teams presented in this report are intended to provide a complementary analysis to existing global-level studies of deep emissions reductions.

To make a strong and convincing case for action at the national level, DDPs must be country-specific and developed and owned by local experts. They need to fit within countries' development strategies and align with their other socio-economic and environmental goals. They need to demonstrate that the short- and long-term challenges countries face, such as economic development, poverty eradication, job creation, inequality reduction, energy and food security, and biodiversity protection, can be addressed in parallel to deep decarbonization. DDPs must take into account country-specific infrastructure stocks and natural resource endowments. They must also take into account the systemic implications and the inherent gradual pace of changing technology, infrastructure, and capital stocks within countries. None of this can be accomplished through aggregate global models and studies, which are not granular enough to present a detailed technical roadmap for policy implementation at the country level

DDPs are indispensable for promoting a national dialogue on decarbonization and launching a process of intense and complex problem solving. Transparent DDPs can enable a public discussion in every country on how best to achieve emission reduction objectives, understand possible trade-offs, and identify synergies or "win-wins." Such technical analysis and national dialogue on deep decarbonization will involve business, civil society, and various expert communities (e.g. engineers, geologists, climatologists, economists, social scientists) to debate the best options for decarbonization, identify bottlenecks, and propose new approaches. DDPs can become a framework for organizing a dynamic process of discussion and problem solving in every country.

DDPs equally are indispensable for building trust across countries, shaping their expectations, and identifying where international cooperation and assistance is required. DDPs show how each country aims to achieve deep decarbonization and demonstrate the seriousness of national commitments to reduce GHG emissions. Transparent DDPs can enhance trust among countries, which is critical for a concerted international response to climate change. They will also help highlight areas that require international assistance and increased international cooperation, particularly on RDD&D of low-carbon technologies.

Interim results from the 15 Deep Decarbonization Pathways (DDPs) developed by the Country Research Teams

In aggregate, the initial DDPs developed by the Country Research Teams outlined in this report achieve deep absolute emissions reductions by 2050. Total CO₂-energy emissions from the 15 preliminary DDPs already reach a level of 12.3 Gt by 2050, down from 22.3 Gt in 2010. This represents a 45% decrease of total CO₂-energy emissions over the period, and a 56% and 88% reduction in emissions per capita and the carbon intensity of GDP, respectively. The interim DDPs do not yet achieve the full decarbonization needed to make staying below the 2°C limit “likely,” defined as a higher than two-thirds probability of success. The Country Research Teams have identified additional opportunities for deep decarbonization that will be incorporated in the next version of the DDPs (see Chapter VI) to be published in 2015. Nonetheless, the aggregate decarbonization pathway is already very substantial and well on its way to becoming consistent with the 2°C target.

The preliminary DDPs already provide key insights and identify unique elements of deep decarbonization in each country. These include the key components of nationally appropriate strategies and the most promising country-specific technology options for deep decarbonization. The initial DDPs also identify the principal challenges that still need to be addressed by the DDPP. Finally, the DDPs provide initial indications of the enabling conditions for the successful implementation of deep decarbonization. Understanding and meeting these conditions will require further refinement through careful analysis, public consultation, and learning by doing.

The three pillars of the deep decarbonization of energy systems

The 15 DDPs developed by the Country Research Teams share three common pillars of deep decarbonization of national energy systems:

- 1) **Energy efficiency and conservation:** Greatly improved energy efficiency in all energy end-use sectors including passenger and goods *transportation*, through improved vehicle technologies, smart urban design, and optimized value chains; residential and commercial *buildings*, through improved end-use equipment, architectural design, building practices, and construction materials; and *industry*, through improved equipment, production processes, material efficiency, and re-use of waste heat.
- 2) **Low-carbon electricity:** Decarbonization of electricity generation through the replacement of existing fossil-fuel-based generation with renewable energy (e.g. hydro, wind, solar, and geothermal), nuclear power, and/or fossil fuels (coal, gas) with carbon capture and storage (CCS).
- 3) **Fuel Switching:** Switching end-use energy supplies from highly carbon-intensive fossil fuels in transportation, buildings, and industry to lower carbon fuels, including low-carbon electricity, other low-carbon energy carriers synthesized from electricity generation or sustainable biomass, or lower-carbon fossil fuels.

Within the three pillars that are common to all countries, individual DDPs show a wide variety of different approaches based on national circumstances. Differentiating national circumstances

include socio-economic conditions, the availability of renewable energy resources, and national preferences regarding the development of renewable energy, nuclear power, CCS, and other technologies. For example, the DDP developed by the Indian team decarbonizes power generation using primarily renewable energy and nuclear power, but not CCS, because the scale of the potential for geological carbon sequestration in India is still uncertain. At the other end of the spectrum, the DDPs developed by the Canadian, Chinese, Indonesian, Mexican, Russian, and UK teams project a significant share of coal and gas-fired power generation with CCS by 2050.

The main decarbonization challenges at the sectoral level

The preliminary DDPs also reveal the sectors in which deep emissions reductions are most challenging, particularly freight and industry. Relative to the state of knowledge about low-carbon strategies in other areas such as power generation, buildings, and passenger transport, decarbonization strategies for freight and industry are less well developed and understood. These two sectors constitute a key focus area for future analysis by the DDPP and a future challenge for global RDD&D efforts.

Some potential solutions have been identified for freight and industry. Decarbonization options for freight include improved propulsion technologies (battery electric, hybrid, compressed or liquefied (natural or synthesized) gas, and hydrogen); modal shifts (e.g. from road transport to trains and ships); and sustainable biofuels and synthesized fuels for air and maritime transport. Decarbonization options for industry include improved efficiency, electrification of boilers, re-use of process waste heat, sustainable biomass (both energy crops and waste material), and CCS.

Some of the identified decarbonization options for industry and freight have yet to be included in all DDPs. Some Country Research Teams will include additional decarbonization options in their revised DDPs. They will also ensure consistency of national projections for industrial production, in particular for energy and mining products, with the forecasted global demand and the domestic needs for infrastructure development by 2050. Given the technological challenges associated with deep emission reductions in the freight and industry sectors, complementary measures to reduce or limit the growth of demand for their products and services will be explored, taking into account countries' socio-economic goals and strategies.

The need for a global technology push

The analysis by the 15 Country Research Teams also confirms that the technical feasibility of deep decarbonization rests on the large-scale deployment of several low-carbon technologies, some of which are not yet fully commercialized or affordable. For this reason, countries and the international community as a whole must undertake a major research, development, demonstration, and diffusion (RDD&D) effort to develop low-carbon technologies and ensure their widespread availability and their affordability.

All Country Research Teams have adopted project-wide assumptions regarding the development and deployment of critical low-carbon technologies:

- There will be sufficient global RDD&D and international cooperation to make all the relevant pre-commercial low-carbon technologies commercially viable and widely available in a timely and scaled manner.
- Critical low-carbon technologies will become competitive and affordable, through the combined effects of carbon pricing, policy incentives, and cost-reduction through learning effects and economies of scale.
- Low-carbon technologies will be made available to all countries through mechanisms for technology cooperation, including funding as necessary, and all barriers to technology diffusion will be removed.

Some key technologies, which are critical for deep decarbonization in all DDPs, are not yet technically mature or economically affordable. They include:

- Advanced energy storage, flexible load management, and integrated portfolio design for balancing power systems with high penetrations of variable renewable energy (e.g. wind and solar)
- Very high performance appliances, controls, and materials for buildings
- Zero emissions vehicles with adequate range, notably battery electric or fuel cell light-duty vehicles
- Sustainable biofuels or synthesized fuels for air and marine transport

Some emerging low-carbon technologies are key in a subset of the 15 DDPs. These include:

- New types of renewable energy technologies (e.g. advanced geothermal, deep offshore wind, and tidal energy)
- Carbon-capture and sequestration (on fossil-fueled power plants and industries)
- Advanced nuclear power technology that sustains public confidence and support

The Country Teams underscore that successful implementation of national DDPs depends on “directed technological change”—that is technological change that is propelled through an organized, sustained, and funded effort engaging government, academia, and business with targeted technological outcomes in mind. No Country Research Team was comfortable assuming that their country alone could develop the requisite low-carbon technologies. Likewise, market forces alone will not be sufficient to promote the required RDD&D at the right scale, timing, and coordination across economies and sectors—even when these market forces are guided by potential large profits from the generation of new intellectual property. Technological success will therefore require a globally coordinated effort in technology development, built on technology roadmaps for each of the key, pre-commercial low-carbon technologies.

Directed technological change should not be conceived as picking winners, but as making sure the market has enough winners to pick from to achieve cost-effective low-carbon outcomes. While directed-technological change is essential to meeting the challenge of deep decarbonization, there are many alternative technologies under development now and that may emerge in the future. Technology roadmaps and policy coordination should always leave room for new developments. Efforts aimed at building public support and acceptance for key technologies will also play an important role.

Early lessons for the global deal to stay within 2°C

The preliminary results and the approach of the DDPP itself reveal the critical importance of preparing country-level DDPs to 2050. These pathways, and the discussion of their results and input assumptions, are essential tools for learning and problem solving. This process is crucial to developing a long-term vision for deep decarbonization and shaping the expectations of countries, businesses, and investors about future development opportunities. The DDPP and similar processes afford a unique opportunity for teams to work together across countries to map out how the global 2°C limit can be operationalized and achieved at the country level.

It highlights the need to introduce long-term backcasting into the scope of the climate negotiations preparing COP21. The current focus of the international negotiations on mitigation is on emission reduction targets to 2025 or 2030. Yet if countries do not work with a longer time horizon and backcast from this long-term target, they are likely to adopt strategies that fall far short of what is needed to stay below the 2°C limit. By its structure, the current incremental approach will fail to consider the deep systemic changes and the key technologies that are still pre-commercial but necessary to reach the target.

What the DDPP process illustrates is that at least two new elements will need to be part of the global deal in 2015 at COP21 in Paris. These do not cover the full scope of the agreement, in particular the need to provide adequate support (financial, technological, and capacity building) to countries that appropriately require it to undertake the necessary mitigation and adaptation actions. But they are nonetheless an essential component of a successful global deal to operationalize the 2°C target, and deep decarbonization would lower the needs and costs of unavoidable adaptation:

- **Country DDPs:** A shared global commitment that each country will develop and make publicly available a (non-binding) DDP to 2050 that is consistent with the 2°C limit and their national circumstances. Official country DDPs (as distinct from illustrative DDPs, developed by researchers) would be predicated on a shared commitment to the global target and to all aspects of global cooperation needed to achieve it, including technology cooperation, financial support, and policy coordination.
- **Global, large-scale RDD&D of low-carbon technologies:** A massive and sustained global public-private effort to develop, demonstrate, and diffuse various low-carbon technologies that are not yet technically mature or competitive and are key to the success of deep decarbonization.

It is our hope that this interim 2014 report and upcoming DDPP reports will make a useful contribution to operationalizing the 2°C target. In particular we hope that the DDPP can help spur the design and international comparison of national DDPs and promote the necessary global cooperation to achieve them. To further this discussion we invite comments and suggestions for improvement on this interim 2014 report before August 15, 2014.

Part I. The Global Challenges of Deep Decarbonization

Chapter I. Taking the 2°C Limit Seriously

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1.1. Staying within the 2°C limit: the solemn responsibility of the global community

Our moment of truth has arrived. Twenty-two years ago at the Rio Earth Summit, the world's governments recognized that humanity was changing the climate system profoundly, posing risks for human wellbeing and sustainable development prospects. They adopted the United Nations Framework Convention on Climate Change (UNFCCC) two years later, and resolved to protect the planet and promote sustainable development by stabilizing "GHG concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system."

Yet, more than two decades later, GHG emissions are still far from stabilizing. In 1994, at the first Conference of the Parties (COP1) of the UNFCCC, CO₂ emissions from the burning of fossil fuels and direct CO₂ emissions from industrial processes were 23 billion tons (gigatons or Gt), and the CO₂ concentration stood at 358.8 parts per million (ppm). By 2013, at COP19, global CO₂ emissions had soared to 36 billion tons, and CO₂ concentrations stood at 396.5 ppm.⁵

Every country has signed on to fight against human-induced climate change, but the world remains dangerously off course from the ultimate objective of the UNFCCC. There is, as of yet, no prospect of stabilizing GHG concentrations at a level that would prevent dangerous human-induced climate change. The Parties to the UNFCCC have now had 19 annual meetings since 1994. These COPs have borne the world's hopes and disappointments in our collective inability to date to head off a growing catastrophe.

At the 16th COP held in Cancun in 2010, the world's governments committed to a new and clear target: to keep the global rise in mean surface temperature below 2°C compared with the pre-industrial average. The COP added a proviso that the 2°C limit may be revised downward to 1.5°C in light of available science. The 2°C limit is the world's most explicit, and many climate scientists would say last-ditch, effort to operationalize the goal of avoiding dangerous anthropogenic interference with the climate system.

⁵ National Oceanic and Atmospheric Administration (NOAA) Earth System Research Laboratory (ESRL) data. <http://www.esrl.noaa.gov/>

A clear goal is set, but the means to achieve it have not yet been established. Since 2010, the Parties have struggled to create a framework of climate mitigation that is up to the task. For several years now, all eyes have been on the road to Paris, COP21 in December 2015, the date that the world's governments assigned themselves to reach an agreement to implement the 2°C limit. December 2015 is our last chance, in the sense that a success at Paris would enable the world to just barely maintain the chance to keep the temperature rise within the 2°C limit. A failure in Paris would almost certainly put the 2°C limit out of reach.

1.2. Business as usual means catastrophic climate change is likely

Despite the 2°C commitment reiterated at every COP since Cancun, global GHG emissions have continued to rise sharply. The climate science is clear and unequivocal: without a dramatic reversal of the GHG emissions trajectory—one that leads to a significant decline in GHG emissions by mid-century and to net zero emissions during the second half of the century—the world will not only overshoot the 2°C limit, but will do so dramatically. The Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) shows that without major efforts to reduce GHG emissions beyond those already committed, the world is on a path to an average temperature increase of 3.7°C to 4.8°C compared to pre-industrial levels. When accounting for full climate uncertainty, this range extends from 2.5°C to 7.8°C.

The business-as-usual (BAU) course is so deeply entrenched that one study after another blithely assumes that the world will overshoot the 2°C limit. One can review any authoritative report on energy trends—by the International Energy Agency (IEA), the US Energy Information Association (EIA), or industry groups such as BP or Shell—and the result is the same: all reports present a “baseline” or BAU trajectory of roughly 4°C. This outcome is somehow received as normal, despite the global commitment stating otherwise. Clearly, our global politics and our energy practices are out of line, though they are implicitly accepted as normal. Yet this is anything but normal. Humanity faces catastrophic risks on our current path.

The risks of unabated climate change are enormous. They threaten every prospect of achieving sustainable development and humanity's fervent hopes to end poverty and achieve a decent life for all on this planet. The current trajectory is not just risky; it is potentially catastrophic. Runaway climate change would threaten the life-support systems of the planet: food production, human health and productivity, and safety from extreme storms and other climate disruptions. Rising sea levels would overtake many of the world's largest urban agglomerations and low-lying countries, such as Bangladesh and small island states. Many threatened regions in today's poor world, particularly the tropics, drylands, forests, and alpine regions, may become uninhabitable, leading to mass migration and suffering.

Some in the developed world might be skeptical that such dangers will reach them. Yet, they are mistaken. Crises in any part of the world can quickly become global, as when droughts, floods, or violence resulting from food shortages result in conflict, mass migration movements, soaring food prices, and more. Disasters such as Hurricanes Katrina and Sandy in the United States, intense heat waves in Europe, recent mega-floods in Serbia, and massive forest fires and droughts in parts of Australia, all clearly demonstrate that even the highly developed countries face dire and often uncontrollable threats when nature is disrupted.

The prospects for successfully adapting to such changes are slim; the environmental shocks would likely overcome human and technological systems. The argument of “economic development first, climate change later” therefore makes no sense. Uncontrolled climate change would gravely threaten economic development.

Avoiding dangerous climate change and achieving sustainable development are, in summary, inextricably linked. Managing the transition to deep decarbonization is critical to ensure that development needs are met within the constraints of profound GHG emissions reductions. But avoiding dangerous climate change is equally essential to safeguard development opportunities in both rich and poor countries.

1.3. Even a 2°C increase in global temperatures entails major risks

Recent scientific evidence suggests that even a temperature increase of only 2°C may generate very severe, pervasive and irreversible risks. Some leading climate scientists are in fact advising to limit global warming to 1°C instead. They cite the grave long-term consequences that a 2°C increase could have on the earth, society, and future generations. Professor Hansen, formerly the top climate scientist at NASA, points out that Earth's paleoclimate history projects that a 2°C global warming is likely to result in eventual sea-level rise of six meters (20 feet).⁶ He and others also emphasize that warming of 2°C could induce “slow amplifying feedbacks.” For example, the Amazon rainforest could eventually die as a result of repeated drought, releasing massive amounts of CO₂ into the atmosphere. Similarly, methane and CO₂ buried in the permafrost in the tundra could be released into the air as the tundra melts. By pushing the climate beyond the experience of the human era of the past 100,000 years, the world risks inducing conditions that are inhospitable for the human species and millions of others, especially when humanity now comprises more than 7 billion inhabitants on a crowded planet.

A 2°C increase in global temperatures is therefore far from risk-free. But keeping below 2°C of global warming is indispensable to maintain climate change within the boundaries of manageable risks and to our ability to adapt to climate change.

1.4. Why the world needs to stick to the 2°C limit

Some observers argue that the 2°C limit has become too difficult to achieve and should be weakened. Others go even further, suggesting that the world should abandon a global emissions target altogether and instead follow a pure bottom-up approach to global emissions reduction. Yet jettisoning or weakening the 2°C limit would be profoundly dangerous for several important and clear reasons.

First, as just described, the burgeoning scientific evidence suggests that 2°C is the upper limit of safety. Not only could a increase in temperatures by 2°C bring untold suffering in many parts of the world from severe climate disruptions such as heat waves, droughts, floods, and intense tropical cyclones, but a rise in temperature of 2°C or more threatens many positive feedback loops that could push the global climate system into runaway and irreversible disruptions.

⁶ Such findings are not reported in the IPCC, which limits forecasts to 2100.

Second, loosening or dropping the internationally agreed goal of limiting the global temperature increase to 2°C without ever having tried seriously to achieve it could spell the death of multilateral attempts to control anthropogenic climate change. The global doubts about the UN and the multilateral system would become profound, especially after more than two decades of failed efforts to implement the UNFCCC. There are already many influential voices that have written off the multilateral processes.

Third, there is no logical foothold or stopping point beyond 2°C. The world will not find a safe resting point, say at 2.5 or 3°C. Loosening the 2°C limit would very likely lead to a world without a quantified climate goal.

Fourth, without a shared climate goal, the package of accompanying cooperative global actions (on financing, technology development and transfer, capacity building, and more) required will also not be put in place. Global goals imply the means for implementing them. Dropping these goals will gravely undermine the will to cooperate on the implementation of climate mitigation actions. Yet, there is little prospect of deep decarbonization for almost any nation unless there is a global cooperative framework, in particular on technology demonstration and scale up. There is simply no capacity for countries to achieve the necessary deep transformations required to decarbonize their economy alone.

Fifth, and perhaps most importantly, many studies indicate that the 2°C limit remains achievable at relatively modest costs globally if the right cooperative framework is put in place. The global scenarios reviewed by the IPCC AR5 for example illustrate that there are technically feasible pathways that keep the global increase in temperature below 2°C, utilizing technologies that are already or close to being commercially available. Similar scenarios by the IEA underscore the same point.

Available studies show that the 2°C limit is technologically feasible and that it is also likely to be economically affordable. They suggest that the global costs of reducing GHG emissions to keep the temperature increase below 2°C are modest compared to the size of the world economy. The IPCC AR5 for example calculates a 0.06 (0.04 to 0.14) percentage point reduction in the annualized consumption growth rates over the period 2010–2100 for the scenarios achieving a stabilization of GHG concentrations between 430 and 480 ppm, which give a likely chance – defined as higher than two-thirds – of keeping the global temperature increase below 2°C.

1.5. How to pursue the 2°C limit seriously

The truth is that governments have not yet tried hard enough—or, to be frank, simply tried in an organized and thoughtful way—to understand and do what is necessary to keep global warming below the 2°C limit. There is, in short, no reason to jettison the 2°C limit before we have really tried. This report describes some of the important steps countries should follow to take the 2°C limit seriously:

- Recognize the global carbon budget and global GHG emissions reduction trajectories to 2050 consistent with the 2°C limit.
- Develop country-level Deep Decarbonization Pathways (DDPs) to 2050 consistent with the 2°C limit, predicated on a shared commitment to the global goal and to all aspects of global cooperation needed to achieve it, including technology cooperation, financial support, and policy coordination.

- Organize a massive global public-private effort to develop, demonstrate, and diffuse various low-carbon technologies that are not yet technically mature or competitive and are key to the success of deep decarbonization.

Chapter II. CO₂-energy Budget to Stay Within the 2°C Limit

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There is a meaningful correlation between total cumulative emissions of GHGs (measured in tons of CO₂ equivalent), their long-term concentrations and radiative forcing (measured in ppm of CO₂ equivalent and watts per square meter, respectively), and the resulting global average temperature response (measured in increase of global average temperatures). The overall relation between cumulative GHG emissions and global temperature increase has been determined to be approximately linear.

However, since there is uncertainty surrounding the relationship of cumulative GHG emissions and global temperature, we must speak in terms of probability. A given cumulative path of GHG emissions will offer a given probability of staying below an increase of 2°C of mean surface temperature relative to preindustrial levels. In general, we are interested in global pathways that are “likely” to stay below 2°C. Likely is usually defined as “a probability of two-thirds or higher.”

The IPCC AR5 review of climate model scenarios has found that in order to have a likely chance of staying within the 2°C limit, the peak concentration of atmospheric GHGs would need to be in the range between 430 and 480 ppm of CO₂ equivalent by 2100.⁷ That in turn implies a limit on total cumulative GHG emissions over time. For the purpose of the DDPP, we are particularly interested in the level of cumulative CO₂ emissions from the burning of fossil fuels and industrial processes permissible by mid-century—which, for simplicity, we call CO₂-energy—since our Country Research Teams are developing pathways to the deep decarbonization of their energy systems to 2050. Below, we describe the steps and assumptions to calculate this “CO₂-energy budget.”

2.1 Total CO₂ budget for the period 2011-2100

Defining a budget for CO₂ only (the largest single source of total GHG emissions at 76%) for the 2011–2100 period requires making assumptions regarding several factors, including: the non-CO₂ GHGs like methane, N₂O, and F-gases, as well as contributions from climate-changing factors such as aerosols and land-use albedo; the timing of CO₂ emission reductions (and therefore the time the carbon cycle has to absorb the CO₂ emitted); and the sensitivity of the climate to CO₂ and the other forcings.

Taking into account these factors, the IPCC AR5 Working Group 3 (WG3) found that the level of cumulative CO₂ emissions for the period 2011–2100 should be within the range of 630 to 1180 Gt

⁷ See IPCC AR5 Working Group III - Mitigation of Climate Change, Chapter 6: Assessing Transformation Pathways, Table 6.3. December 2013. <https://www.ipcc.ch/report/ar5/wg3/>

(billion tons) of CO₂, in order to achieve CO₂ concentrations consistent with a likely chance of keeping within the 2°C limit⁸.

2.2 Total CO₂ budget for the period 2011-2050

To define a CO₂ budget for the 2011-2050 period, we need to take the century-long CO₂ emissions and divide them into two time periods: 2011-2050 and 2051-2100. The bulk of emissions will occur in the first period, since net emissions should decline to zero during the second period.

Some scenarios reviewed by the IPCC AR5 WG3 are based on the idea of “net negative emissions” during the second half of the century. Net negative emissions could be achieved, for example, if the use of biomass for energy production is deployed with carbon capture and sequestration (CCS). Biomass would be burned in power plants, and the power plants would in turn capture and sequester the CO₂. This is called bioenergy plus carbon capture and sequestration (BECCS). There are other potential net negative emissions technologies, including direct air capture of CO₂.

To the extent that negative emissions are available on a large scale in the second half of the century, the CO₂ budget for the first half of the century would be correspondingly higher. But the feasibility and sustainability of large-scale net negative emissions is still under debate. BECCS in particular raises serious issues, since it combines the dual challenge of large-scale biomass production and large-scale storage of CO₂. At the global level, the large-scale use of biomass for energy production could cause deforestation and compete with land-use for food production, although in some countries the sustainable large-scale use of biomass for energy purposes could be feasible. The scale of the geological potential for CO₂ sequestration is also under debate, and CCS would have to be deployed first on fossil-fueled power plants and industries. We have therefore made an assumption in the DDPP that large-scale net negative emissions are still too uncertain to build into our country-level Deep Decarbonization Pathways (DDPs), even though we strongly support research programs that could make net negative emissions a future reality.

Based on the best estimates regarding non-CO₂ forcings and excluding the availability of large-scale net negative emissions, the IPCC AR5 WG3 defines a CO₂ budget for the 2011–2050 period of 825 Gt⁹ and of 950 Gt for the period 2011–2100.¹⁰ This implies 125 Gt of CO₂ cumulative net emissions for the period 2051-2100.

2.3 CO₂-energy budget from the burning of fossil fuels and industrial processes

The CO₂ budget of 950 Gt during 2011-2100 combines CO₂ emissions from land use, the burning of fossil fuels, and industrial processes. Defining a budget for CO₂ from the burning of fossil fuels and industrial processes only (the focus of our country-level DDPs) requires that we make assumptions

⁸ See IPCC AR5 Working Group III - Mitigation of Climate Change, Chapter 6: Assessing Transformation Pathways, Table 6.3. December 2013. <https://www.ipcc.ch/report/ar5/wg3/>

⁹ See IPCC AR5 Working Group III - Mitigation of Climate Change, Annex II, Table A.II.19 December 2013. <https://www.ipcc.ch/report/ar5/wg3/>

¹⁰ See IPCC AR5 Working Group III - Mitigation of Climate Change, Annex II, Table A.II.18 December 2013. <https://www.ipcc.ch/report/ar5/wg3/>

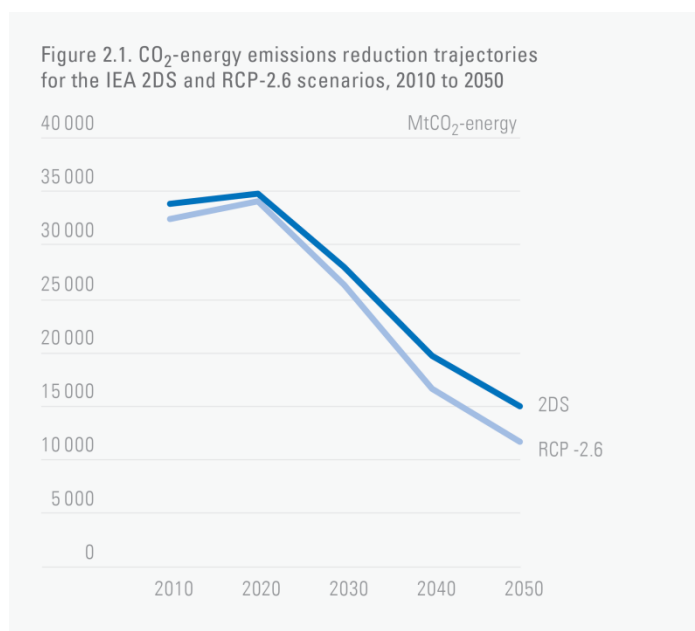
regarding the potential for CO₂ emission reductions in the land-use sector and the potential for net biological sequestration of CO₂ in particular through reforestation, peat production, wetland restoration, and improved agricultural practices. As a preliminary standard, we adopted the same assumption as the IPCC AR5 WG3 of net zero emissions from land-use over this century. This means that the 950 Gt total CO₂ budget for the 2011–2100 period can be considered as a budget for CO₂-energy only. The budget for CO₂-energy only for the 2011–2050 period is somewhat lower than 825 Gt, since land-use is assumed to reach net zero emissions only over the century, not by mid-century.

But we emphasize that there is great uncertainty regarding the precise potential and timing for CO₂ emissions reduction and net biological sequestration of CO₂ in land use, and that more research is urgently needed. It might prove to be impossible to achieve net zero emissions in the land use sector, further reducing the size of the CO₂-energy budget. Alternatively it may prove to be possible to achieve net negative emissions in the land use sector, in which case the permissible budget for CO₂-energy would rise accordingly. We hope to be able to define a more precise CO₂-energy budget for the 2011–2050 period in the next phases of the DDPP.

2.4 Global CO₂-energy emissions reduction trajectories to 2050

Given all these uncertainties, there are many possible global CO₂-energy emissions reduction trajectories that are consistent with a 2°C path. For the purpose of the DDPP, the projected level of annual CO₂-energy emissions in 2050 is of particular interest. The range of 2050 emissions in scenarios surveyed by the IPCC AR5 WG3 that give a likely chance of staying within the 2°C limit is large. It has a median value of approximately 11–12 Gt of CO₂-energy. In particular, the RCP 2.6 scenario, developed by PBL Netherlands Environmental Agency—which gives a probability higher than 66% of staying within the 2°C limit—reaches 11.7 Gt of CO₂-energy in 2050. For comparison, the 2050 level of CO₂-energy emissions projected in the International Energy Agency’s (IEA) 2-degree scenario (2DS¹¹)—which gives a 50% chance of staying below 2°C of global warming—is 15 GtCO₂-energy.

¹¹ See the following for a description of the portfolio of related IEA scenarios:
<http://www.iea.org/publications/scenariosandprojections/>



2.5 Fossil fuel proven reserves and resources

Proven reserves are defined as those fossil fuel amounts that are economically viable under current economic and technological conditions. Resources are defined as amounts in addition to proven reserves that are technologically accessible and potentially economically viable. We also distinguish between conventional and unconventional oil and gas. Conventional oil and gas are deposits that can be extracted by conventional means. Unconventional oil deposits include shale oil, heavy oil, bitumen oil sands, and extra-heavy oil. Unconventional gas deposits include shale gas, tight gas, and coal-bed methane.

By the end of 2012, the proven reserves amounted to 1.3 trillion barrels of conventional oil, 220 trillion cubic meters of conventional natural gas, and 1010 Gt of coal (including 730 Gt of hard coal and 280 Gt of lignite)¹². Proven reserves of unconventional oil were 0.4 trillion barrels, and reserves of unconventional gas are estimated to be 4-10 times higher than those of conventional gas. Taking all fossil fuels together, proven reserves represent approximately 3667-7119 GtCO₂ of potential CO₂-energy emissions. Aggregate fossil fuel resources are enormous, representing approximately 31,352–50,092 GtCO₂ of potential CO₂-energy emissions. Combining reserves and resources, the CO₂-energy content reaches 35,019-57,211 GtCO₂.¹³

¹² See BP Statistical Review of World Energy 2013

Table 2.1. CO₂-energy content of fossil fuel proven reserves and resources

Fossil fuel	Reserves	Resources	Total
Conventional			
Oil	359 - 557	305 - 451	664 - 1008
Gas	275 - 411	829 - 1090	1104 - 1501
Unconventional			
Oil	279 - 396	404 - 499	683 - 895
Gas	1127 - 3765	2253 - 6837	3380 - 10602
Coal	1636 - 1989	27561 - 41214	29197 - 43203
Total	3667 - 7119	31352 - 50092	35019 - 57211

Source: IPCC AR5 WGIII Chapter 7 Table 7.2

The CO₂-energy budget to 2100 for the 2°C limit is a mere 950 GtCO₂. The amount of CO₂ contained in proven reserves is roughly 3-7 times larger than the CO₂-energy budget. Total reserves and resources exceed the CO₂-energy budget by some 35-60 times. The conclusion is stark: there are vastly more reserves and resources than the world can use safely.

This conclusion is true even allowing for a significant share of biological and geological sequestration of CO₂. Even under optimistic assumptions, the deployment of CCS will not enable the use of all fossil fuel resources or even reserves. As a reference, the IEA ETP 2DS scenario assumes CCS of around 125 Gt of CO₂ until 2050.

All elements of CCS are proven at the pilot scale. But the feasibility of large-scale CCS deployment remains under debate, since the scale of geological storage sites where carbon can be sequestered remains uncertain. Twelve CCS projects at stationary point sources operate around the world (most of them on natural gas processing plants, some of them on fertilizer production plants). Nine more CCS projects are under construction. Since CCS is a critical abatement technology in most global mitigation scenarios, including in many of the DDPs developed by the Country Research Teams, countries and businesses need to urgently increase the levels of RDD&D in CCS to test if it can be technically and economically deployed at a large scale. In the absence of CCS, many countries—in particular those relying heavily of fossil fueled power generation—would find it much more difficult to achieve deep decarbonization.

But it is clear from the numbers reviewed above that a very large share of the fossil fuel reserves plus resources will have to stay in the ground or be “stranded”—that is, left unused in the long-term. The already-proven reserves are many times beyond the safe level of cumulative fossil fuel use, yet the energy sector invests hundreds of billions of dollars each year to discover and develop new resources and reserves. This raises the obvious question whether such investments are well directed, or are simply wasteful, developing reserves that can never be safely used. One would instead expect the fossil fuel industries to be investing far more heavily in the RDD&D of CCS in order to increase the proportion of existing reserves and resources that will eventually be usable.

¹³ IPCC AR5 WG3 Table 7.2

Of the three fossil fuels, coal deposits will likely be stranded in the highest proportion. This is for four reasons. First, its reserve and resource levels are much higher than those of oil and gas and vastly greater than any plausible CO₂-energy budget. Second, the CO₂ per unit of energy of coal is much greater than that of oil and gas (22% and 68% higher, respectively).¹⁴ Third, coal use often has very serious adverse side effects, such as air pollution that causes severe disease burdens. Fourth, most coal is used in relatively large stationary sources, e.g. power plants, where lower-carbon and zero-carbon substitutes are relatively easy to identify. Indeed, given the substitutes for coal, it may soon be feasible and necessary for many or most countries to stop building new coal-fired power plants except for those that deploy CCS.

In addition to the stranding of coal deposits, it is clear that the available oil and gas reserves plus resources is also large relative to the CO₂-energy budget. Yet which of those oil and gas reserves and resources will be stranded and which will be developed? The efficient answer is to deploy the lowest-cost oil and gas (taking into account their respective CO₂ content per unit of energy in the cost calculations), leaving the higher-cost oil and gas in the ground. The issue is not conventional versus non-conventional resources per se; it is the relative cost of the development and extraction of the alternatives.

We note that stranding assets will have high distributional consequences. A country with stranded fossil fuel reserves may lose considerable potential income. Therefore, the decisions on how to strand assets (e.g. through consumption or production permits, carbon taxation, etc.) will have large distributional implications for sharing the global effort of emissions reduction that will need to be considered in any successful international framework.

¹⁴ See IEA WEO 2012

Chapter III. Pathways to the Deep Decarbonization of Energy Systems

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3.1 The drivers of CO₂ emissions

Deep decarbonization requires a very significant transformation of energy systems. The ultimate objective of this transformation is to phase out fossil fuel combustion with uncontrolled CO₂ emissions. Only fossil fuels in conjunction with CCS would remain. Since the CO₂ contained in proven reserves and resources of fossil fuels vastly exceeds the 2°C global CO₂-energy budget, the transformation toward a low-carbon energy system cannot be driven by the scarcity of fossil fuels.

The simplest way to describe the deep decarbonization of energy systems is by the principal drivers of energy-related CO₂ emissions—for convenience, since the focus of this chapter is on energy systems, we simply refer to them as CO₂ emissions. CO₂ emissions can be expressed as the product of four inputs: population, GDP per capita, energy use per unit of GDP, and CO₂ emissions per unit of energy:

$$\text{CO}_2 \text{ emissions} = \text{Population} \times (\text{GDP/Population}) \times (\text{Energy/GDP}) \times (\text{CO}_2/\text{Energy})$$

If we take as given the population trajectory and assume a rising trajectory of GDP per capita in line with a successful economic development program, then CO₂ emissions are driven mainly by two factors: Energy/GDP and CO₂/Energy. The first term is the energy intensity, meaning the amount of energy per unit of final output. The second term is the carbon intensity of energy.

The energy intensity of GDP (Energy/GDP) can be reduced through energy efficiency and conservation measures in energy end-use sectors (passenger and goods transportation, residential and commercial buildings, and industry). We refer to “energy efficiency” measures as the technical improvements of products and processes; we use the term “energy conservation” to describe a broader set of measures, including structural and behavioral changes, that lead to lower levels of energy consumed per unit of GDP. Examples of energy efficiency and conservation measures include: improved vehicle technologies, smart urban design, and optimized value chains (for passenger and goods transportation); improved end-use equipment, architectural design, building practices, and construction materials (in residential and commercial buildings); improved equipment, production processes, material efficiency, and re-use of waste heat (in industry).

The carbon intensity of energy (CO₂/Energy) can be reduced in two ways. First, the decarbonization of electricity generation (low-carbon electricity) through the replacement of uncontrolled fossil fuel based generation with renewable energy (e.g. hydro, wind, solar, and geothermal), nuclear power, and/or fossil fuels (coal, gas) with CCS. Second, switching end-use energy supplies (fuel switching) from highly carbon-intensive fossil fuels in transportation, buildings, and industry to lower carbon fuels, including

low-carbon electricity, other low-carbon energy carriers synthesized from electricity generation or sustainable biomass, or lower-carbon fossil fuels.

3.2 The 3 pillars of the deep decarbonization

In sum, the deep decarbonization of energy systems rests on three pillars:

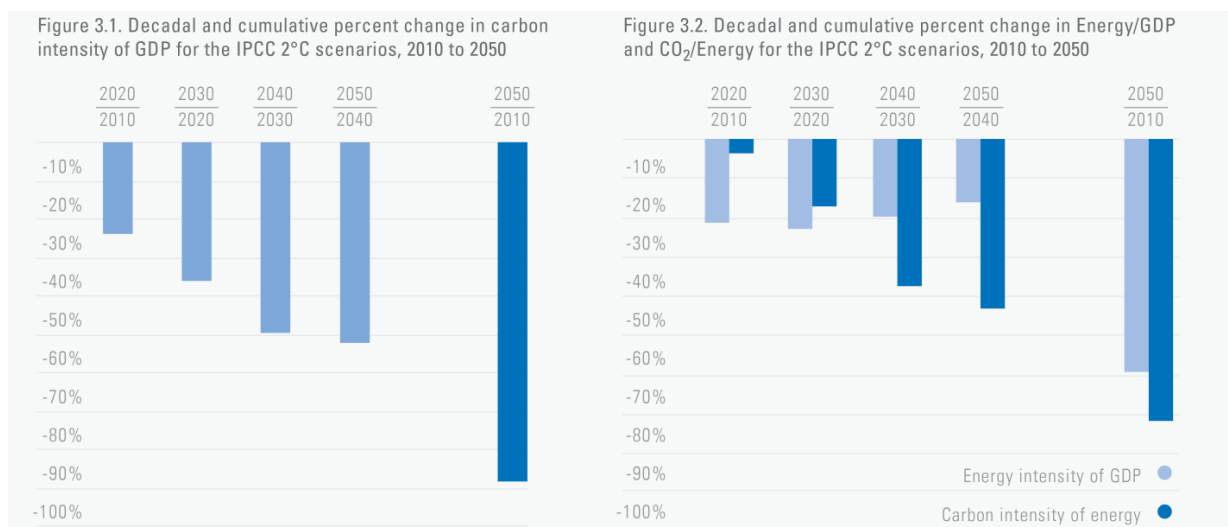
- Energy efficiency and conservation
- Low-carbon electricity
- Fuel-switching

In order to deliver the required deep reductions in CO₂ emissions, countries must implement all three pillars of decarbonization in a coordinated manner. No single approach is sufficient given the magnitude of the deep decarbonization challenge.

In the global scenarios reviewed by the IPCC AR5 WG3 that give a likely chance of staying within the 2°C limit, the carbon intensity of GDP (CO₂/GDP) decreases by approximately 90% compared to its 2010 level. This is the result of a combined 60% reduction in the energy intensity of GDP (Energy/GDP) and 70% reduction in the carbon intensity of energy (CO₂/Energy) compared to their 2010 levels.

The analysis of the scenarios also shows the temporal dynamics of the decarbonization of energy systems. At first, the reductions in the energy intensity tend to be larger than the reductions in the carbon intensity. Energy intensity is projected to fall by around 40% by 2030 relative to 2010, compared with a fall in carbon intensity of approximately 20% relative to 2010. But by mid-century, the decrease in the carbon intensity of energy plays a bigger role than the decrease in the energy intensity of GDP in the overall decrease of carbon intensity of GDP.

These dynamics are driven, in part, by the effects of electrification. In the short-run, electrification only has a small effect on the CO₂ intensity of energy, since electricity generation is still rather carbon-intensive. Though as the electricity supply is decarbonized over the longer term, electrification plays a big role in the decrease of the CO₂ intensity of energy.



Chapter IV. Research, Development, Demonstration, and Diffusion of Low-Carbon Technologies

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4.1 The need for accelerated development of low-carbon technologies

Deep decarbonization of the world's energy systems requires the deployment of new low-carbon technologies to transform energy production and consumption patterns. This in turn will require accelerated research, development, demonstration, and diffusion (RDD&D) of these emission-reducing technologies to make them reliable, cost-competitive, and widely available in every country.

Many of the technologies required for improving energy efficiency, decarbonizing electricity generation, and switching to low-carbon fuels are already technologically mature and commercially viable. They are poised to achieve much higher penetrations in the presence of policies that provide the right incentives and lower market barriers. Examples include renewable energy-based electricity generation technologies such as hydropower, wind, and solar photovoltaic and concentrating solar power; ethanol production from biomass-derived sugars and starch; power and heating technologies based on hydro-geothermal resources; fuel-efficient, hybrid, and battery electric light-duty vehicles; natural gas, electric hybrid, and hydrogen fuel cell-powered buses and fleet vehicles; and a wide range of energy-efficient lighting, heating, cooling, and process technologies in the building and industrial sectors.

But existing and commercially available technologies alone will not be sufficient in many national contexts to achieve deep decarbonization. New energy supply and end-use technologies will be needed, requiring various levels of RDD&D in order to achieve widespread uptake. A number of key technology areas requiring focused attention are described below. Some of these technologies are still under development. Some have been demonstrated in pilot projects or in small commercial niches but not yet at large scale. Some are technically viable but at too high a cost for mass adoption. Some lack the complementary infrastructure needed for their deployment, and some face barriers of public concern about safety, reliability, or environmental impacts.

4.2 Key technology areas for RDD&D

Below is a high-level overview of key technology areas for low-carbon RDD&D, based on recent literature, including IEA technology roadmaps, the IPCC AR5 WG3 report, and the Global Energy Assessment (IIASA, 2012). This list of technologies is not comprehensive and represents a snapshot of a continuously evolving energy technology landscape. Many other new technologies are in development today that may emerge in the future. RDD&D efforts for decarbonization should therefore be careful not to preclude any technologies from playing a role in future decarbonization efforts. The focus needs to be on reaching cost-effective emissions reductions.

The 15 DDPs developed by the Country Research Teams do not all rely on the same technology mix for decarbonization. In particular, some DDPs do not use CCS, while others do not use nuclear power. But all achieve the objective of deep decarbonization of their national energy systems through technologies that are not yet deployed at large scale.

The remainder of this chapter focuses on key technological hurdles that need to be overcome through public and private RDD&D in order to make deep decarbonization possible in all countries. We underscore that the commercial deployment of these technologies will require a broader mix of adequate financing, effective policies (including putting a price on carbon emissions and direct technological support), and public acceptance and support. A full treatment of RDD&D is beyond the scope of this interim report.

4.2.1 Carbon capture and sequestration

Carbon capture and sequestration (CCS) commonly refers to the capture of CO₂ at large stationary point sources such as coal and natural gas-fueled power plants, refineries, cement plants, and steel mills that emit exhaust gases with a relatively high concentrations of CO₂.¹⁵ In some cases, the CO₂ is captured after combustion through a chemical process that separates it from the other exhaust gases. In other cases the CO₂ is removed from fuels through other chemical processes before combustion. Pre-combustion and post-combustion CCS technologies have a number of variants. A special variant is “oxyfuel” combustion, in which fuel is combusted in pure oxygen rather than air, resulting in a relatively pure CO₂ stream after the removal of water in the exhaust stream. After the CO₂ is captured at the point source, it is transported by pipeline to an appropriate geological site for storage underground, typically in saline aquifers more than 800 m below the surface.

CCS has not yet been proven as a whole system at large scale, although individual components of CCS (capture, transport, and sequestration) are established technologies. CCS at small scale is already done commercially in applications where CO₂ is pumped into partially depleted oil wells for enhanced oil recovery (EOR). In this case, the injection of high-pressure CO₂ generates commercial value by increasing oil production from existing wells. The economics of CCS for EOR therefore are not primarily driven by the carbon removal objective.

To date, 12 CCS projects operate around the globe at stationary point sources—mostly at natural gas processing plants and some on fertilizer production plants. At last nine more CCS projects are under

¹⁵ Air capture, a non-point source form of carbon capture, is discussed below in the negative emissions technologies section.

construction. Two large pilot projects for CCS power generation in North America are expected to go online within the next year or two. With construction and operating experience at scale, the relative merits of pre-combustion, post-combustion, and oxyfuel CCS technologies for specific applications, emissions requirements, and economic conditions, will be better understood.

In the long-term, the largest market for CCS systems will most likely be found in the electric power sector where coal-burning plants constitute the greatest and most concentrated point source of CO₂. The main challenges of CCS reside in scale, cost, and verification. The sheer volume of CO₂ under consideration is large: for every ton of coal entering a CCS-equipped power plant, about three tons of CO₂ must be captured and stored. Open questions include the optimal power plant design to facilitate carbon capture; the design of an effective, reliable, and economical infrastructure to transport CO₂; the choice of geological sites for storage at the scale of tens or hundreds of billions of tons of CO₂ over coming decades; and the mechanisms for assuring that stored CO₂ in fact remains out of the atmosphere.

4.2.2 Energy storage and grid management

Recent sharp declines in the cost of solar photovoltaic modules and more gradual declines in price of wind turbines have reduced the direct costs of electricity from time-varying renewable energy resources to levels comparable to that from other fuels in many countries. The cost of solar and wind energy, per se, is therefore no longer a substantial impediment. The main challenge remains the intermittency of these energy sources and therefore their inability to provide reliable power on a desired schedule.

Power grids must be able to match energy demand and energy supply on a moment-by-moment basis in order to maintain grid functionality and stability. This is traditionally accomplished with large generators, such as coal-fired and nuclear power plants, that provide shock absorption and built-in energy storage by way of their fuel reservoir and massive rotational inertia. These stable base-load generators are complemented by flexible and readily dispatchable units, such as gas turbines, to make for a supply system capable of following demand at will. As the penetration level of intermittent and non-dispatchable renewable resources increases, the electric grid must rely on other low-carbon methods of balancing supply and demand, likely requiring a more refined coordination of diverse resources in space and time.

Three principal approaches are available to balance an electric power system with a high penetration of time-varying renewable resources: first, to compensate for the intermittency with other generation; second, to coordinate and control electric demand so as to coincide with power availability (known as “demand response” and “flexible load”); and third, energy storage. Examples of the first approach include grid networks that link uncorrelated or negatively correlated supplies of intermittent energy, as well as hybrid systems that combine wind and solar energy with gas-powered electricity generation. However, gas hybrid systems are limited in how much natural gas can be used while meeting the falling target emissions intensity of the grid.

Demand response and flexible load offer a large potential resource for adjusting the temporal profile of loads, often taking advantage of thermal energy storage at the end use location. The main challenges of both of these approaches are in the realm of information management, communication, control, and economic incentives. The costs of sensor and communication technologies have declined dramatically

so that the potential for decentralized, automatic demand response capability in millions of individual devices is now available. Also, the emergence of electric vehicles with flexible charging capability suggests that an increasing capacity for demand response is becoming available.

Storing excess energy for delivery during periods of lower supply is the most obvious approach to matching electric demand and supply since it fits readily into the traditional design philosophy of the grid, although it is not necessarily the least costly. A variety of electric storage technologies are known and have been demonstrated on a broad range of time scales, from seasonal to daily, hourly, and second-by-second storage. Short-term storage may also be used for improving electric power quality and local reliability.

Large-scale pumped hydroelectric storage has been cost-effective in many countries for decades. Where it is available—for example, Norway’s mountain reservoirs that store Denmark’s wind power—the intermittency problem can be solved. However, topography, water availability, and environmental concerns greatly limit the feasible locations for pumped hydro storage. Many other storage technologies exist, including batteries, flywheels, compressed air, molten salts, hydrogen (through hydrolysis), and synthetic hydrocarbons (e.g. using captured CO₂ plus renewable energy to create liquid hydrocarbons). Substantial development and demonstration is required to determine the best matches between diverse storage technologies and cost-effective applications, and to commercialize these technologies at a large scale.

4.2.3 Advanced nuclear power

There are presently 40 countries with nuclear energy. Some of these are proposing to phase out their nuclear power fleet, others plan to scale back, and still others are planning to expand their nuclear capacity dramatically. Yet high costs, safety considerations, proliferation concerns, issues of waste management, and public resistance especially following the Fukushima accident currently hinder a decisive scale-up of nuclear energy. Public support for nuclear technology may have important non-technical dimensions—for example, philosophical differences over appropriate strategies for nuclear waste disposal, as well as symbolic links between nuclear energy and weapons—that are not readily addressed by engineering improvements. Technical advances, however, also play a critical role. Breakthroughs in safety systems, reliability, fuel security, fuel recycling, and dependably low costs will likely be needed in order for nuclear energy to remain a significant part of the decarbonization pathways of major emitting economies.

The term fourth-generation nuclear power generally refers to a range of nuclear fission energy technology advances that involve the modularity of production systems, smaller-scale units, alternative systems for fuel reprocessing, alternative (e.g. thorium) fuels, as well as improved, automatic, and passive safety systems. Design goals include greater simplicity so that reactors are less vulnerable to construction delays and cost overruns; safe operability of reactors as dispatchable, load-following units; and proliferation resistance, i.e. making it much more difficult to divert materials from any point in the fuel cycle for nuclear weapons. Passive reactor safety is another key feature, meaning that the reactor core is assured by physical first principles to be safe from meltdown even in the absence of active cooling (e.g. cooling based on water pumping that itself requires electric power).

4.2.4 Vehicles and advanced biofuels

The decarbonization of the transport fleet, beginning with personal vehicles but also extending to heavy-duty vehicles, aviation, and ocean shipping is crucial to stay within 2°C. A range of cutting-edge technologies, such as high-performance batteries, hydrogen fuel cells, and advanced biofuels, hold the potential to decarbonize much or all the transport sector. Yet most low-carbon transport technologies are pre-commercial, at least at a large scale. For electric vehicles, lithium ion (Li-ion) batteries are expected to improve incrementally but new battery technologies will likely be required to achieve higher energy and power densities, lengthen vehicle range, and lower up-front vehicle costs.

Biofuels, especially liquid biofuels, offer the prospect of decarbonization with the continued use of existing infrastructure and technologies, including internal combustion engines, oil pipelines, and gas station pumps. Yet biofuels have a clear downside. Many existing biofuels, e.g. maize-based ethanol in the United States, compete with other critical land uses, such as food and feed production and ecosystem needs like land and water utilization.

Advanced biofuels aim to overcome the competition between biofuels, food, and ecosystems. Possible technologies for such advanced biofuels include bioengineered organisms (e.g. algae, bacteria) to produce biofuels and the processing of non-foodstuffs from non-arable land into biofuels (e.g. cellulosic biofuels produced from wood products). Efforts to produce fuels directly from sunlight, water, and carbon dioxide, without using biological organisms (“artificial photosynthesis”), are still at an early research stage and focus primarily on producing hydrogen. Success here could greatly decrease the land area required to produce a unit of fuel as compared to biomass, but important challenges, such as competing land uses, limited water resources, and sustainable sources of carbon for fuel synthesis will still need to be overcome.

4.2.5 Industrial processes

Process heat in industry is one of the most challenging sources of energy-CO₂ emission to decarbonize. Many industrial processes, such as smelting, cement production, steelmaking, oil refining, and other distillation processes, require vast inputs of heat, typically with very large CO₂ emissions. In principle, many of these heat processes could be electrified, or the heat could be produced with zero-emission fuel cells (e.g. hydrogen-based cells). Electrical energy can provide increased efficiency through the appropriate use of directed-heating technologies (e.g. electric arc, magnetic induction, microwave, ultraviolet, radio frequency). Given the diversity of these processes and the varying contexts in which they are used (scale and organization of the industrial processes), it is highly uncertain whether industrial processes can be decarbonized using available technologies. Much greater efforts of RDD&D are therefore required in this under-studied area to ensure deep decarbonization by mid-century.

4.2.6 Negative emissions technologies

Many low-carbon scenarios, including some in IPCC AR5, project an “overshooting” of the carbon budget in the first half of the 21st century, which must then be offset through net negative emissions in the second half of the century. The popular placeholder for net negative emissions is the integration of biomass energy (BE) with CCS, both as technologies for electricity generation and biofuel production. BECCS combines the dual challenge of large-scale biomass production and large-scale storage of CO₂.

The feasibility of each component of BECCS is uncertain, and their combination is therefore even less certain at this stage.

An alternative approach for net negative emissions would be the direct air capture of CO₂ followed by geological storage. Air capture refers to technologies that extract CO₂ from the atmosphere at the ambient concentration of CO₂ (i.e. 400 ppm). The advantage of direct air capture is that it can be done anywhere without the need for transport of the CO₂ to a storage site. A disadvantage is that the process of isolating and removing the CO₂ from air at low ambient concentrations is technically challenging, currently expensive, and unproven at scale.

4.3 The role of technology roadmaps and roundtables

There are strong reasons to believe that the necessary technologies for deep decarbonization are within reach from an engineering and cost standpoint. But their commercial readiness needs to be accelerated by providing appropriate policy support and by building public-private partnerships on RDD&D. Effective global strategies for deep decarbonization must include strategies for promoting the development and diffusion of low-carbon technologies.

Previous examples of successful technology RDD&D share a number of characteristics: clear goals and timelines for technology performance were set; public and private actors organized around long-term technology roadmaps; industry both competed and cooperated to identify promising lines of inquiry and demonstration; grants were issued on a highly competitive basis; and intellectual property was frequently shared or open source. Key RDD&D mechanisms include technology roadmaps and technology roundtables. They complement market-based instruments for low-carbon transition such as carbon taxation, emissions permit systems, and regulations.

Technology roadmaps have been used successfully in many technology areas, including semiconductors and genetics, to identify priorities for research and technology development. Such roadmaps help mobilize and organize the public and private players in expert communities around shared priorities and ensure effective use of scarce resources for RDD&D. They will be a key tool in driving directed technological innovation for low-carbon technologies. The scope and content of these technology roadmaps should be frequently updated, to make sure the necessary RDD&D push does not preclude any technology that could play a role in the achievement of cost-effective emissions reduction in every sector.

Multi-stakeholder technology roundtables can develop these technology roadmaps. Such roundtables should gather governments, businesses, investors, and other critical stakeholders with an interest in a particular technology. The roundtables would prepare and update technology roadmaps, identify priority areas for public and private RDD&D, and mobilize public and private funds for RDD&D. As one example, the IEA has been operating technology roundtables for key energy technologies.

Chapter V. Developing Country-Level Deep Decarbonization Pathways (DDPs)

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5.1 The objective of developing country-level DDPs

The Deep Decarbonization Pathways Project (DDPP) is a collaborative initiative to understand and show how countries can transition to a low-carbon economy and how the world can meet the internationally agreed objective of limiting the increase in global mean surface temperature to less than 2°C. Currently the DDPP comprises 15 Country Research Teams composed of leading researchers and research institutions from some of the world’s top emitting countries, representing more than 70% of global GHG emissions and at different stages of development: Australia, Brazil, Canada, China, France, Germany India, Indonesia, Japan, Mexico, Russia, South Africa, South Korea, the UK, and the USA. Each DDPP Country Research Team develops a “pathway” for deep decarbonization, with the intent of taking into account their country’s socio-economic conditions, development aspirations, infrastructure stocks, natural resources endowments, and other relevant factors.

The DDPs developed by the Country Research Teams presented in this report are intended to provide a complementary analysis to existing global-level studies of deep emissions reductions. Prior to the DDPP, only a few countries had studied pathways with emissions reductions large enough by 2050 to be consistent with the objective of staying within the 2°C limit. Global studies, including those by IPCC and IEA, have offered a framework for analyzing of deep decarbonization at a high level and have identified total worldwide emission reduction trajectories that would be consistent with particular temperature change limits, including 2°C. Global studies also highlight common actions and technological challenges associated with deep decarbonization across many regions. On their own, however, global studies can be insufficient to make a clear and convincing case for action at the country level. At times, the assumptions underlying global studies may be inconsistent with individual countries’ socio-economic development objectives and may lack enough granularity on individual country’s economic sectors and existing infrastructure to present a technical roadmap for policy implementation at the country level.

This interim report of the DDPP focuses on an initial analysis of the technical feasibility of DDPs within each country. The 2015 DDPP Report will refine the analysis of the technical decarbonization potential, exploring options for even deeper decarbonization, and also better taking into account existing infrastructure stocks. At this stage will have not yet looked in detail at the issue of the costs and

benefits of mitigation actions, nor considered the question of who should pay for them. The 2015 DDPP report will also take a broader perspective, and go beyond technical feasibility, to analyze in more detail how the twin objectives of development and deep decarbonization can be met through integrated approaches, and identify policy frameworks for implementation. This chapter describes the methodology adopted by the consortium of 15 Country Research Teams of the DDPP for the technical feasibility stage of the analysis.

5.2 Backcasting approach consistent with the 2°C target

The term “backcasting” is used to denote a process in which a target is fixed for a future date, and then a pathway towards achieving the target is identified by moving backward in time. Our project falls squarely within the backcasting framework. We have taken the 2°C limit in global temperature increase as the target; translated this target into a global CO₂-energy budget for the period 2011-50, a 2050 per-capita emissions benchmark, and sectoral performance indicators benchmarks; and the Country Research Teams explored pathways to 2050 that would be line with both the global target and their own national circumstances.

5.2.1 Not a burden-sharing approach

We have not allocated the cumulative CO₂-energy global budget across countries, but rather have used it as a benchmark for exploring DDPs. In past international climate negotiations, government officials have struggled to reconcile different views on how to fairly divide a certain global carbon budget or GHG emissions reduction target into national carbon budgets. These disagreements include whether or how to take into account historic emissions, the potential options and cost for mitigation, and the basis for GHG accounting rules. Such disagreements over the equitable sharing of global mitigation efforts have been a stumbling block for many years in UNFCCC negotiations, leading to insufficient international action to date.

The DDPP has sought to de-emphasize the contentious question on precise allocation of individual budgets or targets, and instead to focus on common, bold actions that will be eventually needed within nearly all countries. The plain fact is that, regardless of the precise allocation rules on GHG emissions, to stay within the 2°C limit every major emitting country will have to undertake a deep transformation of their energy systems to low-carbon energy by 2050.

5.2.2 Level of per capita emissions by 2050 as a benchmark, not as a target

To guide the exploration of their DDPs, the Country Research Teams used a 2050 global average per capita emissions level as a benchmark but not as a target in a strict sense. For the purposes of developing the DDPP 2050 benchmark, we have chosen the IEA 2DS scenario as our reference scenario. Globally, the cumulative emissions trajectory from the IEA 2DS results in a 50% chance of staying within the 2°C limit, and the 2DS scenario reaches 15 Gt of CO₂-energy by 2050. This 2050 level translates to a benchmark of 1.6 tons of CO₂-energy emissions per capita by 2050, assuming a global population of 9.5 billion by 2050, in line with the medium fertility projection of the UN Population Division. The reason for this choice was not to constrain the analysis within a 50% chance of staying within the 2°C limit. In fact, during the next phase the Country Research Teams will explore further options for deep decarbonization, and they could lead to a higher than 50% chance of staying within

the 2°C limit. But the IEA is a key DDPP Partner Organization and has shared the global assumptions and country results of the 2DS with the Country Research Teams to assist them in the development of their own DDPs.

The reason why the convergence of per capita emissions by 2050 cannot be used as a single criterion for the equitable allocation of the global carbon budget across countries is that it fails to capture important differences across countries related either to their technical potential for decarbonization, capabilities to implement mitigation actions, existing economic structure and energy infrastructure, or historical and cumulative emissions. While recognizing these important limitations, it provides a useful benchmark to guide the exploration of country-level DDPs. Indeed, very few countries with CO₂-energy per capita above 1.6 tons today will be able to go far below this level by 2050. On the other hand, catch-up economic growth in low-income countries that currently emit less than 1.6 tCO₂ per capita will increase their per capita emissions by 2050, even as they decrease the carbon intensity of their economic growth. As a consequence, if very few countries can go below 1.6 tons of CO₂-energy emissions per capita by 2050, and very few countries can be significantly above, then all countries should converge close to the global average.

5.2.3 Sectoral performance indicators as benchmarks, not as targets

In addition to the level of per capita emissions by 2050, the Country Research Teams have also used sectoral performance indicators to guide the exploration of their DDPs. Compared to per capita emissions, sectoral performance indicators are a better way to account for countries' structural differences. For example, by using this indicator, a country could have higher emissions per capita than the world average, not as a result of lower efforts to decarbonize its industry, but as a consequence of a higher share of industry in its GDP than the world average. We have used the scenarios reviewed by the IPCC AR5 WG3 to define sectoral performance indicators for power generation, buildings, transport, and industry consistent with the 2°C limit. As the convergence of per capita emissions, sectoral performance indicators have important limitations and do not account for possible limitations in the technical mitigation potential, different capacities to implement these actions, or historical and cumulative emissions. But we have used them to ensure that their sectoral strategies in the DDPs developed by the Country Research Teams were thoroughly evaluated.

Table 5.1 Range and median value of sectoral performance indicators in the IPCC 2°C scenarios

Sector	Sub-sector / Region	Indicator	Benchmark in 2050 Median value	Benchmark in 2050 Range
Power generation	–	Carbon intensity of power generation (gCO ₂ /kWh)	20	-30 – 50
Buildings	OECD	Final energy demand per capita in buildings (GJ)	37.2	29 – 43
	EIT		31.6	25 – 42
	Asia		11.6	9.7 – 13.8
	Africa & ME		10.3	9.7 – 13
	Latin America		11.8	10.4 – 15.2
Transport	Passenger transport	Energy intensity of passenger transport (GJ/p-km, index 1=2010 value)	0.75	0.58 – 0.78
	Freight transport	Energy intensity of freight transport (GJ/t-km, index 1=2010 value)	0.65	0.45 – 0.9
	Total Transport	Carbon intensity of (tCO ₂ /GJ, index 1=2010 value)	0.7	0.6 – 0.85
Industry	Cement	Carbon intensity of industrial production (tCO ₂ /ton industrial product)	–	0.24 – 0.39
	Iron and steel		–	0.47 – 0.84
	Paper		–	0.16 – 0.20

5.3 Bottom-up approach, with transparent technological assumptions

A key element of the DDPP approach was to define a common set of shared assumptions across countries, in particular those regarding the availability of technologies that are not yet commercially available. As discussed in detail in chapter IV, achieving deep decarbonization indeed rests on the accelerated deployment at scale of technologies that are not yet commercially available or not currently competitive with conventional technologies. Achieving full commercialization of these technologies is

often beyond the reach of any individual country or company. The DDPs developed by the Country Research Teams assume that the world invests massively, through public and private partnerships, in the development and early deployment of these technologies. Only these assumptions made it possible for Country Research Teams to project that the technologies they needed to achieve deep decarbonization would be available to them.

Table 5.2. Shared technological assumptions in the DDPP for when improved low-carbon technologies will become available for deployment at scale

Sector	Technology	Starting date of deployment at scale
Power	CCS (coal and gas)	2025 - 2030
	Advanced geothermal	2025 - 2030
	Advanced energy storage	2030 - 2035
	IV gen nuclear	2035 - 2040
Transport	Global availability of long range EVs across all vehicle types	2020 - 2025
	Second generation biofuels	2020 - 2025
	Hydrogen fuel cells	2030 - 2035
Industry	CCS in industry (close to pure CO ₂ streams)	2020 - 2025
	Electric boilers and process heaters	2020 - 2025

The depth and breadth of technology deployment strongly depends on country-specific circumstances (including the availability of alternative technological options, the infrastructure to support the deployment of technologies, and public acceptance and support). All of these technologies did not have to be deployed by the dates listed in each and every DDP. But Country Research Teams had the option to utilize the technologies if their country has the physical potential (e.g. geological potential for carbon storage) and if the technologies were necessary and cost-effective to achieve the objective of deep decarbonization.

Moreover, we emphasize that the DDPP is still at an interim stage in considering the full range of technology options. There is continued debate around certain technologies such as the future of CCS, fourth-generation nuclear power, and advanced biofuels, both among the Country Research Teams and more generally. We will therefore base the 2015 report on a more detailed and considered assessment of the timing, scalability, and financing of the various low-carbon technology options.

5.4 Summary of general assumptions

To summarize, the national deep decarbonization pathways produced by the DDPP Country Research Teams are based on a number of assumptions and enabling conditions:

- All countries take strong, early and coordinated actions to combat climate change.
- All countries operate in a supportive global policy environment that is firmly directed at the 2°C limit.
- There is ample public-private partnership and cooperation to enable the rapid development, demonstration, and diffusion of the requisite low-carbon technologies in all key sectors.
- Open global markets ensure the global diffusion of low-carbon technologies and their cost reduction through scale and learning effects.
- Major global cooperative efforts speed technology development and improve the reach and performance of low-carbon technologies, ranging from renewables to nuclear power to CCS to energy efficiency.
- Financial flows are re-directed from high-carbon to low-carbon portfolios and projects.
- Financial support is provided implicitly to countries with lower capacities to implement mitigation policies and finance low-carbon investments, though such support is not modeled in this phase of the project.

Low-carbon technologies become available and affordable to all countries, for example through a technology cooperation mechanism and fund.

Previous studies have frequently assumed the use of large quantities of offsets to minimize costs. The implicit assumption is that large emitters could fund emissions reductions in low-emitting countries in exchange for reducing the need for local reductions. As noted previously, this assumption becomes unlikely under global deep decarbonization scenario in line with 2°C limit, as all countries will have to make real efforts to come close to the 1.6 tons per capita global average or sectoral performance indicator benchmarks. For this reason, we did not explore global “offsets” in the national scenarios. We assume that the volume of such offsets will at best be relatively small.

Chapter VI. Aggregate Results and Cross-Country Comparisons from the 15 National Deep Decarbonization Pathways (DDPs)

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6.1 Introduction

All results presented in this chapter are drawn directly from the DDPs developed by the 15 Country Research Teams. These results are preliminary: they represent an initial analysis of the technical feasibility of DDPs within each country. No definitive judgments based on the details of the country DDPs or their aggregate results should therefore be drawn at this stage.

The focus in the country analyses was on achieving deep reductions in CO₂ emissions in 2050. These preliminary analyses will be revised in the coming months to explore the options for even deeper decarbonization pathways, better take into account the existing infrastructure stocks, and focus more on CO₂ emissions trajectories and cumulative CO₂ emissions from 2010-2050.

6.2 Deep decarbonization in the context of sustainable development

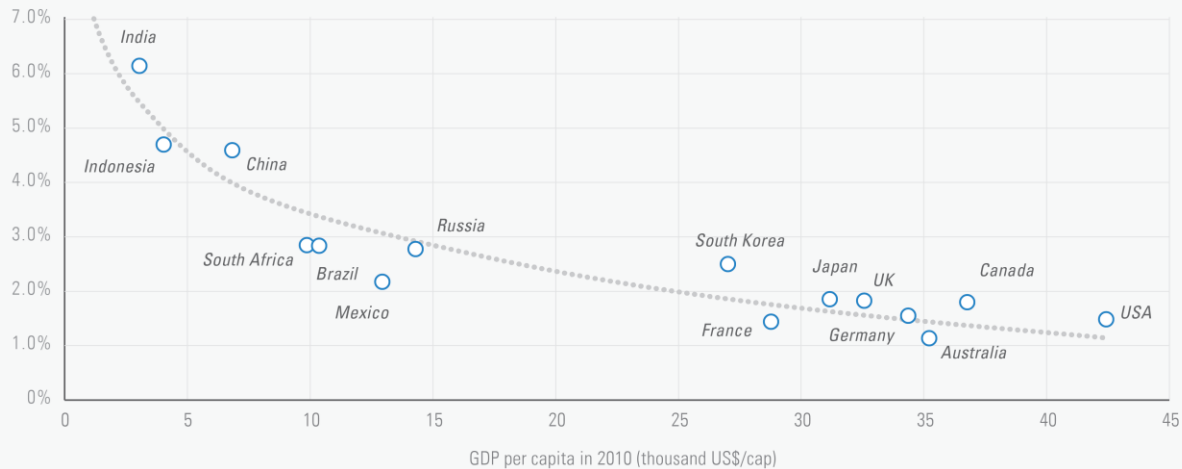
The full costs of the DDPs developed by the Country Research Teams have not yet been examined in detail. But the DDPs are based on socio-economic assumptions, which reflect each Country Research Team's vision of its national development trajectory to 2050.

6.2.1 Economic growth assumptions

All 15 DDPs assume continued—and for some countries rapid—economic growth to 2050. Assumed GDP growth rates are especially strong in today's middle-income economies, which start from lower levels of GDP per capita than high-income countries today and therefore have room for catch-up

growth (Figure 6.1). As a result of sustained economic growth, all 15 DDPs anticipate higher levels of GDP per capita in 2050 than South Korea today.

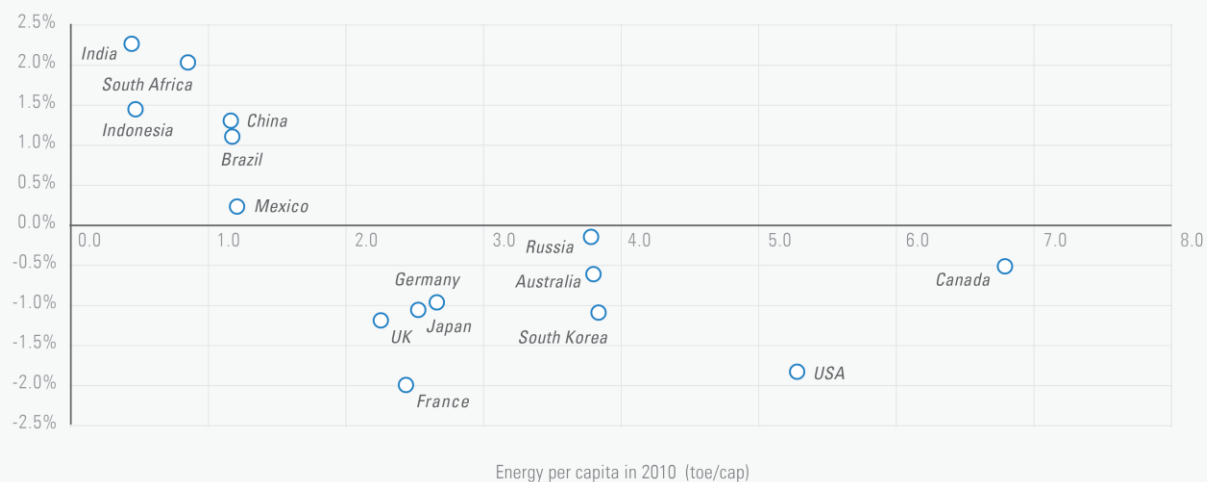
Figure 6.1. Average annual growth rate of GDP per capita between 2010 and 2050



6.2.2 Energy demand

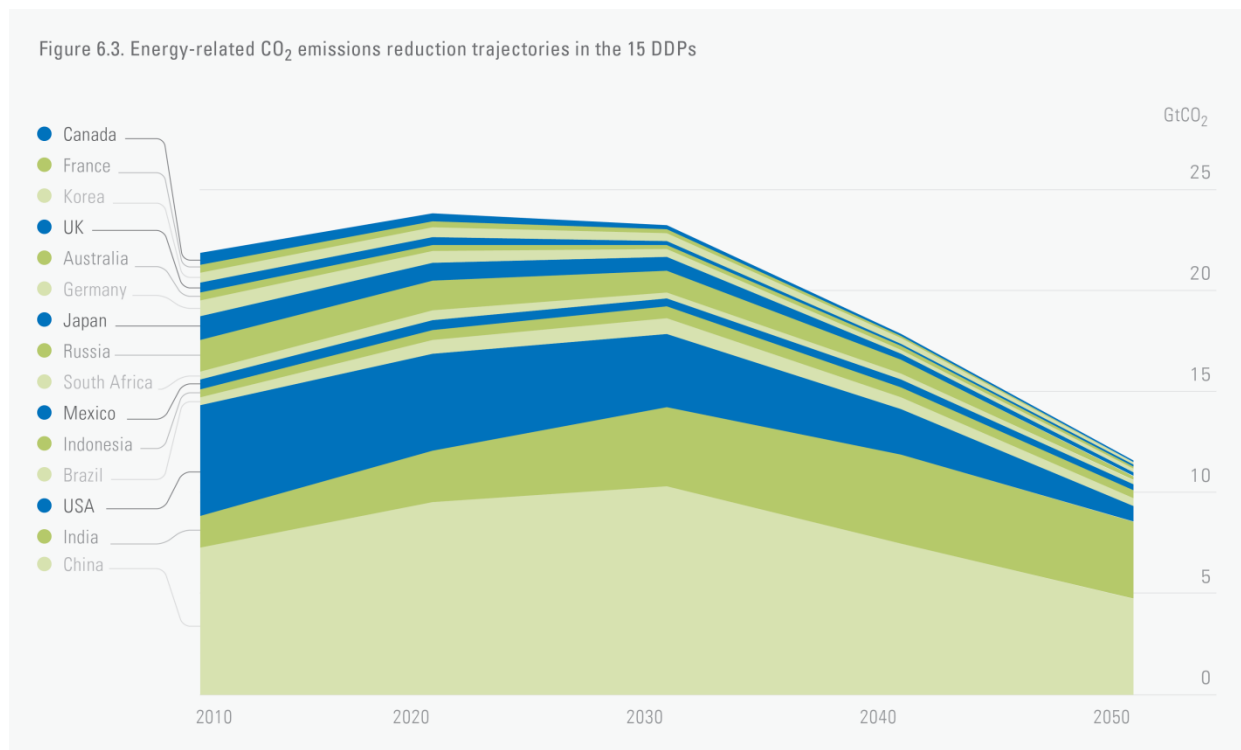
Across the 15 DDPs, average energy consumption per capita converges to two metric tons of oil equivalent (toe) by 2050 (Figure 6.2). It declines in absolute terms in high-income countries, where energy efficiency improvements outweigh population and GDP growth. In middle-income countries, on the other hand, energy consumption increases in absolute terms as a result of improved energy access and rapid GDP growth, in part driven by energy-intensive industries. However, this increase is lower than it would otherwise be because of improvements in energy efficiency.

Figure 6.2. Average annual rate of change of energy per capita between 2010 and 2050



6.3 Aggregate results

All 15 DDPs achieve very significant reductions in CO₂-energy emissions by 2050. In aggregate, CO₂-energy emissions from the 15 DDPs fall to 12.3 Gt by 2050, which is a 45% reduction from the 22.3 Gt that these 15 countries emitted in 2010 (Figure 6.3).



This decline in CO₂-energy emissions is even more significant when accounting for continued population and GDP growth over the 2010-2050 period. Across the 15 DDPs, population and GDP (in 2005 US\$) are expected to grow by 21% and 346%, respectively, from 2010-2050. In aggregate, the 15 DDPs thus achieve a 56% decrease in per capita CO₂-energy emissions (from 5.4 tCO₂-energy per capita to 2.4 tCO₂-energy per capita) and a 88% decline in the CO₂-energy intensity of GDP (from 464 to 55 tCO₂ per \$ GDP) by mid-century (Figures 6.4 and 6.5). This corresponds to an average 2% annual decrease of emissions per capita and a 5.2% annual decrease of emissions per unit of GDP over 2010-2050.

In aggregate, the 15 DDPs also represent a very significant departure from current trends. Between 2000 and 2010, average per capita CO₂-energy emissions increased by 1.1% per year, and CO₂-energy intensity of GDP decreased by only 1.5% per year. In the aggregate DDP, trends in total and per capita emissions are reversed, and the declining trend in CO₂-energy intensity of GDP is accelerated.

Figure 6.4. Average energy-related CO₂ emissions per capita, historical and DDPs for 15 countries

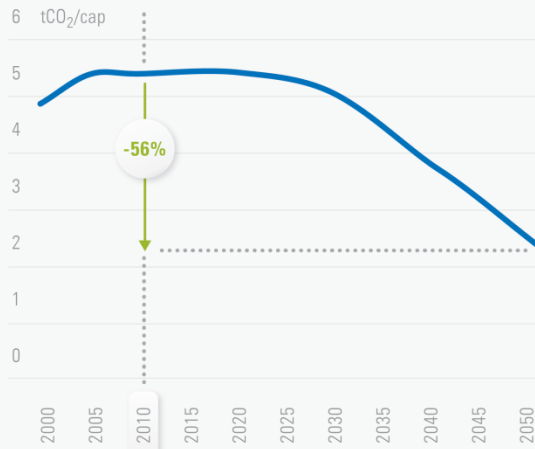
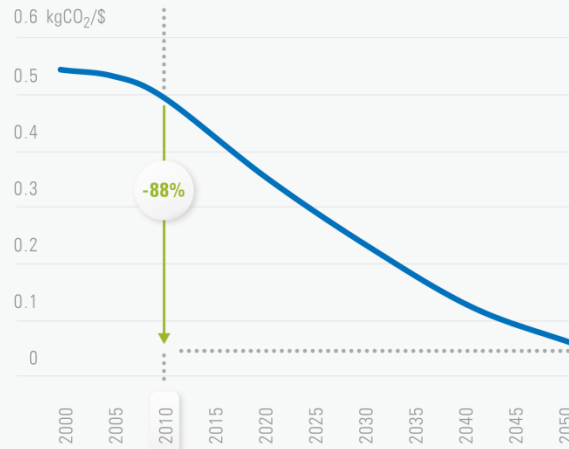


Figure 6.5. Average energy-related CO₂ intensity of GDP, historical and DDPs for 15 countries

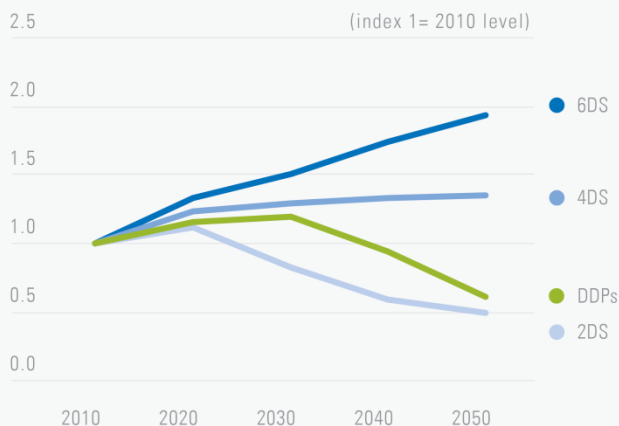


The aggregate DDP also marks a very significant departure from projected trends under business as usual (BAU) trajectories or weak climate policy scenarios. The DDPP Country Research Teams did not produce BAU scenarios of their own, as the focus instead was on DDPs. For an illustrative comparison, we look to the IEA Energy Technology Perspectives (ETP) scenarios, which are available for 7 of the 15 countries covered by the DDPP: Brazil, China, India, Mexico, Russia, South Africa, and the U.S. These 7 countries represent 78% of the total emissions from our 15 countries in 2010 and 92% of total projected emissions in 2050, which makes the comparison meaningful:

- The **IEA 6°C Scenario (6DS)** is largely an extension of current trends. In the absence of efforts to stabilize atmospheric concentrations of GHGs, average global temperature is projected to rise at least 6°C in the long term.
- The **4°C Scenario (4DS)** takes into account recent pledges made by countries to limit emissions and step up efforts to improve energy efficiency. It serves as the primary benchmark in ETP 2014 when comparisons are made among scenarios and it projects a long-term temperature rise of 4°C.
- The **2°C Scenario (2DS)** is the main focus of ETP 2014. It describes an energy system consistent with an emissions trajectory that recent climate science research indicates would give at least a 50% chance of limiting average global temperature increase to 2°C.

Our seven country DDPs achieve a roughly 70% reduction in 2050 CO₂-energy emissions relative to an extension of current trends (6DS), a more than halving of 2050 emissions relative to recently promised mitigation efforts (4DS), and are close to, but slightly higher than, the 2DS (Figure 6.6).

Figure 6.6. Combined seven country DDPs compared to the CO₂-energy emissions reduction trajectories of IEA scenarios (2DS, 4DS, and 6DS)



Note: The comparison only includes the DDPs for Brazil, China, India, Mexico, Russia, South Africa, and the USA to match the countries analyzed as part of the IEA scenarios.

It is still too early for the DDPP to compare the cumulative emissions from our 15 DDPs with the global CO₂-energy budget for 2011–2050 to have a likely chance of staying within the 2°C limit. As already emphasized, the primary focus of the analysis at this stage was reaching the lowest possible level of emissions in 2050, driven by our per capita emissions and sectoral performance indicators benchmarks, not the lowest possible level of cumulative emissions to 2050. Under reasonable assumptions for the rest of the world, the 2050 level of emissions of our 15 DDPs is still too high to give a 50% chance of keeping below 2°C. As the comparison with the IEA 2DS scenario for a subset of 7 of our countries also shows, our DDPs have higher emissions during the 2011–2050 period, not only by 2050. As a consequence, the cumulative emissions from our 15 DDPs is also certainly higher than the global CO₂-energy budget for 2011–2050 to have a 50% chance of staying within the 2°C limit. But this should not be interpreted as proving that strong early mitigation actions such as those in the IEA 2DS are impossible; it is only a consequence of the methodology adopted at this stage, focusing on the 2050 level of emissions.

Given the purpose of the analysis at this stage, we are encouraged by the initial results, which show that the decarbonization achieved by 2050 is already very substantial and well on its way to becoming consistent with the 2°C limit. In the coming months, DDPP Country Research Teams will explore options for even deeper decarbonization pathways and will pay more attention to the management of the transition to 2050, with the objective of lowering cumulative emissions.

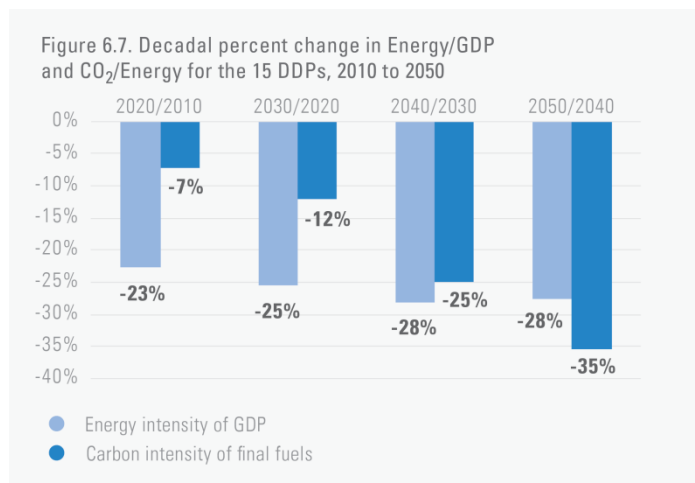
The interim DDPs developed by the Country Research Teams help to illuminate key elements of deep decarbonization strategies across countries, the main options in different countries, and the most important challenges moving forward. The rest of the chapter presents and discusses these preliminary findings.

6.4 Examining the pillars of deep decarbonization at country level

All 15 DDPs share three common “pillars” for the deep decarbonization of their national energy systems: energy efficiency, low-carbon electricity, and switching to low-carbon fuels.

All 15 DDPs achieve a large decrease in CO₂ intensity of GDP (tCO₂ emitted per \$ GDP) by 2050 compared to 2010: 88% on average. This is the result of the combined effects of: (1) a decrease in the final energy intensity of GDP (toe consumed per \$ GDP)¹⁶ and (2) a decrease in the CO₂ intensity of energy (tCO₂ emitted per toe of final energy consumed). On average, the energy intensity of GDP decreases by 70% between 2010 and 2050, and the CO₂ intensity of energy decreases by 60%.

The relative importance of these two elements in the DDPs changes over time (Figure 6.7). Reducing energy intensity of GDP is more important in the early phase, while reductions in the CO₂ intensity of final energy consumption play a larger role in the long-term. The dynamics in Figure 7 are driven, in part, by the effects of electrification. All Country Research Teams use decarbonization of electricity supply and electrification of energy end uses as a strategy for deep decarbonization, to different extents. In the short-run, electrification only has a small effect on the CO₂ intensity of energy, since electricity generation is still rather carbon-intensive. Though electrification plays a big role in the decrease of the CO₂ intensity of energy over the longer term as, electricity supply is decarbonized. These kinds of sequencing challenges and their implications for cumulative CO₂ emissions will be further explored in the next phases of the DDPP.



6.5 Sectoral strategies

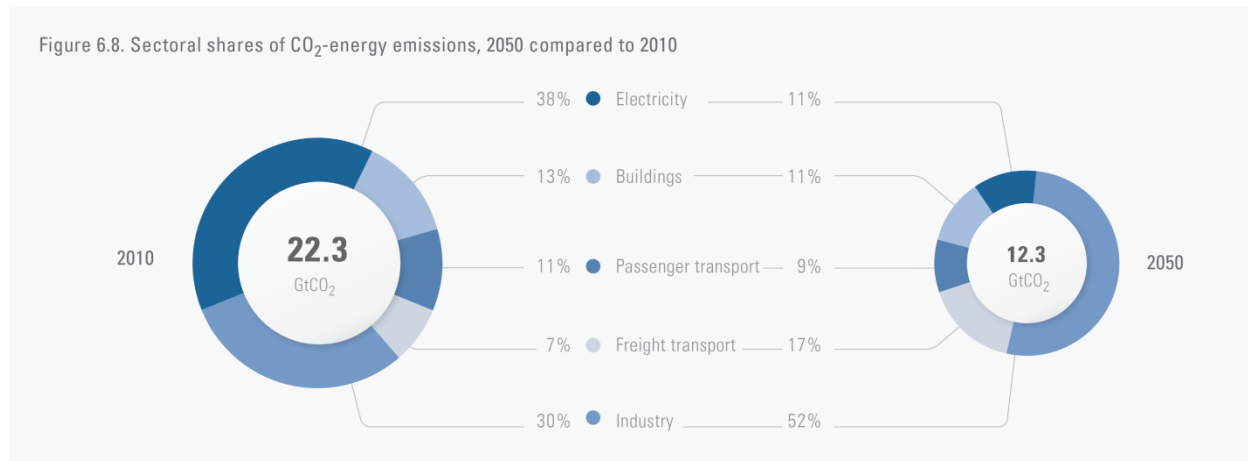
6.5.1 Sectoral shares of total emissions

Across the 15 DDPs, different sectors contribute to different levels of CO₂ emission reductions (Figure 6.8). The power sector achieves the largest reduction in emissions, with an 85% reduction in 2010 emissions (8,651 Gt CO₂) by 2050 (1,258 Gt CO₂). Its share in total emissions falls from 38% to 11%. Direct CO₂ emissions from the residential building and passenger transport sectors also fall in absolute

¹⁶ The decrease of the final energy intensity of GDP combines technical efficiency and structural economic change towards less energy-intensive activities.

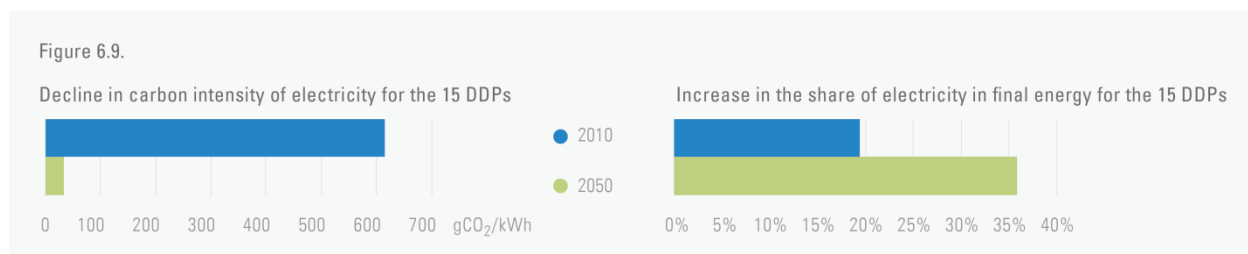
terms, by 57% and 58%, respectively, but their share in total emissions decreases only slightly, from 13% to 11% and 11% to 9%, respectively.

CO₂ emissions from freight transport and industry appear to be relatively more difficult to reduce. Emissions from freight transport increase slightly, by 13%, while industry emissions decrease only by 14%. As a consequence, the share of freight and industry in total emissions increases significantly by 2050, from 7% to 17% and 30% to 52%, respectively. This demonstrates the importance of finding additional and innovative ways to reduce emissions in these two sectors.



6.5.2 Power generation: switch to low-carbon electricity

Electrification and the decarbonization of electricity plays a central role in all 15 DDPs. Electricity has a much larger role in energy supplies. The share of electricity in final energy consumption almost doubles from 2010-2050, rising from 19% to 35%. Power generation is almost completely decarbonized in all countries. On average, the CO₂ intensity of power production is reduced by 94%, from 617 gCO₂ per kilowatt-hour (kWh) in 2010 to 34 gCO₂ per kWh by 2050 (Figure 6.9).



To reach such a low level of carbon intensity, power needs to be generated almost exclusively from zero- or low-carbon sources in all countries: renewable energy, nuclear power, or fossil fuels with CCS. Across countries, the DDPs achieve the deep decarbonization of power generation through a diverse mix of low-carbon energy sources because countries have different potential for renewable energy, geological storage capacity for CCS, and social preferences and degrees of public support for nuclear power and CCS (Figure 6.11). But by 2050, almost all electricity in all 15 DDPs is generated from zero- and low-carbon sources (Figure 6.10).

Figure 6.10. Carbon intensity of electricity production (tCO₂/toe)

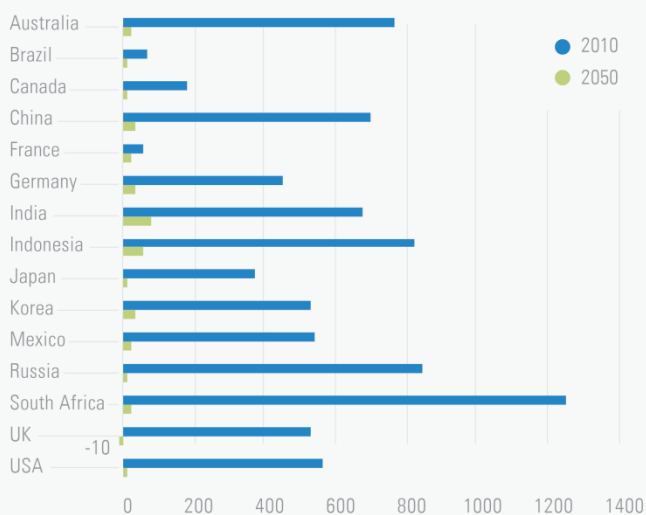
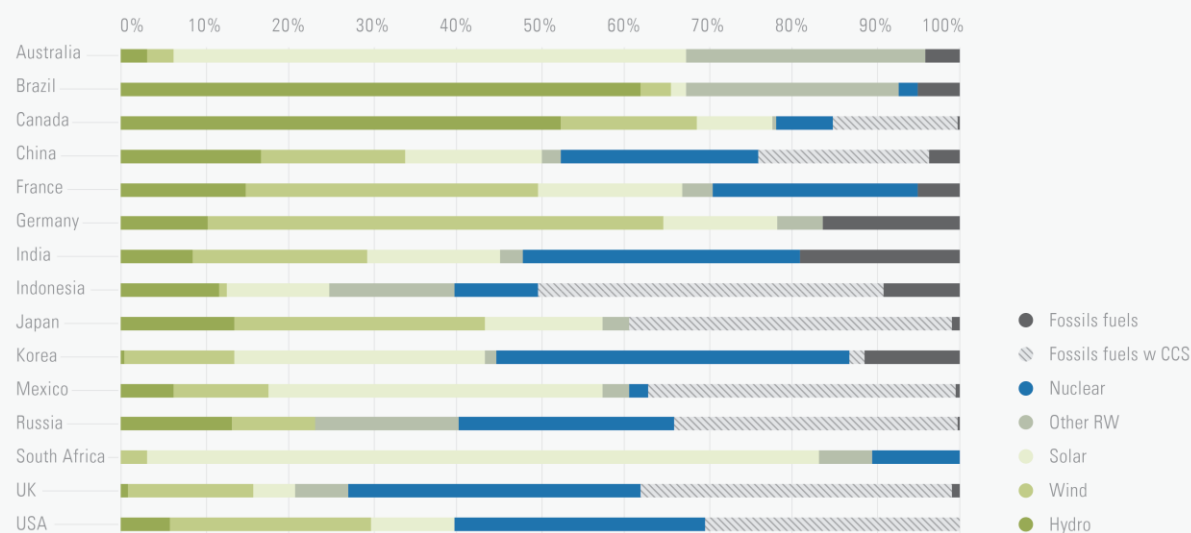


Figure 6.11. Electricity generation mix in 2050



6.5.3 Residential buildings

Measuring aggregate improvements in the energy efficiency of residential buildings is difficult because of the many uses of energy in buildings, such as heating, cooling, cooking, and appliances. The relative importance of these energy uses varies both between and within countries, in part due to differences in climatic conditions. Energy efficiency indicators (e.g., energy use per square meter or per capita) are thus imperfect for cross-country comparison and are not reported here. For the CO₂ intensity of residential energy use, all 15 DDPs show a significant decrease (Figure 6.12), driven primarily by increased electrification of residential energy in most countries (Figure 6.13) and increased use of solar thermal energy and combined heat and power (CHP) in others.

Figure 6.12. Carbon intensity of residential energy (tCO₂/toe)

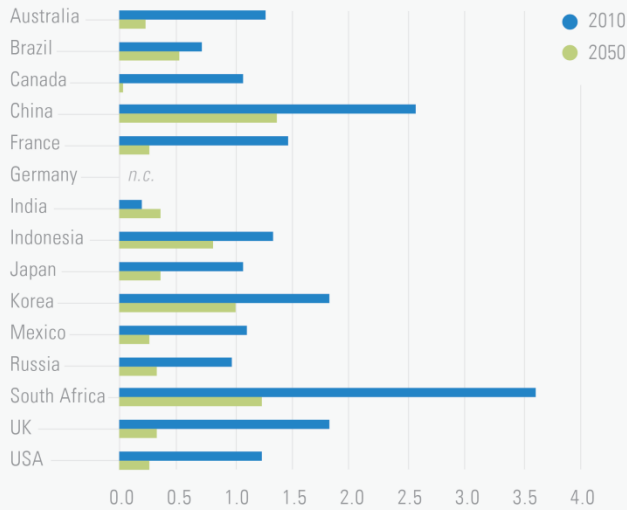
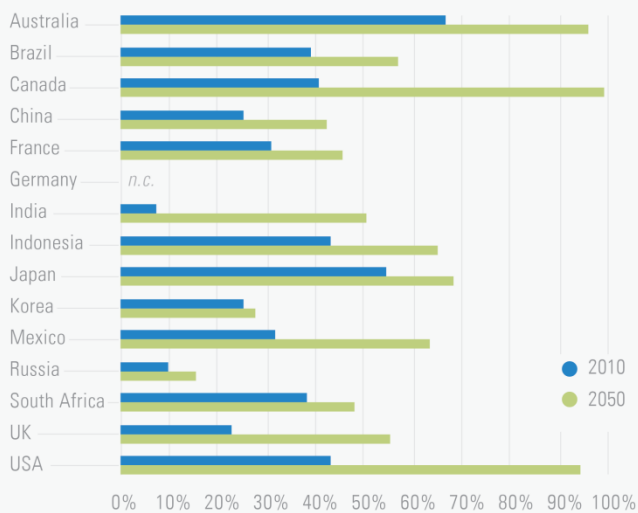


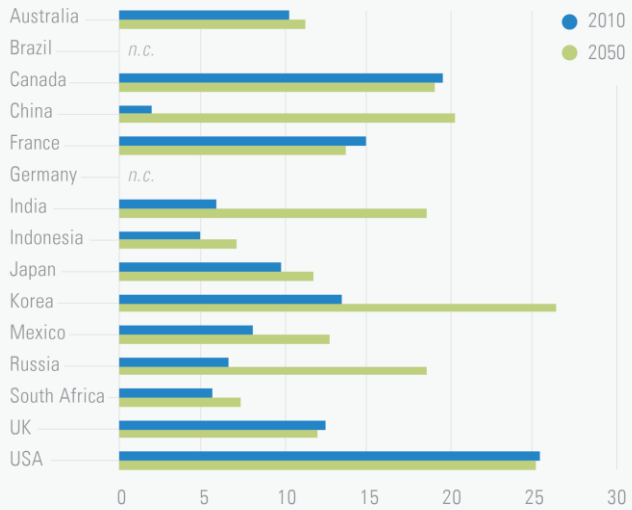
Figure 6.13. Share of electricity in residential energy use



6.5.4 Passenger transport

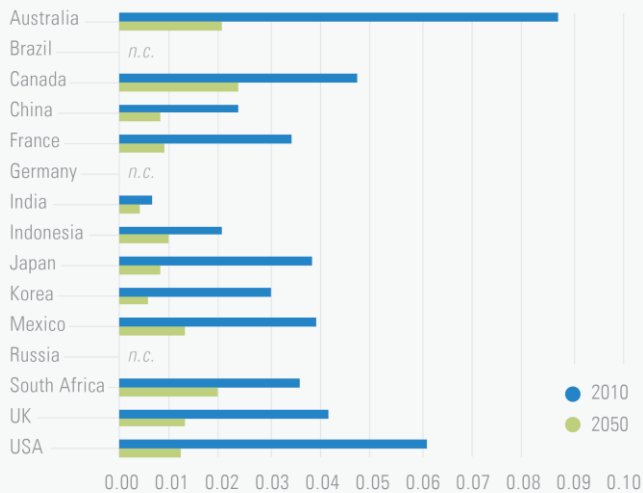
Among the 15 DDPs, most high-income countries see a modest reduction (Canada, France, U.S.) or a small increase (Australia, Japan, Korea, UK) in passenger mobility (passenger kilometers traveled per capita) between 2010 and 2050 (Figure 6.14). Russia, the only high-income country with low 2010 levels of passenger mobility, sees a large increase in mobility that brings it more in line with other high-income countries. Some middle-income countries (e.g., China, India) see a sharp increase in passenger mobility, converging to levels that match, or are close to, today's high-income countries. In other middle-income countries (e.g., Indonesia, Mexico, South Africa), increases in passenger mobility are more moderate.

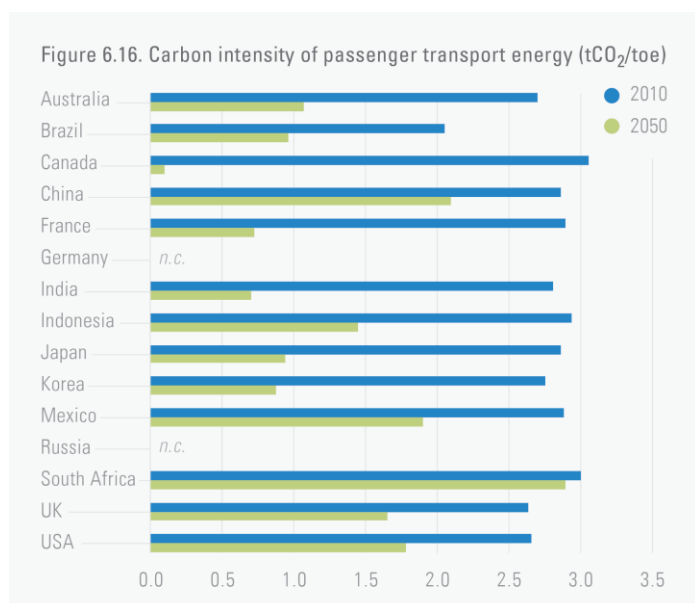
Figure 6.14. Passenger mobility (thousands of p-km per capita)



All 15 DDPs achieve a sharp decrease in the energy intensity of passenger transport (toe per passenger kilometers traveled) (Figure 6.15), combined with a decrease in the CO₂ intensity of energy used for passenger transport (tCO₂ per toe of final energy consumed) (Figure 6.16). The electrification of passenger vehicles plays an important role in decarbonizing the energy used in passenger transport, but Country Research Teams use other decarbonization strategies as well, including biofuels and fuel cell vehicles powered by renewable hydrogen.

Figure 6.15. Energy intensity of passenger transport (toe / thousands of p-km)





6.5.5 Freight transport

All 15 DDPs (except one) decouple freight mobility (freight ton-kilometers) from GDP growth (Figure 6.17). However, total CO₂ emissions from freight transport increase because reductions in the energy intensity of freight transport (toe per ton-kilometer traveled) and the CO₂ intensity of freight transport energy (tCO₂ emitted per toe) are relatively small (Figures 6.18 and 6.19).

The 15 DDPs illustrate that, in general, freight transport is more difficult to decarbonize than passenger transport. Although there are several options for reducing the CO₂ intensity of freight transport—electrification, compressed or liquefied low-carbon gas, modal shifts, and sustainable biofuels—they all face challenges in deploying at the scale needed to achieve significant CO₂ reductions. The results from these preliminary DDPs underscore the importance of a strong global R&D push on technologies and strategies to reduce CO₂ emissions in freight transport. Beyond technology, the sector should also explore ways to organize freight transport differently (through modal shifts) and to reduce the need for freight transport through optimized production, consumption, and transportation patterns.

Figure 6.17. Freight mobility intensity of GDP (t-km/\$)

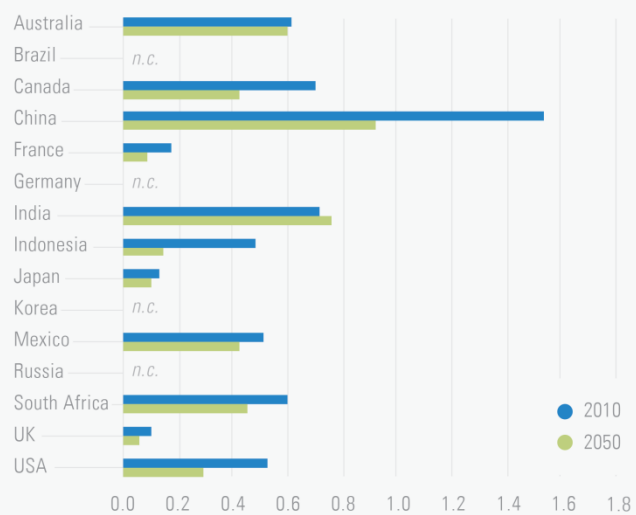
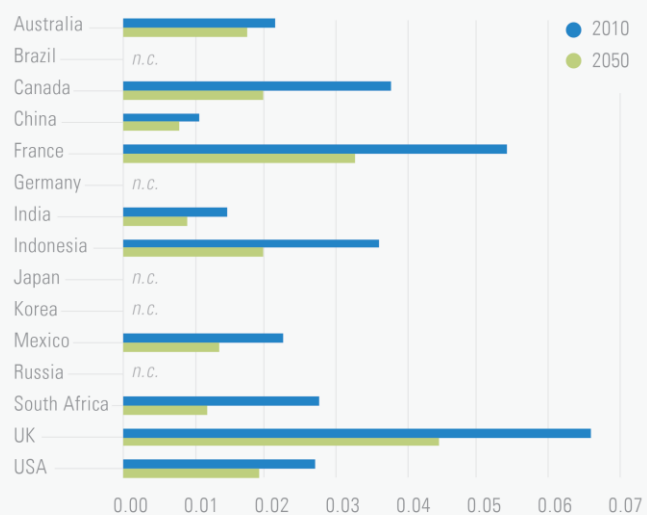
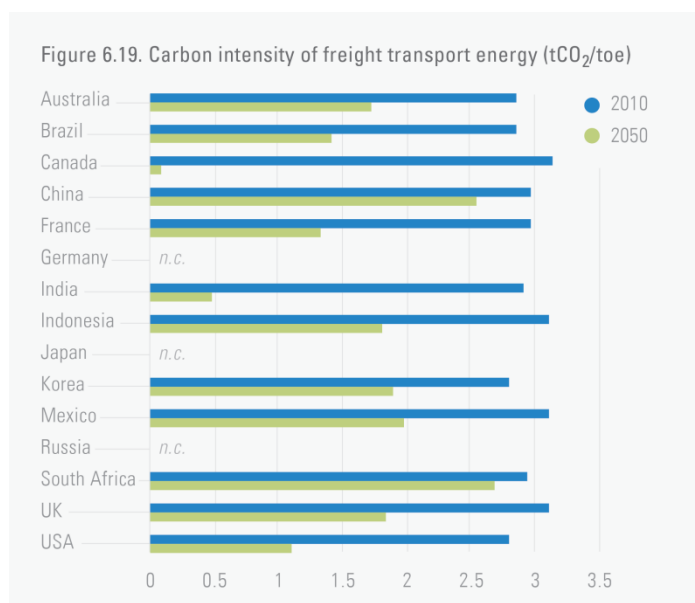


Figure 6.18. Energy intensity of freight mobility (toe / thousands of t-km)





6.5.6 Industry

As with residential buildings, measuring aggregate energy efficiency in industry is difficult because of the diversity of sub-sectors within industry. National comparisons are difficult because of differences in industrial sector composition between countries and the complex nature of the modern global trading system. Nevertheless, there are similarities in decarbonization strategies across countries. All 15 DDPs include aggressive energy efficiency measures to reduce energy consumption in industry. Using three main strategies—electrification, fuel switching, and CCS— most DDPs achieve large reductions in the CO₂ intensity of energy used in industry (Figure 6.20). Electricity’s share of industrial final energy consumption increases significantly across all countries (Figure 6.21).

Even with reductions in energy CO₂ intensity in industry, aggregate industrial emissions in the 15 DDPs rise over time. By 2050, industrial emissions account for 51% of total emissions, up from 31% in 2010. These results suggest the importance of developing innovative technology pathways for reducing CO₂ emissions from key industrial sectors (i.e., tCO₂ per ton output), as well as the less materials-intensive production methods (i.e., requiring fewer tons of materials) and less carbon-intensive production materials.

Figure 6.20. Carbon intensity of industrial energy (tCO₂/toe)

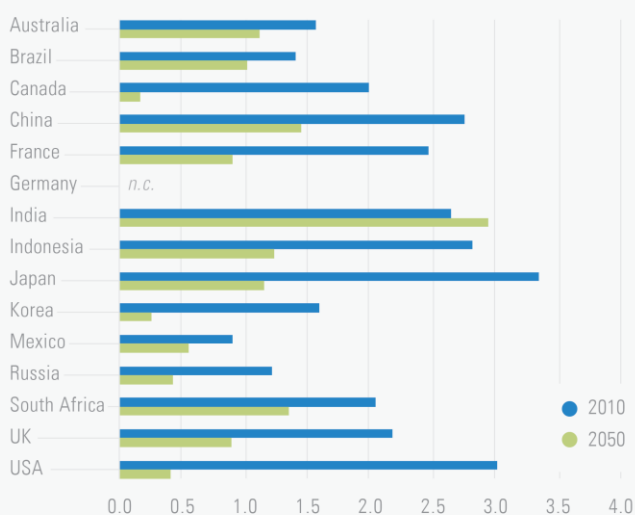
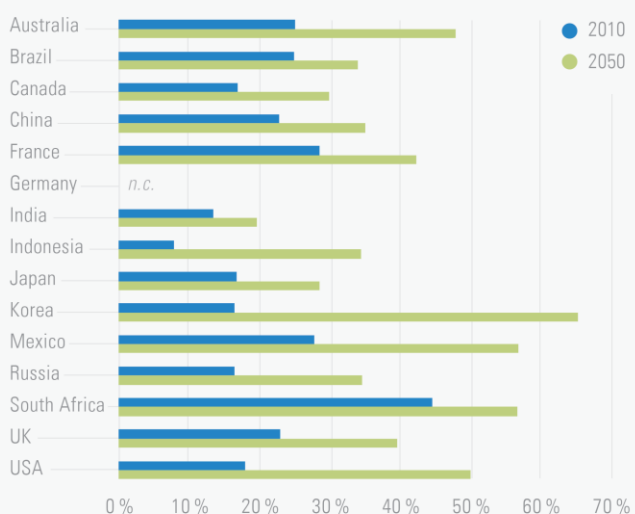


Figure 6.21. Share of electricity in industrial energy use (%)



6.6 Areas for further analysis

The DDPP results thus far, while preliminary, illustrate both the technical possibilities and the challenges for deep decarbonization across a wide range of national contexts. As a next step, and before we quantify the costs and benefits of decarbonization, identify national and international finance requirements, analyze in more detail how the twin objectives of development and deep decarbonization can be met through integrated approaches, and map out the policy frameworks for implementation, the DDPP Country Research Teams will explore four areas that were not included in the first round of analysis of the technical feasibility.

First, the Country Research Teams will explore a greater array of technology options, including some that are still at the pre-commercial stage. So far, they have incorporated emerging technologies and energy system configurations to different extents in their analyses, and there is likely still potential to

further reduce CO₂ emissions per unit of activity (e.g., CO₂ per passenger kilometer traveled) in the DDPs, although the feasibility of technology deployment at the national level will have to be examined carefully. Second, teams will further explore energy drivers in their models through scenario analysis. Most of the DDPs are based on conservative assumptions about activity drivers, and reducing the level of these drivers will reduce CO₂ emissions (e.g., reductions in passenger kilometers traveled will reduce CO₂ emissions from passenger transport). Third, teams will consider in further details the issue of infrastructure stocks, Fourth, teams will estimate cumulative CO₂ emissions from 2010-2050, rather than focusing only on a single year (2050).

An important outcome of the DDPP so far is that it has fostered interactive learning and a cooperative problem-solving mindset among the participants. Teams have shared their technical and macroeconomic assumptions, sectoral expertise, and data sources. The backcasting approach, which was new to many of the Country Research Teams, created a framework for innovative thinking and produced creative results. Over the eight months since the project began, including several face-to-face meetings, this process has led to the development of much more ambitious DDPs than found in many previous studies of national mitigation potential.

This interim report is only a start. But it is our hope that this report, as well as the more comprehensive report to be published during the first half of 2015, will make a useful contribution to the debate by spurring the development and international comparison of country-level DDPs and by promoting the global cooperation required to achieve them.

Part III. National Deep Decarbonization Pathways Developed by Country Research Teams¹

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South Africa	143
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United States	180

¹ This interim 2014 DDPP report includes 12 country chapters. The remaining three chapters (Brazil, Germany, and India) will be made available online at deepdecarbonization.org in the coming weeks. The full set of 15 country chapters will be included in the full 2014 DDPP report to be published in September.

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1. Country profile

1.1. The national context for deep decarbonization and sustainable development

Australia is a mid-sized developed economy with high per capita greenhouse gas emissions. Exports of energy, minerals, and agricultural commodities have always played an important role in the Australian economy, with the relative importance of specific commodities changing over the decades in response to international demand.

Australia has abundant renewable and non-renewable energy resources and relatively easily recoverable reserves of coal, gas, and uranium. Australia is one of the leading exporters of coal and domestic coal production is forecast to continue to increase.² With a number of liquefaction projects under construction, the country is also set to soon become the world's largest exporter of liquefied natural gas (LNG).³ In addition, Australia is a major supplier of minerals such as bauxite, alumina, iron ore, uranium, copper, and lithium. Australia's abundant renewable energy resources and significant sequestration potential through carbon plantings could be harnessed under decarbonization.

Australia's economy is highly emissions-intensive due to the extensive use of coal in electricity supply. Electricity accounts for two-thirds of Australia's greenhouse gas emissions with coal fired power accounting for 69% of generation and gas providing a further 19%. The remainder is mostly supplied by renewable energy technologies, including hydroelectricity (6%), wind (2%), bioenergy (1%), and solar photovoltaic (PV) (1%).⁴ Australia exports uranium but does not generate any electricity from nuclear power.

² BREE, 2014. Australia is the world's largest exporter of metallurgical coal and the second largest thermal coal exporter by volume.

³ BREE, 2014. Seven new liquefied natural gas liquefaction facilities are expected to enter the export market by 2022.

⁴ BREE, 2013a. Oil and other sources (including multi-fuel fired power plants) contribute 2%. On average, solar PV and wind have grown 95% and 20% over the past five years, respectively. The data is for 2011/12.

Service industries, including education, tourism, and finance are important in Australia's economy, contributing more than half of Australia's GDP. The competitiveness of exports from these sectors is strongly influenced by exchange rates, and these industries are likely to expand over the medium term.

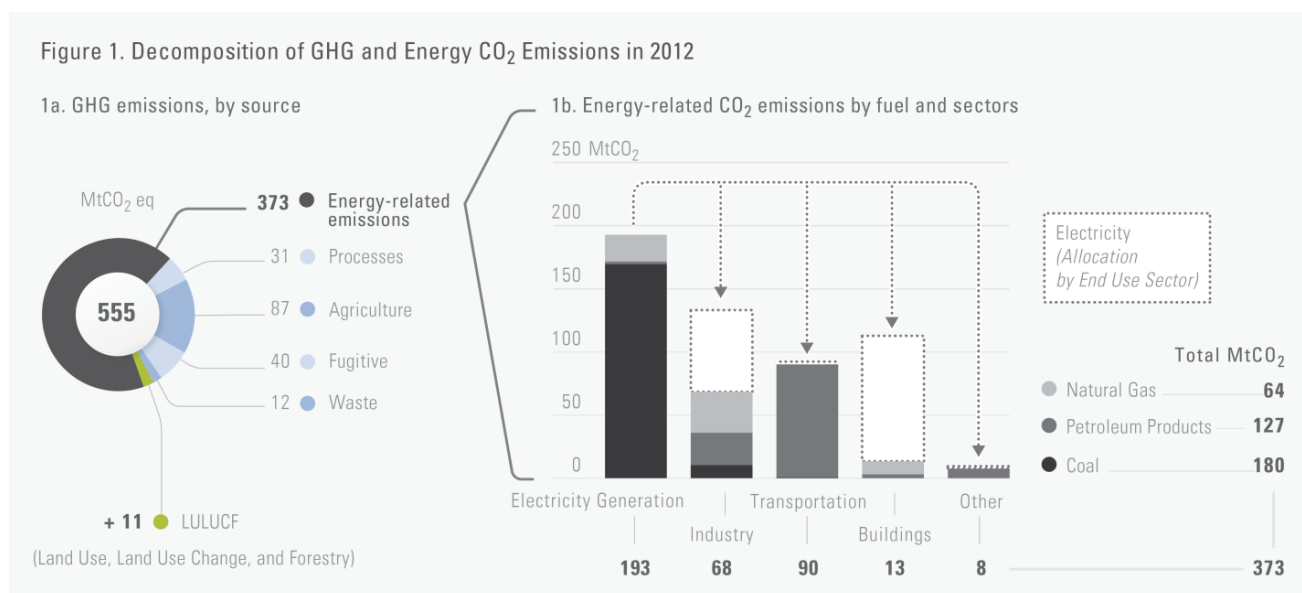
Global deep decarbonization would significantly change demand for Australian exports while domestic decarbonization would require fundamental changes in Australia's energy system over the coming decades. These changes would present both challenges and opportunities for Australia, both within the energy sector and more widely.

1.2. GHG emissions: current levels, drivers, and past trends

Australia's per capita emissions are among the highest in the world. This is due to:

- The predominance of coal-fired generation in Australia's electricity supply;
- The relatively large contribution of energy and emissions-intensive industrial activity to the Australian economy;
- The historically low cost of energy;
- The economic importance of agriculture; and
- The long distance transport requirements resulting from the concentration of Australia's population in urban centers and large distances between the urban centers.

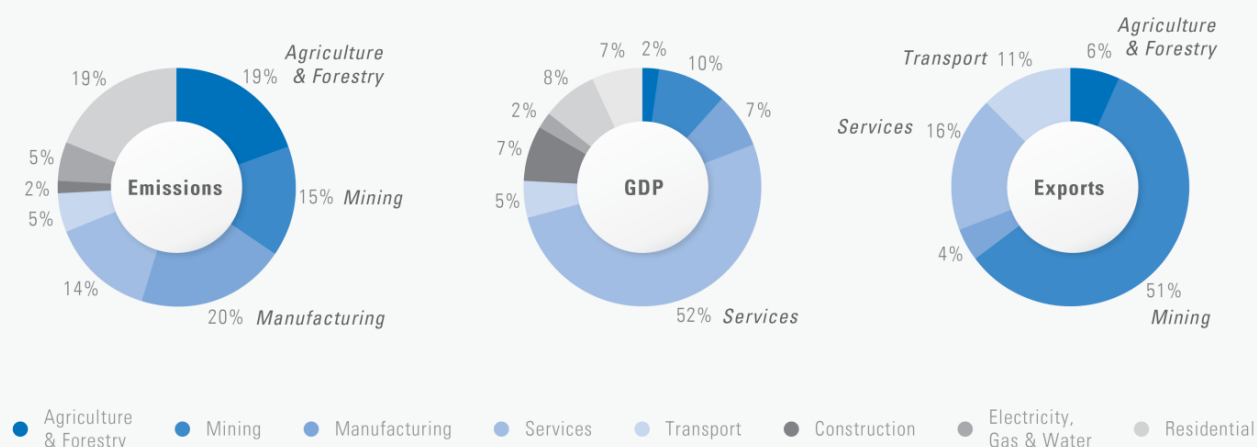
Figure 1a shows Australia's 2012 greenhouse gas emissions by source and Figure 1b shows the decomposition of energy-related CO₂ emissions (i.e. from fossil fuel combustion).



Source: BREE, 2013b, Department of the Environment, 2014. Data variations are due to rounding error.

Australia's economic circumstances are somewhat unique in the global context insofar as emissions from mining and manufacturing contribute a relatively large share (over one third) of Australia's total greenhouse gas emissions, of which about one third are process and fugitive emissions. In addition, about 15% of Australia's total emissions are attributable to agriculture, including methane emissions from livestock. Figure 2 shows the proportional contribution of industry sectors to Australia's total greenhouse gas emissions, GDP, and export revenues.

Figure 2. Composition (%) of total greenhouse gas emissions, GDP and exports, 2012.



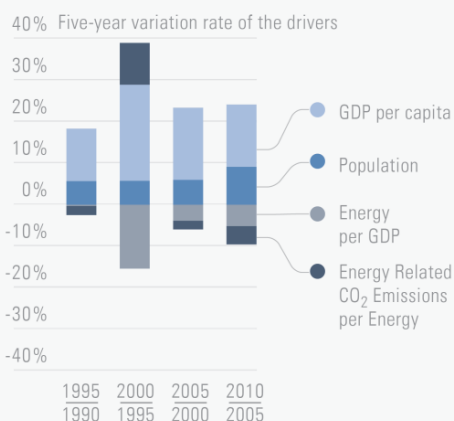
Source: ABS, 2012; Department of the Environment, 2014.

However, Australia has made some recent progress in decarbonizing its economy. Over the past two decades Australia's greenhouse gas emissions have remained stable while the size of the economy has almost doubled. As a result, the emissions intensity of Australia's GDP has nearly halved and emissions per capita have decreased by approximately 25% over this period (see Figure 3f). Increasing emissions from energy use were roughly offset by reduced deforestation and increased plantation forestry.

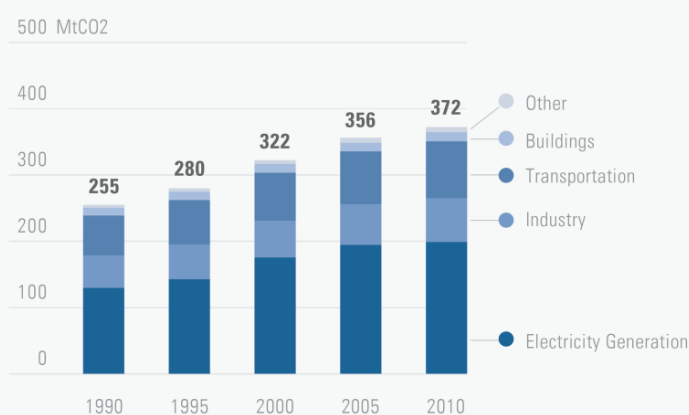
Since 2008/09, emissions from fuel combustion have stabilized, driven by a significant expansion in renewable energy, a drop in demand for grid-supplied electricity, and a tripling in the rate of energy efficiency improvement in large industrial companies. Rising energy prices and government programs and policies (including standards and subsidies for energy efficiency, carbon pricing, and support programs for renewable energy) have helped achieve this outcome.

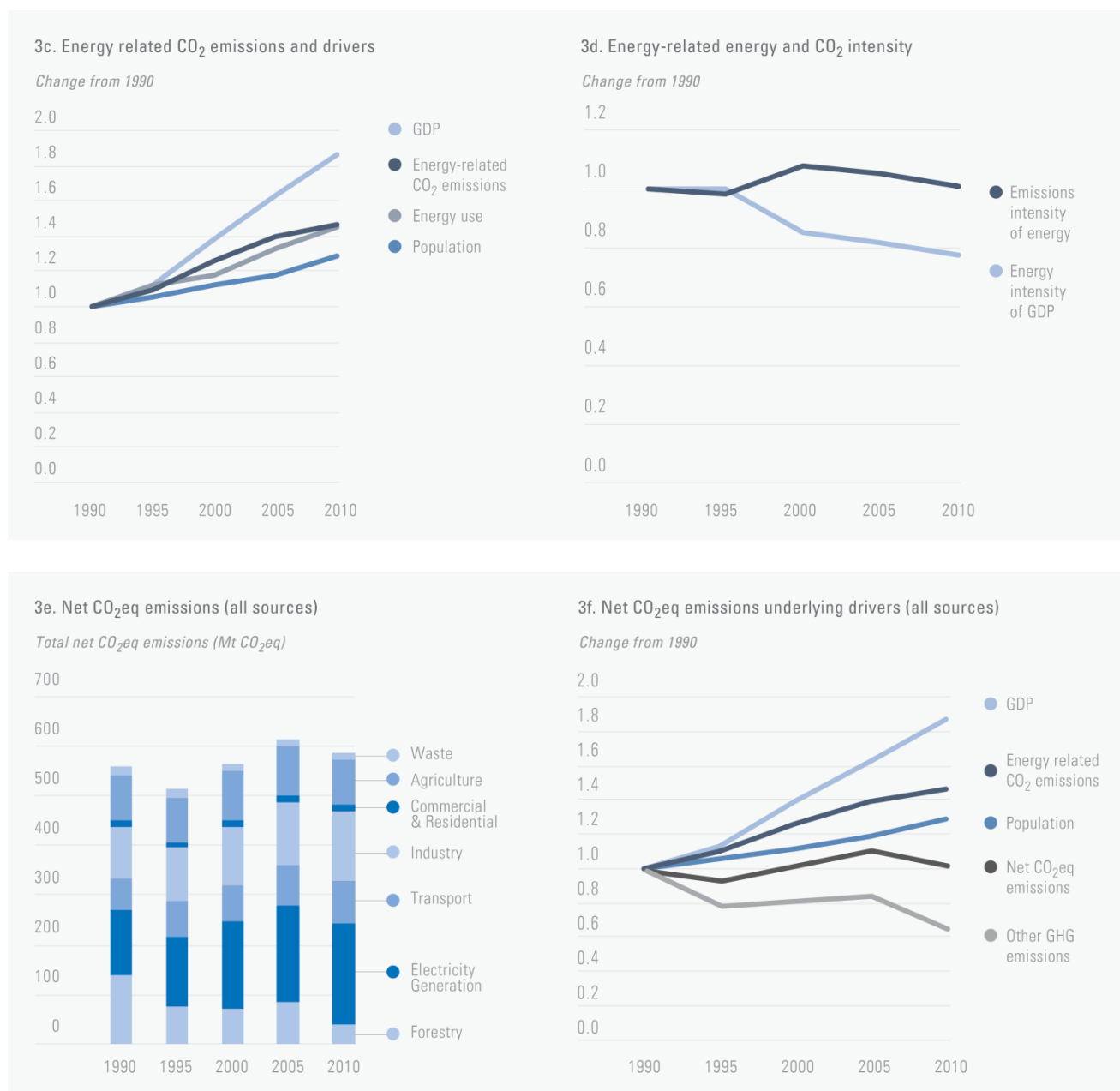
Figure 3. Decomposition of historical energy-related CO₂ Emissions, 1990 to 2010

3a. Energy-related CO₂ emissions drivers



3b. Energy-related CO₂ emissions by sectors





Source: ABS, 2012, 2013; BREE, 2013b; Department of the Environment, 2014.

Note: Figure 3a and 3b for international comparison.

2. National pathways to deep decarbonization

2.1. Illustrative deep decarbonization pathway

2.1.1. High-level characterization

Australia has a broad range of options for decarbonizing its economy and multiple possible pathways could be modelled. However the analysis in this report describes and presents results for one illustrative pathway in line with the global project parameters and methodology. The modelling for the illustrative pathway prioritizes continued economic growth and focuses on technological solutions, with less emphasis on change in economic structure or consumption patterns beyond current projections.

Assumptions about the availability and cost of technologies are deliberately conservative in the context of a decarbonizing world.

Potential step changes in technology and economic structure are not included in the example pathway but are being explored qualitatively. The possibility that some technologies included in the example pathway are not available, or end up being more costly than assumed in the modelling, has been explored in section 2.3.

The analysis builds on previous Australian work, including Commonwealth Science and Industrial Research Organisation (CSIRO) power, land, and transport sector modelling.⁵ It has also been informed by the feedback gathered via consultation with over 40 industry and academic experts, which identified that stakeholder views diverge on the viability, likely extent and costs of options such as carbon capture and storage (CCS), carbon forestry, and bioenergy.

Summary (aggregate vision for 2050)

Australia can maintain economic growth and prosperity, and decarbonize by 2050. The results from the illustrative pathway show that between now and 2050, real GDP grows at 2.4% per year on average, resulting in an economy nearly 150% larger than today. Productivity keeps rising, with 43% growth in real wages and exports growing at 3.5% per annum. Table 1 summarizes the economic and population growth trajectory.

However economic growth is not uniform across the economy. Growth driven by the increase in activities such as renewable energy generation and forestry is offset by significant reductions in primary industries such as coal production, oil extraction, and heavy manufacturing. This is discussed in section 2.1.2 under the 'Industry' heading.

Table 1. Development Indicators and Energy Service Demand Drivers

	2012	2020	2030	2040	2050
Population [millions]	22.72	25.53	29.17	32.62	36.01
GDP per capita [\$A/capita]	65,715	72,240	80,862	91,291	102,677

In 2012, Australia's energy related emissions were approximately 17 tCO₂ per capita and for Australia to contribute to the objective of limiting global temperature to <2°C, this would need to decrease by an order of magnitude by 2050. In the illustrative pathway, Australia's energy-related emissions are substantially reduced to 3.0 tCO₂ per capita in 2050, and are lower still at 1.6 tCO₂ per capita if emissions directly attributable to the production of exports are excluded. Within the modelling parameters of the illustrative pathway, including the forecast growth in global demand for energy and mineral commodities,⁶ deeper decarbonization of Australia's energy-related emissions would likely require technological advances that increase the viability and/or reduce the cost of decarbonization options.

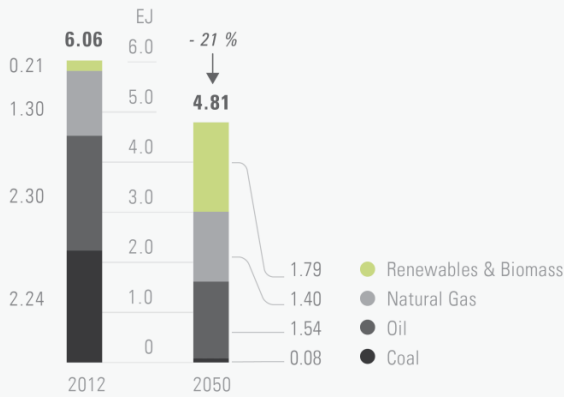
⁵ Graham et al., 2013; Reedman & Graham, 2013.

⁶ IEA, 2009, 2012.

Australia's total primary energy use decreases by 21% from 2012 to 2050 while final energy use increases by 22% (see Figure 4a and 4b). There are significant changes in the fuel mix; coal use is almost entirely phased out (the only remaining use is for coking coal in iron and steel), and there is an increase in renewables and biomass, and gas use. Australia's energy-related CO₂ emissions pathway from 2012 to 2050 is shown in Figure 5a to 5c.

Figure 4. Energy Pathways, by source

4a. Primary Energy



4b. Final Energy

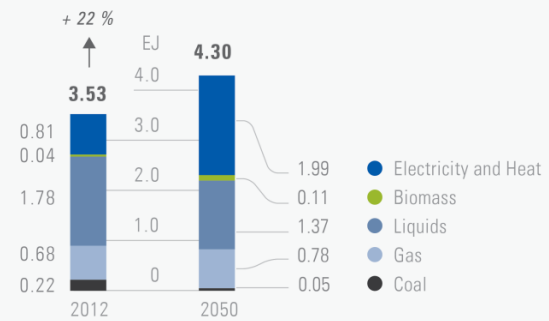
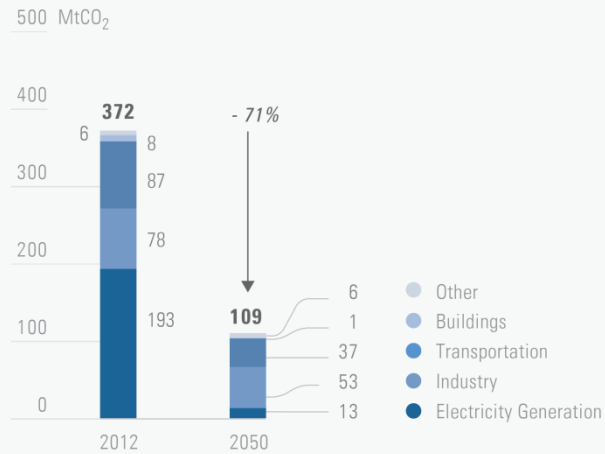
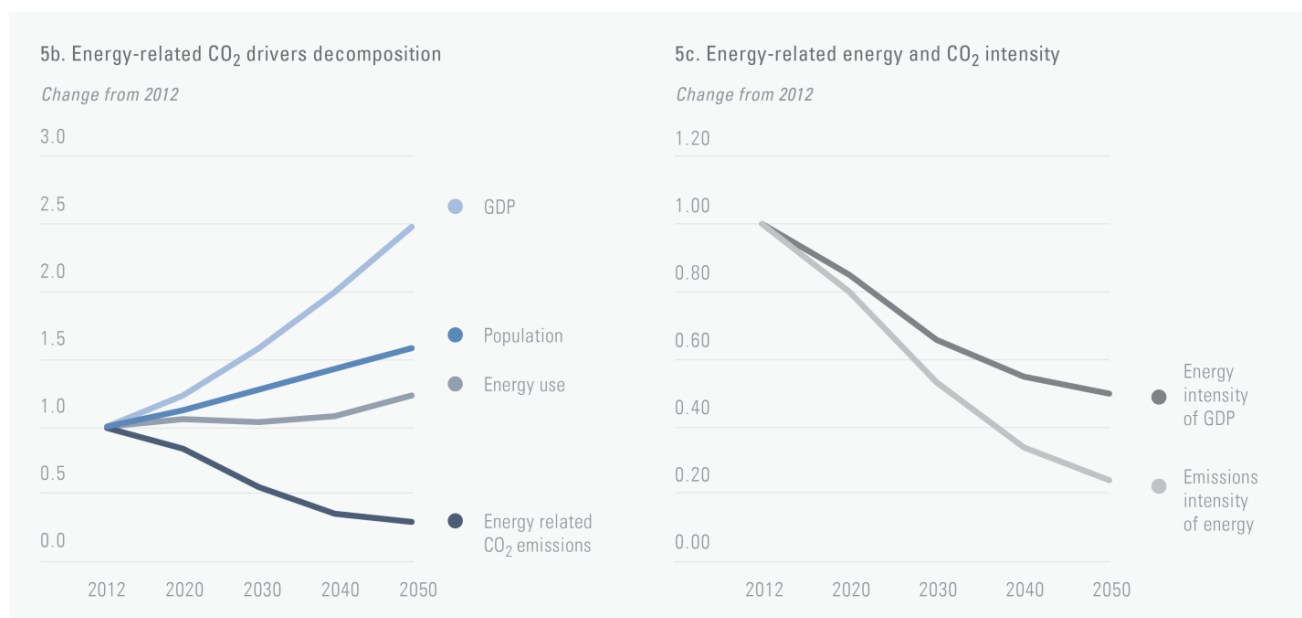


Figure 5a. Energy-related CO₂ Emissions Pathway, by Sector, 2012 to 2050



Note: For international comparison.



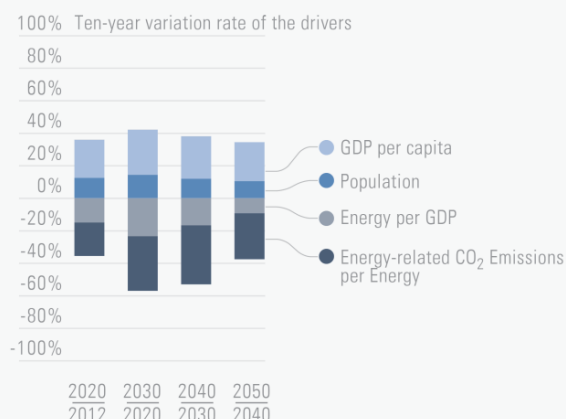
Pillars of decarbonization (energy)

Decarbonization of energy transformation (mainly electricity generation) combined with electrification (supplied by decarbonized electricity) and fuel switching leads to nearly a 75% reduction in the emissions intensity of energy use across all economic sectors. The contribution of these pillars is shown in Figure 6b, while a description is provided below:

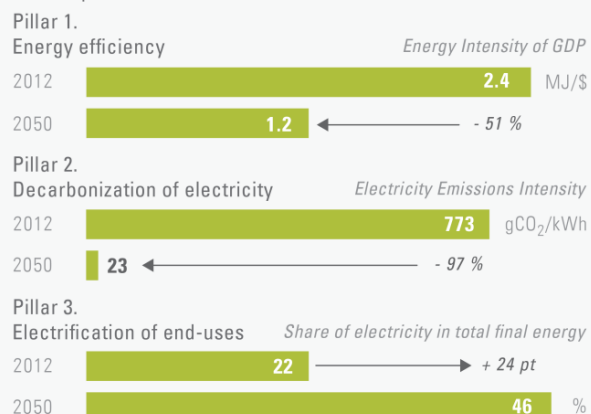
- **Structural change:** The illustrative pathway only assumes changes in economic and/or industrial structures that occur in response to domestic and global macroeconomic trends. These include global demand for commodities, existing and emerging trends in consumer preferences, continued growth of the service sector, and a plateauing of distance travelled per capita in cars and other modes of transport. In combination, these changes lead to a halving of final energy use per dollar of real GDP by 2050.
- **Energy efficiency:** Energy efficiency is assumed to continue to improve at current rates until 2020, but accelerates thereafter, especially in the building and transport sectors.
- **Electrification and fuel switching:** Electrification becomes widespread, especially for cars, buildings and industrial processes such as heating processes or material handling. Thermal coal use in industry is considerably reduced via a shift to gas and biomass wherever possible. Freight fuels move away from diesel with a significant shift to gas.
- **Decarbonization of energy transformation:** Electricity generation is almost completely decarbonized via 100% renewable grid-integrated supply of electricity, with some on-site gas fired electricity generation particularly in remote (non-grid integrated) areas. Other mixes of technologies for electricity generation are modelled as variants (refer to section 2.3). There is significant replacement of direct fossil fuel use with bioenergy.

Figure 6. Energy-related CO₂ Emissions Drivers, 2012 to 2050

6a. Energy-related CO₂ emissions drivers



6b. The pillars of decarbonization



Note: For international comparison.

Non-energy emissions (industry, agriculture, forestry and land use)

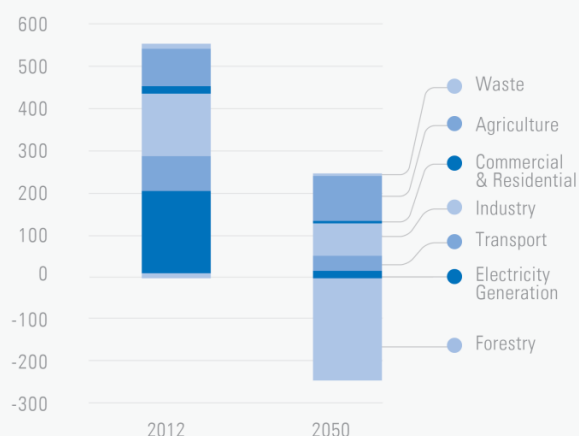
The illustrative pathway includes considerable reductions in non-energy emissions, including industrial process and fugitive emissions. The modelling assumes that best practice is applied in farming and livestock production, and that global beef demand decreases slightly in response to increases in price (due to its relatively high emissions intensity and land constraints).

Australia has substantial potential to offset emissions via land sector sequestration. The illustrative pathway includes a shift in land use toward carbon forestry, driven by carbon abatement incentives, where profitable for land holders; but it does not include the sale of emissions offsets into overseas markets. Figure 7 shows the underlying drivers of decarbonization (Figure 7b) and the pathway of decarbonization (Figure 7a) for all emissions sources and sinks.

Figure 7. Net CO₂eq emissions (all sources) and underlying drivers, 2012-2050

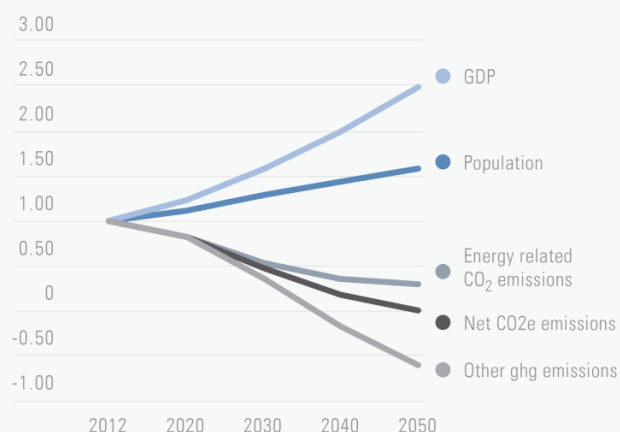
7a. Net CO₂eq emissions (all sources) by sector

Total net CO₂eq emissions (Mt CO₂e)



7b. Net CO₂eq emissions (all sources) drivers - decomposition

Change from 2012

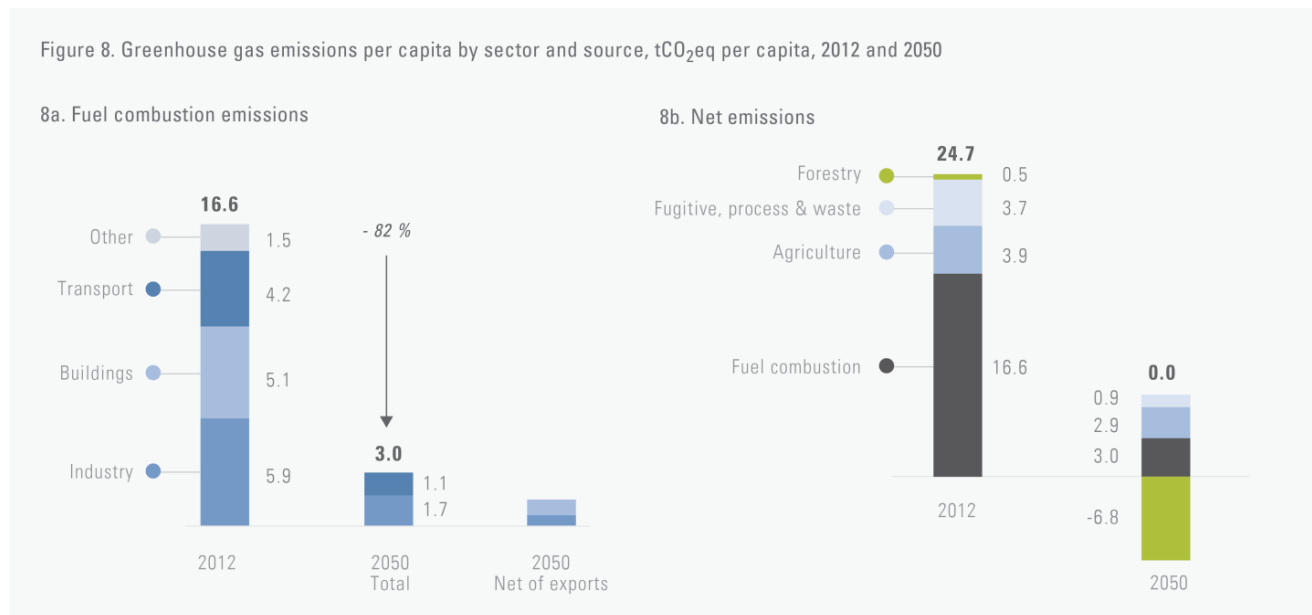


After accounting for all emissions sources and sinks, the pathway includes intermediate emissions reductions milestones of 19% below 2000 levels in 2020, at least 50% below 2000 levels in 2030, and to net zero emissions by 2050. The cumulative emissions to 2050 are compatible with Australia's carbon budget recommended by Australia's Climate Change Authority,⁷ an independent body established under the Climate Change Act 2011. This would require strong mitigation action in all sectors of the economy, in the context of a strong global decarbonization effort.

2.1.2. Sectoral characterization

The trajectory of decarbonization pathways varies substantially among sectors, depending on the availability and relative cost of technologies required in each sector. In 2050, industry is the largest contributor to energy emissions, due to continued high levels of activity in mining and manufacturing, followed by transport (see Figures 7 and 8). Nearly half of Australia's energy emissions in 2050 are directly attributable to exports, mostly for production of industrial commodities (see Figure 8).

By 2050, fuel combustion emissions reduce by about 80% compared to 2012. The main contributor to Australia's non-energy emissions in 2050 is agriculture, as currently there are limited options for reducing emissions from the agricultural sector. Sequestration via carbon forestry of approximately 7 tCO₂e per person is required for Australia to achieve zero net emissions (see Figure 8).



Power (electricity generation)

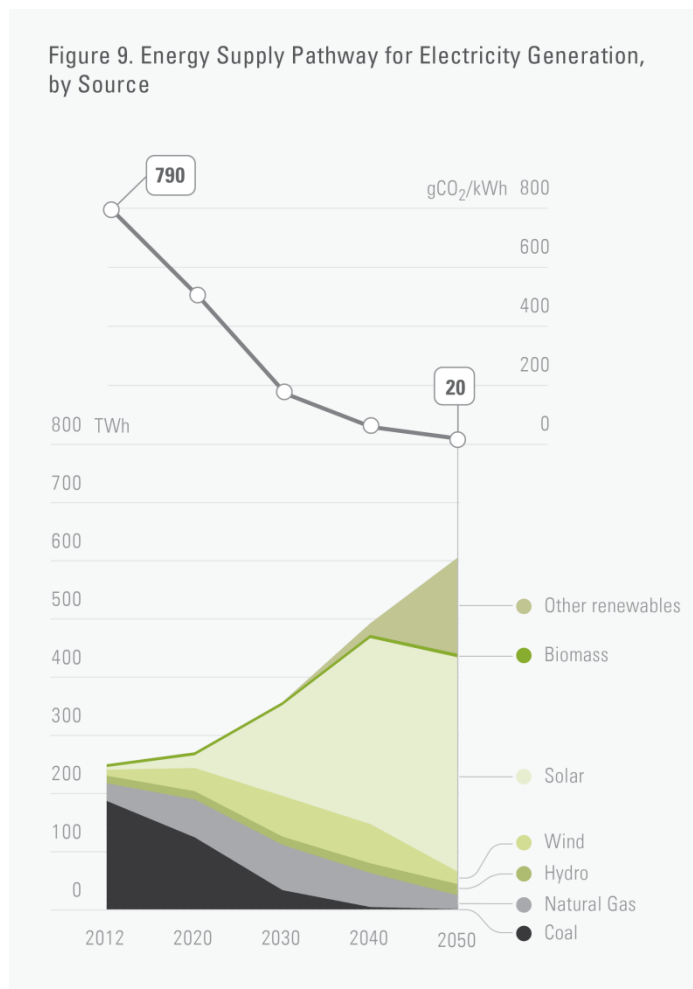
Electrification across all sectors drives a two and one-half fold increase in electricity demand by 2050, however the substantial change in Australia's electricity generation mix leads to a greater than 95% reduction in the emissions intensity of electricity to 0.021 tCO₂/MWh.

In 2050, 84% of electricity demand is met by grid-integrated renewable energy generation, mostly from rooftop and large scale solar photovoltaic panels, onshore wind, enhanced geothermal systems, wave,

⁷ Climate Change Authority, 2014.

biomass, and solar thermal generation (see Figure 9). This is possible through the inclusion of both flexible and variable renewable energy technologies as well as advances in energy storage technologies, which would also be widely used in the transport sector.⁸ The remaining electricity demand is met by distributed supply, mostly from renewable energy generation with one quarter (or 4% of total demand) supplied by on-site gas fired electricity generation in remote (non-grid integrated) areas.

The mix of power generation technologies modelled for the illustrative pathway is based on work by the Commonwealth Scientific and Industrial Research Organisation (CSIRO).⁹ Depending on the development of technologies, costs and regulatory frameworks, a near-zero emissions power system could comprise different energy sources and mixes (variants are explored in section 2.3).



Industry

By 2050, industrial energy emissions decrease by nearly 60% while the economic value added of industrial activities more than doubles. Metal ores, metals, and gas contribute nearly two thirds of the

⁸ This can be thought of as a “co-benefit” or “spill-over” effect whereby a sector is unintentionally impacted by an action taken by another sector.

⁹ Electricity generation plant technology performance and costs are based on BREE (2012, 2013c), and the capital cost reduction time path developed by Hayward & Graham (2012).

total industrial energy-related emissions in 2050, and 80% of these emissions are attributable to commodities produced for exports.

Across the mining sector, energy intensity doubles instead of tripling or quadrupling (in the absence of energy efficiency improvements). At the same time, manufacturing sector energy efficiency improvements continue in line with recent trends for the first two decades then capital stock replacements by more energy efficient stock drive increased energy efficiency.

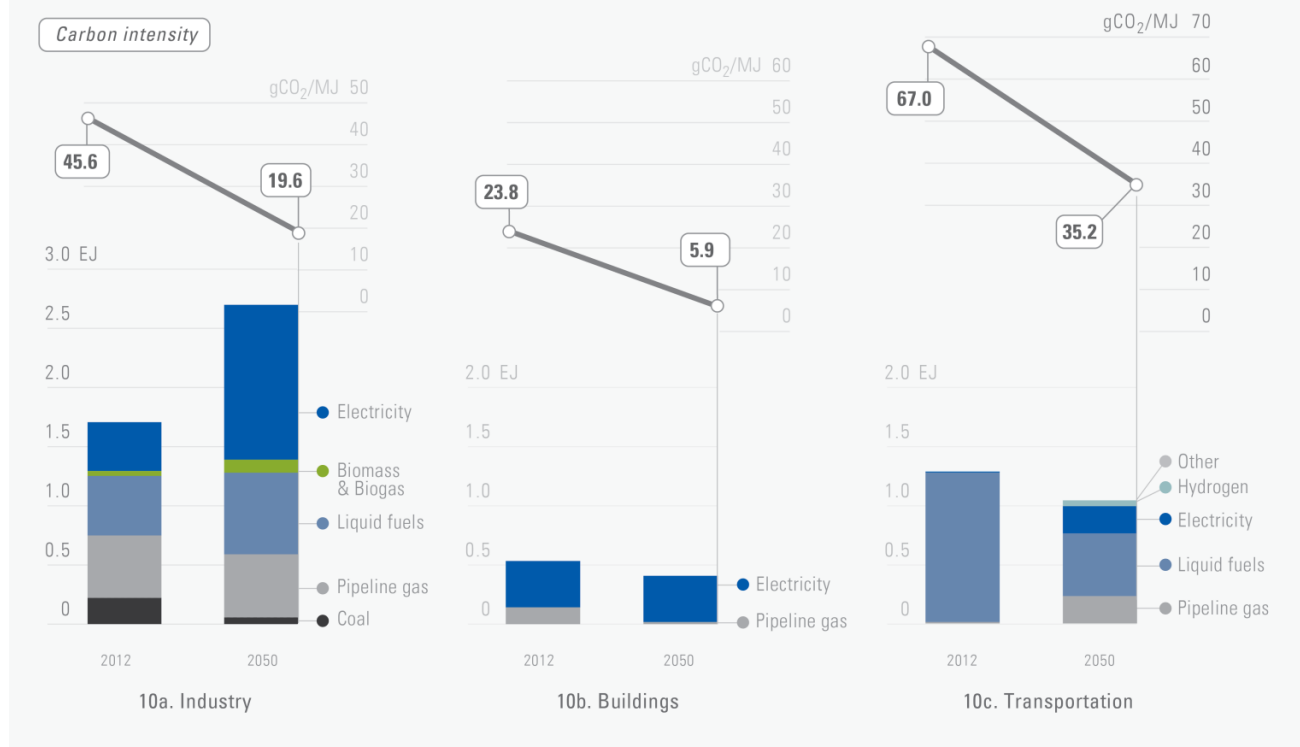
Industrial processes are electrified where feasible, and there is a shift from coal to gas and increased use of bioenergy (Figure 10a). Process emissions and fugitive emissions are reduced via various means including process improvements, materials substitution, the partial use of bio-coke in iron and steel production, increased combustion/catalyzation of gases with high global warming potential, and CCS. CCS is also applied to industrial process and fugitive emissions, as well as to CO₂ emissions from fuel combustion for the liquefaction of natural gas, where it has been applied for fugitive emissions.

Global decarbonization drives changes in global demand for commodities. In particular, reduced demand for coal¹⁰ and oil is expected to drive decreases in coal and oil production of 60% and 30% respectively. For some manufacturing activities, including metals production (iron, steel, and iron ore) growth slows, and consequently their proportional contribution to economic activity decreases. Conversely, demand for non-ferrous metals and other minerals such as uranium and lithium is expected to increase.

In addition, some domestic trends are estimated to continue, such as the progressive closure of all oil refining capacity in Australia – approximately one-third of this capacity is expected to be substituted by biofuel refining. Figure 10a shows the industry energy demand by fuel source.

¹⁰ For the illustrative pathway, Australia's production of coal is assumed to decrease in line with global demand. Further analysis could be conducted in the future on the relative competitiveness of the Australian coal industry in a decarbonizing world, which could help refine estimates of future Australian coal production.

Figure 10. Energy Use Pathways for Each Sector, by Fuel, 2012 – 2050



Buildings

Greenhouse gas emissions from commercial and residential buildings reduce by 95% to 2050 due to significant energy efficiency, electrification of direct fuel use (e.g. gas for heating), and the use of decarbonized electricity. Energy use per square meter of commercial building and per residential dwelling decreases by approximately 50%. There is strong growth in distributed, grid integrated electricity generation, in particular rooftop solar PV. Figure 10b shows the building energy demand trajectory.

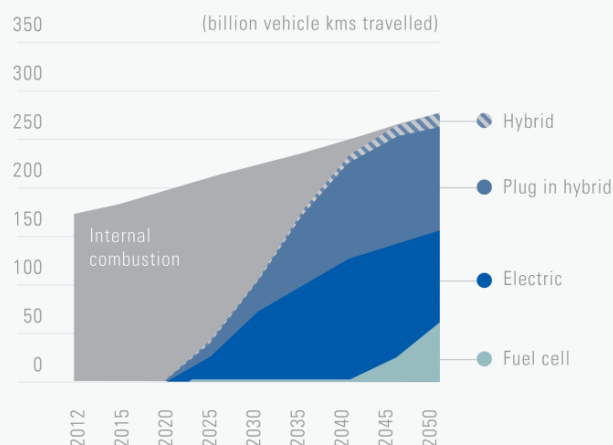
Transport

A substantial shift from internal combustion engine vehicles to electric and hybrid vehicles, and to a lesser extent hydrogen fuel cell vehicles, results in over 70% improvement in the energy efficiency of cars and light commercial vehicles. Gas is used extensively for road freight. As a result, oil use for road transport decreases by 85% between 2012 and 2050 while vehicle kilometers travelled nearly double. Biofuels replace 50% of oil use in aviation, as this is one of the only decarbonization options currently available for this sector.

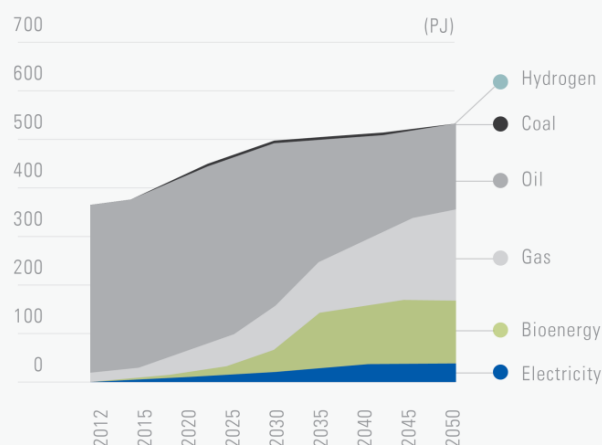
Figure 10c shows the transport energy demand trajectory and Figure 11 shows the composition of drive train technologies from 2012 to 2050 for cars and light commercial vehicles, and the fuel mix for freight and aviation over the same period.

Figure 11. Transformation of the transport sector

11a. Cars and Light commercial vehicles drive type



11b. Fuel use for freight and aviation transport



Agriculture and forestry

Soil and livestock emissions are reduced through the implementation of best practice farming techniques, in particular for beef (e.g. intensification of breeding, improvement in feeding and pasture practices, as well as enhanced breeding and herd selection for lower livestock methane emissions). In addition, a small relative reduction in beef demand is expected to result from increases in beef prices in a decarbonized world. Together, these factors drive a 45% reduction in emissions intensity of agricultural activity. However, this is not sufficient to compensate for the growth in activity that sees agricultural emissions grow by 20% between today and 2050. Some of this production, and the associated emissions, is attributable to exports.

Feedstocks for the production of bioenergy are sourced from agricultural and forestry residues and wastes, dedicated energy crops, and grasslands, and are used primarily in the aviation and mining sectors. The increases in agriculture and forestry activities required to collect and gather this biomass has been accounted for in the modelling.

As already described in section 2.1.1, Australia has great potential to offset emissions via forestry bio-sequestration. Under price incentives for afforestation, large shifts in land use from agricultural land (in particular grasslands) to carbon forestry would become profitable. However, this would require significant development of supply chains as well as regional capabilities and workforces.

For the illustrative pathway, the total uptake of carbon forestry was capped by the volume required to meet the budget recommended by Australia's Climate Change Authority, equivalent to approximately 40% of the total economic potential identified.

2.2. Assumptions

Potential for renewable resources, geological carbon storage and energy efficiency

The potential for generating energy from renewable resources in Australia is far greater than Australia's total energy use today.¹¹ As such, the challenge for Australia is not the availability of renewable resources, but harnessing the potential.

Australia also has substantial potential for geological carbon storage with large potential storage basins across the country, including a number in close proximity to fossil fuel reserves and major industrial areas.¹² The industrial-scale Gorgon Carbon Dioxide Injection Project is one of the world's largest CCS projects under development; it is expected to commence operation in 2015, and all government approvals for capturing and re-injecting carbon dioxide from the extraction and processing of natural gas have been granted for this project.¹³

Despite recent increases, Australia's rate of energy efficiency improvement is lower than in other major developed economies. Thus, considerable potential for energy efficiency improvements remains and is modelled in the illustrative pathway. Energy efficiency improvements are driven by much higher energy efficiency in the new housing stock (and domestic appliances within) required to be built for Australia's growing population. In addition, many of Australia's aging industrial assets are replaced with more energy efficient capital stock by 2050 as part of natural asset life cycles. Transport systems also have significant potential for greater energy efficiency through modal shift and urban planning.

Conditions influencing the example pathway

The electrification of industrial processes will be necessary for all country pathways and electrification technologies are likely to be a global R&D focus. Large technological advances in the potential for electrification (e.g. heat pumps and conveyors) are assumed, even though many such technologies are not yet available and/or not yet widely deployed.

Australia's non-energy emissions are substantial compared with other industrialized countries and currently there are very few options for reducing or offsetting a large proportion of non-energy emissions other than the use of bioenergy, CCS, and carbon forestry. Hence these technologies are likely to be critical to Australia's decarbonization pathway.

Carbon forestry has large potential to offset emissions (more than twice the amount that has been modelled) so it could contribute more to decarbonization in the event that other technologies do not contribute to decarbonization to the extent anticipated.

The role of CCS in sequestering industrial process and fugitive emissions, and fuel combustion emissions in LNG production, is highly dependent on CCS being demonstrated as viable (including the long-term risks of fugitive emissions), socially acceptable, and cost-effective, also at smaller scales.

¹¹ AEMO, 2013; see also Geoscience Australia & ABARE, 2010

¹² CO2CRC, 2011

¹³ CCS Institute, 2014; CO2CRC, 2011

2.3. Alternative pathways and pathway robustness

Pathway robustness

By reducing total energy demand, energy efficiency improvements enable low carbon energy supply to contribute a greater proportion to total energy supply. Energy efficiency is also the most cost-effective way of reducing emissions.

Electrification of industry and the use of bioenergy and/or CCS may be interchangeable decarbonization options, depending on the scale of substitution and corresponding marginal costs. As such, if one or more of the technologies is not deployed to the extent assumed in the modelling, Australia could still have the potential to decarbonize.

The use of bioenergy for fuel switching in industry will necessitate increased feedstock collection, aggregation, processing and distribution to end-use locations, and a focus on supply chain development. If additional bioenergy is required there may be trade-offs in the allocation of land for feedstocks with other land use needs including agriculture, carbon forestry, and ecosystem services. This may limit the potential for further bioenergy fuel substitution in industry.

Electricity generation variants modelled

For the illustrative pathway, 100% grid-supplied renewable energy electricity generation was modelled; two additional electricity generation technology mixes were modelled as variants to demonstrate contingency for any uncertainty about the viability of the 100% grid-supplied renewable energy electricity pathway. All three mixes result in a similar relative emissions intensity of electricity generation by 2050, well below the present intensity of 0.77 tCO₂e/MWh, as summarized in Table 2. Emissions from all electricity generation technology mixes could be further reduced by the use of biogas in on-site and peak gas generation (provided further resources in biogas are secured).

Table 2. Electricity generation variants modelled

Technology	Generation mix in 2050	Emissions intensity of electricity in 2050
100% renewables grid	96% renewables 4% gas (onsite)	0.02 tCO ₂ e/MWh
CCS included	65% renewables 7% coal CCS 14% gas CCS 14% gas	0.05 tCO ₂ e/MWh
Nuclear included	65% renewables 22% nuclear 13% gas	0.04 tCO ₂ e/MWh

2.4. Additional measures and deeper pathways

The illustrative pathway does not model behavioral changes or step changes in technology, and only structural changes in response to domestic and global macroeconomic trends. However, deeper pathways could be achieved via the following:

Behavior change

- Smaller houses, greater range of tolerance in heating/cooling requirements (where feasible), less travel, more widespread availability and better public transport, increased proportion of less emissions-intensive products in shopping, decreased beef consumption.
- Substitution of business travel with teleconferencing, preferential sourcing of less emissions-intensive products and services.

Structural change

- Urban design for shift to rail for passenger travel and freight transport.
- Proactive and accelerated transition from emissions-intensive manufacturing and mining to more services.

Step changes in technologies

- Bioenergy potential in Australia is partially dependent on improvements in agricultural productivity, given agricultural residues are a large component of potential feedstocks. If agricultural productivity improves then the potential of bioenergy could increase. For example, based on the highest estimates of combined feedstock availability, an additional 1000 PJ of biomass could be used to replace gas and oil use in industry and transport, driving a further emissions reduction of nearly 30 MtCO₂ in 2050 or 0.8 tCO₂/capita.
- If CCS for small scale fuel combustion applications could be developed cost-effectively, it could be applied to reduce energy emissions from many of Australia's energy-intensive sectors. For example, CCS applied to a third of all cement and non-ferrous metals production sites (excluding aluminum) could lead to a further reduction in industrial emissions of over 4 MtCO₂ in 2050 or 0.12 tCO₂/capita.
- Breakthroughs in fuel cell technology could lead to fuel cell vehicles penetrating the market sooner than modelled. For example, if half of the gas used for road freight was replaced by hydrogen by 2050, this could lead to a further reduction in transport emissions of 5.5 MtCO₂, or 0.15 tCO₂/capita.
- The cost of renewable energy technologies has fallen faster than anticipated and further breakthroughs could speed up decarbonization, offering greater flexibility of future decarbonization options.
- Breakthroughs in storage technology, particularly batteries, could see a more rapid adoption of electrification and distributed renewable energy generation.
- Material efficiency (e.g. through 3D printing) could significantly reduce emissions by reducing the demand for minerals and base metals, depending on the life cycle emissions of materials required for manufacture.

2.5. Challenges, Co-benefits, and Enabling Conditions

Challenges

There are various technological, economic, social and political challenges to implementing decarbonization pathways in Australia. However this report focuses on the technological challenges, which include:

- Demonstrating the viability of decarbonization technologies (e.g. CCS, energy storage, emerging renewables such as wave and enhanced geothermal systems, and rigorous carbon forestry accounting standards);

- Developing the supply chains and workforce for new technologies and services (e.g. bioenergy, carbon forestry technologies and accounting methods).

Co-benefits

In a decarbonized world, Australia's abundant renewable energy resources could form the basis of a new comparative advantage in low carbon energy generation, replacing the existing comparative advantage possessed through fossil fuels. Realizing this comparative advantage could result in a revival in energy-intensive manufacturing such as aluminum smelting, and the potential to develop renewable energy carriers for export markets, such as biogas or solar-thermal based energy carriers. The prerequisite for these co-benefits is that all major producing economies face strong carbon constraints, either through their domestic frameworks or through import demand favoring products from zero-carbon sources.

Australia has the opportunity to be a global leader in CCS expertise and technology development thanks to its great potential for carbon capture and storage. Prospects for the extraction, refining and export of minerals such as non-ferrous metals and ores, uranium, lithium, and other precious metals may also be attractive.

Australia's substantial potential for bioenergy generation and bio-sequestration could contribute, for instance, to the economic revitalization of regional and rural communities, biodiversity protection, and improved water quality.¹⁴ Indigenous-led carbon mitigation projects, applying traditional land management practices, offer the opportunity to simultaneously address climate change, biodiversity, health, and social and cultural inclusion challenges.¹⁵

Other co-benefits include better air quality and improved health due to reduced fossil fuel use, increased production levels due to improved energy efficiency, and workforce productivity gains in more naturally lit and energy efficient workplaces.

Enabling conditions

The fundamental enabler for the decarbonization of the Australian economy is the simultaneous decarbonization of all other major industrialized countries. For Australian industries to remain competitive in global markets, their competitors in other countries must also be exposed to the decarbonization pressures and drivers. This will also encourage public and private sector R&D efforts focused on low carbon technologies such as electrification, CCS and bioenergy.

2.6. Near-term priorities

Australia faces the risk of locking in energy-intensive assets, especially for new vehicles, buildings, industrial plants, mines, and power stations. To ensure new technology developments can contribute effectively and efficiently to deep decarbonization, clear signals about Australia's likely long-term emissions pathways are required to inform investment decisions. Government has a vital role to play in providing predictability of policy settings in order to minimize investment hold-ups and to reduce the risk of suboptimal investment decisions.

¹⁴ See for instance Eady, Grundy, Battaglia & Keating, 2009; Stucley et al., 2012.

¹⁵ Green & Minchin, 2012.

The development of decarbonization technologies and their costs is subject to steep and often unpredictable learning curves. A portfolio approach to R&D investment in technologies is required to maximize the chances of developing technologies that will achieve the deepest emissions reductions at the lowest costs. Long-term approaches for the development and deployment of these solutions will be required, and key areas for further investigation include:

- R&D for renewable energy technologies, storage and grid-integration;
- Planning for increased electrification of the economy, including the transport system;
- CCS, including R&D and deployment of stand-alone industrial applications;
- Investigation of options for zero-carbon energy industries;
- Continued energy efficiency improvement throughout the economy;
- Applied research and on-ground experiments to determine tree species, soil types, and growing conditions that will maximize the potential for carbon forestry;
- R&D on advanced bio-sequestration options and large-scale production of biofuels; and
- Reducing food waste and the emissions attributable to the food production.

Transition to a decarbonized world will require new forms of international collaboration, and a concerted approach to collaborative national knowledge creation and problem solving.

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1. Country profile

1.1. The national context for deep decarbonization and sustainable development

To contribute to a path that limits the global increase in temperature to less than 2°C, Canada would need to dramatically reduce CO₂ emissions from energy- and industrial process-related activities. Emissions would need to be transformed from 20.6¹⁶ tonnes of carbon dioxide equivalent per capita (tCO₂e/cap) in 2010 to less than 2 tCO₂e/cap in 2050. This represents a nearly 90% reduction in emissions from 2010 levels by 2050.

The Canadian context presents a number of challenges related to achieving deep decarbonization:

- **First, national circumstances create structural impediments to decarbonization.** Challenges include Canada's vast land area (which drives substantial transportation demand), climate (which drives winter heating and summer cooling demand), and the importance of the resource extraction sector to the economy.
- **Second, Canada's natural resource development aspirations are consistent with a global 2°C pathway only if deep decarbonization technologies are deployed.** Global demand for fossil fuels and other primary resources is projected to rise even in deep decarbonization scenarios. As a result, the continued development of Canada's fossil fuel and mineral natural resources for global export can be consistent with a 2°C pathway. However, this requires that transformative GHG mitigation technologies be deployed at every stage, including extraction, processing, and end-use.
- **Third, significant political, economic, and technical barriers to deep decarbonization need to be overcome, both in Canada and abroad.** Technical constraints currently limit the availability of many options (such as hydrogen use for personal travel), and significant research, development, and deployment efforts will be needed both domestically and internationally. Cost and competitiveness outcomes are other challenges that must be overcome for technologies to be widely deployed (such as CCS). Finally, even options that meet both of these feasibility criteria may fail to be implemented due to public opposition and political pressures.

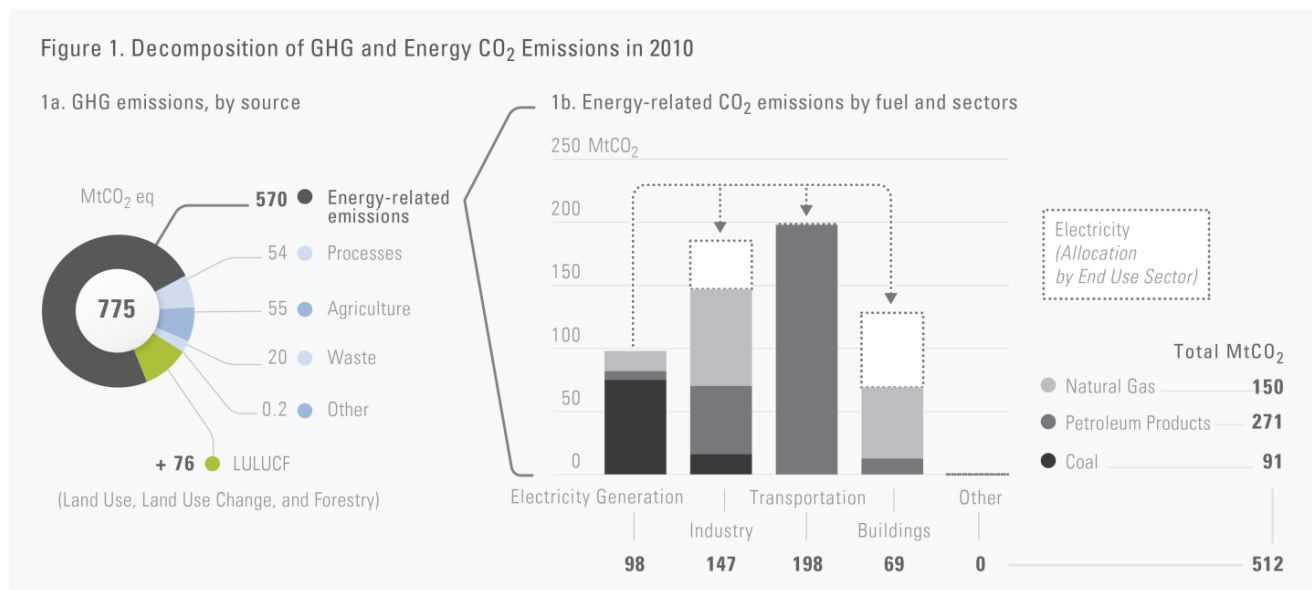
The Canadian analysis presented in this chapter considers and incorporates these factors. However, in order to achieve the objective of the current phase of the DDPP process—identifying national technological pathways to deep decarbonization—the analysis also looks beyond current political realities and envisions a hypothetical future in which Canada and other nations are aligned on the need

¹⁶ Excludes LULUCF emissions

to implement stringent policies to drive these changes and international competitiveness concerns associated with differential action are alleviated. Another important simplifying assumption in the analysis is that the Canadian emission reductions are achieved domestically, despite the fact that access to globally sourced GHG reduction opportunities will be politically and economically important to Canada's decarbonization effort. These assumptions are necessary in order to look beyond the status quo and investigate the transformative technological pathways that deep decarbonization in Canada will require. The insights gained from this analysis can then be used to inform policy discussions, as well as identify the implications of global decarbonization-driven technological shifts for Canada's economy.

1.2. GHG emissions: current levels, drivers, and past trends

In 2010, total Canadian GHG emissions (including LULUCF) were 775.2 MtCO₂e, equivalent to 22.8 tCO₂e per capita (20.6 excluding LULUCF). As shown in Figure 1, emissions are dominated by the industrial and transportation sectors and driven by the use of fossil fuels, particularly refined petroleum products and natural gas.

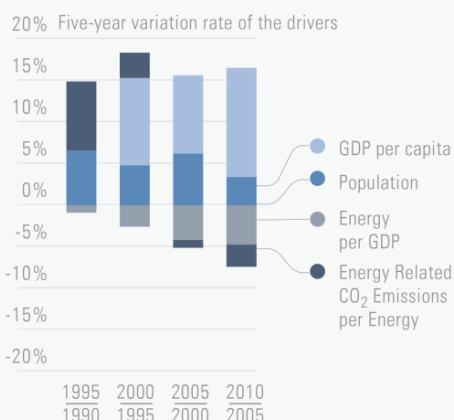


Note: Combustion CO₂ emissions does not include upstream fugitive emissions (58 Mt in 2010).

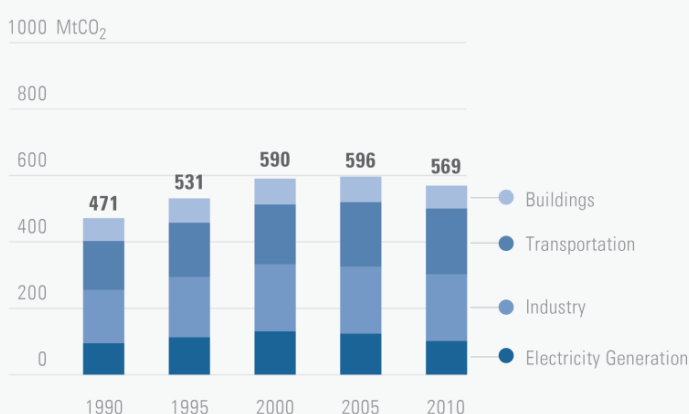
Between 1990 and 2010, energy-related emissions rose by 101 Mt CO₂e, driven by population and economic growth (Figure 2a). Industrial output (particularly in the oil and gas sectors) has risen substantially, and the growing population and economy have spurred increasing transportation demand. These factors have been offset by improvements in energy efficiency: between 1990 and 2010 energy efficiency regulations drove an improvement of approximately 15% in the average fuel efficiency of the Canadian car fleet and approximately 25% in the heating energy intensity of new residential buildings.

Figure 2. Decomposition of historical energy-related CO₂ Emissions, 1990 to 2010

2a. Energy-related CO₂ emissions drivers



2b. Energy-related CO₂ emissions by sectors



While the overall carbon intensity of energy use did not change significantly between 1990 and 2010, Canadian electricity production has started shifting toward lower and zero emission sources. The Canadian federal government recently imposed regulations effectively requiring all new and retrofitted electricity generation to have the GHG intensity of a natural gas combined cycle gas turbine or better. Each province also has carbon regulations in place that drive electricity decarbonization, such as feed-in-tariffs and a coal-fired power ban in Ontario, a flexible levy on marginal industrial emissions in Alberta, a renewable portfolio standard in New Brunswick and Nova Scotia, and a net zero GHG standard for new generation in British Columbia.

2. National deep decarbonization pathways

2.1. Illustrative deep decarbonization pathway

2.1.1. High-level characterization

The Canadian deep decarbonization pathway examines the major shifts in technology adoption, energy use, and economic structure that are consistent with continued growth in the population and economy and a nearly 90% reduction in GHG emissions from 2010 levels by 2050. It is important to remember that this pathway is not a forecast, but rather an illustrative scenario designed to identify technology-related needs, challenges, uncertainties, and opportunities. The analysis is based on a set of global and domestic assumptions about key emissions drivers, technology availability, and economic activity. In order to reveal the technological pathways to deep decarbonization in Canada, current political realities were suspended, and important assumptions were made related to demand for Canadian oil and gas exports, commercial availability of transformative technologies, the availability of globally sourced GHG reductions, and the extent to which global decarbonization creates new export opportunities for Canadian goods and services. These assumptions are discussed at the end of this section. A technology-specific energy-economy model (CIMS) was then used to simulate the energy-using technology pathways that firms and individuals would follow under the DDPP scenario. The results provide insight into the key areas where decarbonization will occur, as well as where deep emission reductions will be challenging to achieve.

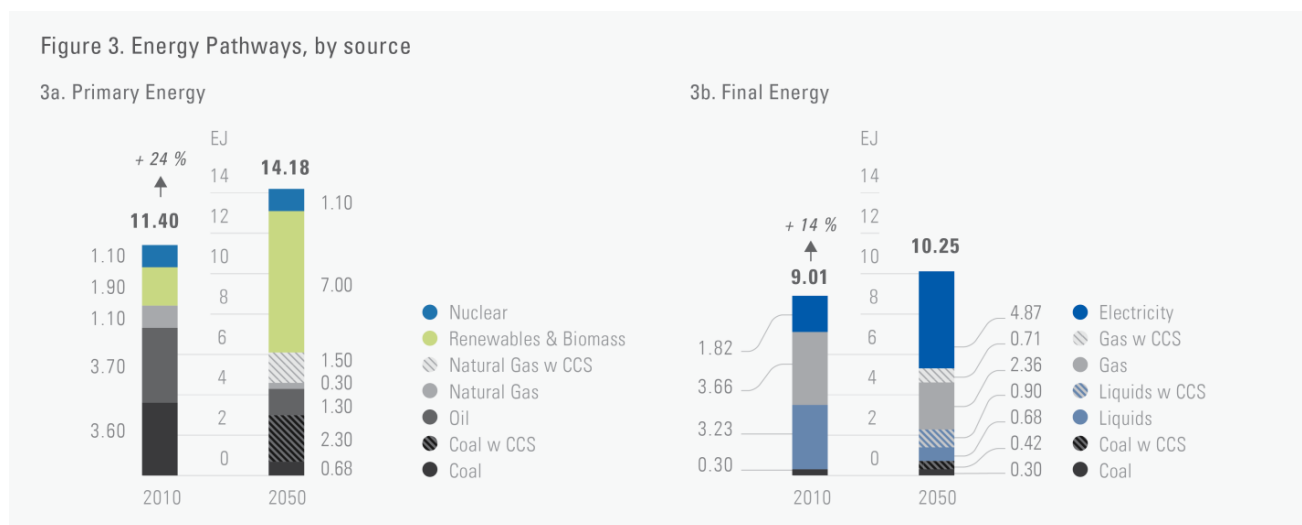
Summary of Results

The Canadian deep decarbonization pathway achieves an overall GHG emission reduction of nearly 90% (651 MtCO₂e) from 2010 levels by 2050, while maintaining strong economic growth (see Table 1).¹⁷ Over this period, GDP rises from \$1.26 trillion to \$3.81 trillion (real \$2010 USD), a tripling of Canada's economy.

Table 1. Development Indicators and Energy Service Demand Drivers

	2010	2020	2030	2040	2050
Population [Millions]	33.7	37.6	41.4	44.8	48.3
GDP per capita [\$ /capita, 2010 price]	37,288	49,787	57,754	67,500	78,882

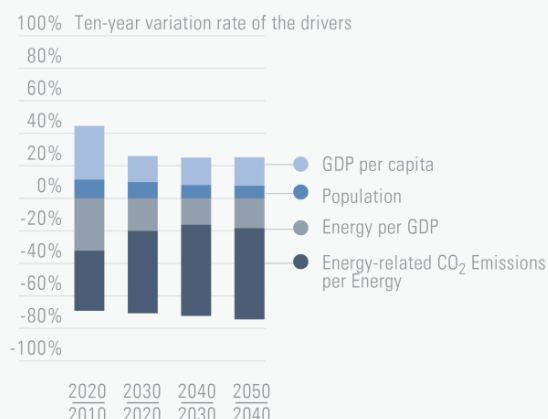
The reduction in emissions is driven most significantly by a dramatic reduction in the carbon intensity of energy use, as renewables and biomass become the dominant energy sources, and there is broad fuel switching across the economy toward electricity and biofuels (Figure 3 and Figure 4a). Electricity production nearly completely decarbonizes (Figure 4b). Overall, the carbon intensity of Canada's total primary energy supply declines by 90% between 2010 and 2050. This result is resilient to several technology scenarios. If biofuels are not viable the transport stock could transition to increased use of electricity generated with renewables and fossil fuels with CCS, especially if better batteries become available. If CCS is not available, the electricity sector could decarbonize using more renewables and/or nuclear, and vice versa.



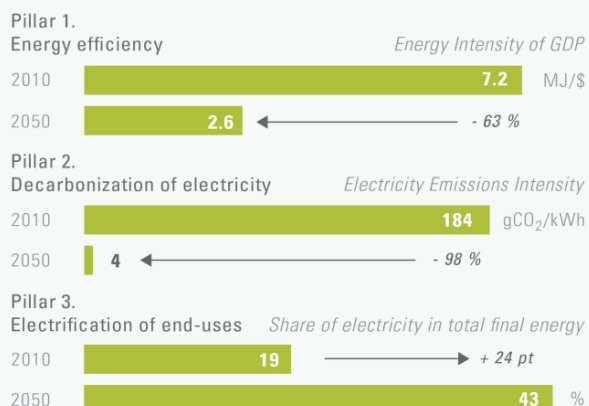
¹⁷ Net LULUCF emissions are omitted in the DDPP process.

Figure 4. Energy-related CO₂ Emissions Drivers, 2010 to 2050

4a. Energy-related CO₂ emissions drivers



4b. The pillars of decarbonization



The other major driver of emission reductions is the dramatic reduction in the energy intensity of the economy between 2010 and 2050, as shown in Figure 4a and Pillar 1 of Figure 4b. End-use energy consumption rises by only 17% over this period, compared to a 203% increase in GDP. This is due to both structural changes in the economy and energy efficiency. The economy diversifies away from the industrial sector to some extent, and within the industrial sector, output from the refining, cement, and lime sectors falls compared to the reference case scenario, while output from the electricity, biodiesel, and ethanol sectors rises. Output from the oil and gas sector falls slightly from the reference case, but it still doubles.

In combination, these factors drive a nearly complete decarbonization of the buildings, transportation, and electricity sectors. As shown in Figure 5, by 2050 Canada's remaining emissions in the deep decarbonization scenario come primarily from industry.

Key Scenario Characteristics

Two of the core foundations of the Canadian deep decarbonization pathway—nearly complete decarbonization of the buildings and transportation sectors—are well understood, with significant progress already achieved. Other elements of the pathway are less certain and more susceptible to global factors, including global demand (and hence emissions) from the heavy industrial and energy extraction and processing sectors and the availability of transformative GHG abatement technologies.

To address these uncertainties, the Canadian analysis is based on four key characteristics:

- 1) **International demand for crude oil and natural gas remains substantial under a deep decarbonization scenario.** As a result, oil and gas production (as well as the end use of fossil fuels) substantially decarbonize by 2050, and the sector is able to remain a thriving contributor to the national economy. This assumption is discussed further in Technical Options and Assumptions for National Deep Decarbonization.
- 2) **The analysis assumes that all emission reductions are achieved domestically, despite the importance of lower-cost global reductions to achieving decarbonization in Canada.** This assumption is being made by all country teams, since the DDPP process is focused on

identifying the decarbonization pathways and technical changes that are likely to drive deep emission reductions in each country. However, in practice, international cooperation to maximize the efficiency of worldwide emission reduction efforts will be critical.

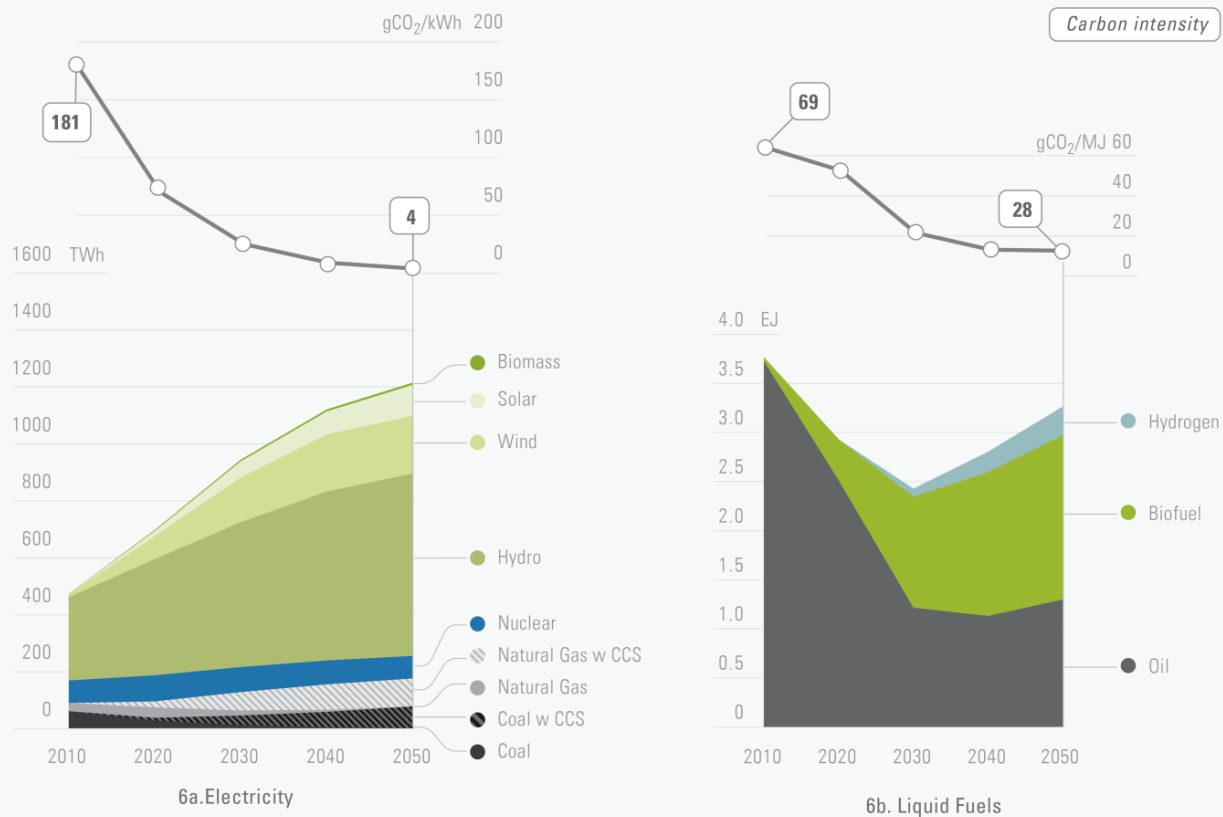
- 3) **Global demand patterns for Canadian goods and services do not change.** Depending on the decarbonization pathways followed by other countries, demand for various Canadian goods and services could increase, potentially including **biomass (as cellulosic ethanol or biodiesel), primary metals** (iron, nickel, zinc, rare earths, and uranium), fertilizers (both from mined potash and nitrogen/ammonia-based sources derived from natural gas), and/or energy efficiency technologies (particularly in the vehicle sector). However, the scope and scale of this impact is highly uncertain. These dynamics will be explored in future phases of the DDPP.
- 4) **There will be significant domestic innovation and global spillovers in transformative low-carbon technologies,** leading to the commercial viability of next-generation cellulosic ethanol and biodiesel, as well as CCS in the electricity generation, natural gas processing, hydrogen production, and industrial sectors. These assumptions are discussed further in Technical Options and Assumptions for National Deep Decarbonization.

2.1.2. Sectoral characterization

Energy Supply

In the deep decarbonization scenario, the Canadian energy supply is transformed between 2010 and 2050. Over this period, consumption of electricity rises nearly 70%, from 505 to 1,354 TWh, while the sector's total emissions fall by 95%, from 101 to 5 MtCO₂. As shown in Figure 6, this is led by an increase in the share of renewable energy (hydro, wind, solar, and biomass) in the generation mix and supported by the use of CCS to decarbonize coal and natural gas-fuelled generation. Nuclear output was assumed to remain constant, due to facility siting and political challenges.

Figure 6. Energy Supply Pathways, by Resource



Oil and natural gas consumption decline, while biofuels become the core liquid fuel, and hydrogen enters the energy mix (Figure 6b). Sufficient access to the feedstocks for cellulosic ethanol and biodiesel was assumed; however, the electricity generation mix does not include net sequestration of biomass, given insufficient information regarding the availability of sufficient sustainable feedstock.

Due to these fuel supply shifts, by 2050 the electricity, transportation, and building sectors have almost completely decarbonized, and the Canadian emissions profile is dominated by a subset of industrial emissions that are very difficult and expensive to reduce (Table). The following sections highlight the key changes that drive emission reductions in each of these sectors.

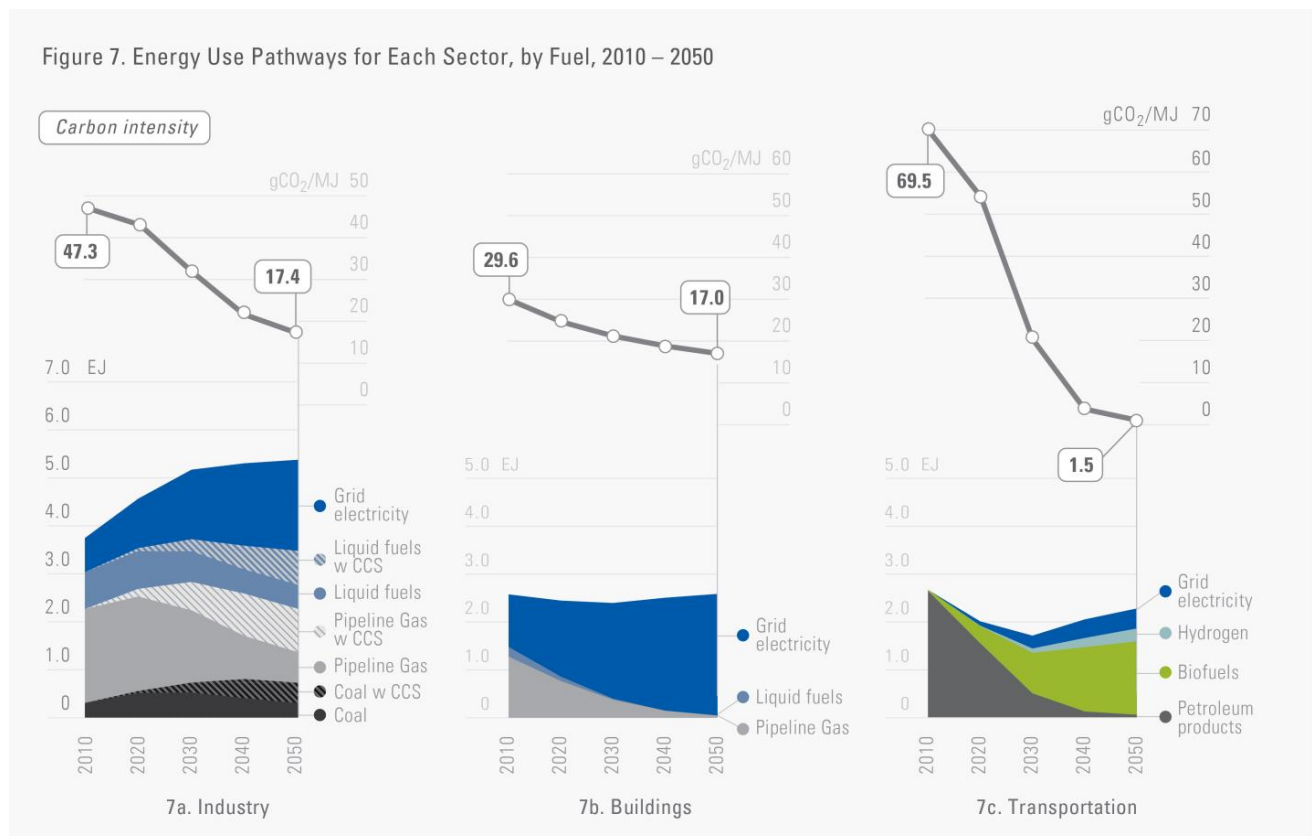
Table 2: Remaining GHG Emissions in 2050 by Sector (% of Total)

Sector	% of Total
Electricity	5.9%
Transportation	5.9%
Buildings	3.5%
Industry	74.9%
Agriculture	11.1%

Note: Total exceeds 100% due to rounding.

Transportation

Overall transportation sector emissions fall by 97% between 2010 and 2050, from 198 to 5 MtCO₂. In the personal and freight transportation sectors, this decarbonization is initially driven by vehicle efficiency improvements and then by substantial fuel switching to biofuels (predominantly cellulosic ethanol for personal transport and biodiesel for freight transport), electricity, and hydrogen (Figure 7c).



Note: Carbon intensity for each sector includes only direct end-use emissions and excludes indirect emissions related to electricity or hydrogen production.

Energy efficiency regulations have already led to substantial GHG reductions in the transportation sector, and new vehicle stock is on track to almost completely decarbonize by the late 2030s or early 2040s if regulatory goals continue to strengthen at their recent rate.

Passenger kilometers travelled remain fairly constant, while freight movement per dollar of GDP falls by 35% between 2010 and 2050, as the economy becomes less dependent on the movement of freight. Structurally, there is a slight mode shift from personal vehicles to mass transportation (transit, bus, and rail), while in the freight transportation sector, the use of heavy trucks declines substantially, primarily in favor of rail.

Buildings

Overall building sector emissions fall by 96% between 2010 and 2050, from 69 to 3 MtCO₂. The bulk of the emission reductions are the result of fuel switching, with natural gas use virtually eliminated and electricity providing nearly all of the sector's energy by 2050 (Figure 7b). Air and ground source heat pumps are the primary energy supply technologies in use, with some peaking with baseboard electric heat.

Per capita residential floor area remains fairly constant, while the commercial sector becomes more space efficient, and commercial floor area per dollar of GDP falls by 36%. Building energy efficiency has already improved substantially, and forthcoming energy efficiency regulations will continue to drive reductions in space heating energy use, keeping the sector on a trajectory toward nearly complete decarbonization.

Industry

Industrial emissions fall by 80% between 2010 and 2050, from 313 to 64 MtCO₂e. The structure of the industrial sector shifts, with output from the refining and cement and lime sectors falling compared to the reference case and output from the electricity, ethanol, and biodiesel sectors rising. While slightly lower than in the reference case, output from the oil and gas sector still doubles. The vast majority of the industrial sector's emissions reductions are a result of fuel switching (particularly to electricity) and the widespread adoption of CCS to reduce chemical by-product and process heat related emissions (Figure 7a). Process emission controls are also put in place for the cement and lime, chemical production, iron and steel, and oil and gas extraction sectors.

Agriculture

While not the focus of the DDPP at this stage, this study included an analysis of strategies to reduce agricultural non-CO₂ GHG emissions, and the Canadian decarbonization pathway includes an 83% reduction in these emissions between 2010 and 2050 (from 55 to 9.5 MtCO₂e). These reductions result from efforts to reduce atmospheric emissions due to enteric fermentation, manure management, and agricultural soils, and include measures such as methane capture, controlled anaerobic digestion and flaring or generation, and no-till agricultural practices.

2.2. Assumptions

The Canadian decarbonization pathway is dominated by four major dynamics, providing insight into the key areas where Canada can take action to decarbonize:

- Reinforced and deepened energy efficiency improvement trends in all energy end-uses;

- Eventual decarbonization of the electricity sector;
- Fuel switching to lower carbon fuels and decarbonized energy carriers (e.g. electricity, transport biofuels and hydrogen); and
- Direct GHG reduction for industrial processes and thermal heat generation (e.g. via carbon capture and storage and process changes).

This section discusses each of these decarbonization opportunities and the key assumptions and uncertainties involved.

Improved energy efficiency for all energy end-uses

End-use energy efficiency improvements are a key decarbonization pathway in Canada, particularly in the transportation and buildings sectors. Energy efficiency roughly doubles in both sectors by 2050, which is consistent with the trajectory already established by existing and forthcoming efficiency regulations.

Decarbonization of electricity generation

Decarbonizing electricity production is essential, since it is a precondition to reducing emissions throughout the rest of the economy through electrification. To decarbonize Canada's electricity generation stock, investment in a wide range of low-emitting electric generation technologies will need to more than double from baseline levels in the deep decarbonization scenario.

Our modelling assumes that the cost and capacity factors of wind and solar improve to a degree that allows 17% of generation to come from wind and 10% from solar PV. Both require restructuring of electricity markets and transmission grids to allow for and encourage high intermittent renewable content.

In addition to intermittent renewables, significant deployment of CCS will be required to facilitate large-scale switching to decarbonized electricity. The analysis assumes that post-combustion CCS will be commercially viable for the electricity sector by 2020 and that eventually solid oxide fuel cells (which provide a virtually pure CO₂ waste stream) or a technology of equivalent GHG intensity will be used to achieve approximately 99% CO₂ capture.

Fuel switching to decarbonized energy carriers

The Canadian decarbonization pathway includes significant fuel switching to decarbonized energy carriers, with the transportation, industrial, and residential/commercial sectors switching to electricity, hydrogen, and advanced biofuels. Fuel switching in the transportation sector will require further developments in batteries (less so for hybrid and plug-in hybrid vehicles) and hydrogen storage. Fuel switching to advanced biofuels will also depend on the development of a decarbonized fuel source with adequate feedstocks (e.g. cellulosic ethanol and biodiesel based on woody biomass or algae) and significant technological innovation to make these fuels commercially available.

Direct GHG reduction in industrial processes

To achieve significant decarbonization, a cost-effective method of reducing chemical by-product (e.g. from natural gas processing and hydrogen, cement, lime, and steel production) and process heat-related emissions is essential. This will require the deployment of CCS in these sectors, along with other transformative technologies that are not yet commercially available (e.g. down-hole oxy-combustion or

in-situ electrothermal extraction in the petroleum extraction sector and switching from pyro to hydro metallurgy in metal smelting).

Assumptions

As mentioned previously, the Canadian deep decarbonization pathway assumes that international demand for crude oil and natural gas remains substantial. If international oil prices remain above the cost of production, continued growth of the Canadian oil sands sector (with decarbonization measures) can be consistent with deep emission reduction efforts and would support continued economic development.

The literature conflicts on whether production from the oil sands can be cost-effective in a deep decarbonization scenario; the answer depends on policy, the cost of reducing production emissions, and assumptions regarding transport energy use and efficiency. However, the International Energy Agency's World Energy Outlook 2013 indicates that even in a 450 ppm world, oil sands production could remain at levels similar to today or higher.¹⁸

2.3. Alternative pathways and pathway robustness

Several elements of the Canadian decarbonization pathways are well understood and are expected to provide an essential foundation for deep decarbonization under all pathways, such as energy efficiency improvements in the buildings and transportation sectors. Other elements depend on technological innovation and stronger climate policy signals, and their future contribution to Canadian emissions reductions is more uncertain. The commercial availability of CCS falls into this latter category, since the technology is not commercially viable with current climate policy stringency.

If CCS does not achieve commercial viability in the electricity production sector or is blocked due to public acceptability concerns, alternative decarbonization pathways could be based on increased generation from either nuclear power or renewables. The Canadian decarbonization pathway assumes that nuclear generation is limited to current installed capacity, due to the challenges associated with siting new facilities. However, if public acceptance and siting challenges were overcome, this constraint could be relaxed. Renewables such as solar and wind power are already projected to play a major role in electricity generation by 2050. They have the theoretical potential to expand further, but their intermittency is a limiting factor, and further expansion would depend on development of a North American-wide high voltage direct current transmission grid to balance renewable supply and demand or significant breakthroughs in storage technologies.

The analysis also assumes substantial deployment of CCS to address process heat emissions in natural gas processing, hydrogen production, and industrial sectors. If this does not occur, the key alternative is direct electrification of industrial processes, such as substituting hydro metallurgy for pyro metallurgy.

The Canadian decarbonization pathway also includes significant fuel switching to cellulosic ethanol and biodiesel in the transportation sector, which relies on the assumption that these fuels will be commercially viable. However, the transportation sector has more flexibility than many other sectors, since biofuels, electricity, and hydrogen all contribute to the sector's emission reductions. If biofuels are

¹⁸ International Energy Agency (IEA). 2013. *World Energy Outlook 2013*. www.worldenergyoutlook.org

not available, alternative decarbonization pathways could be based on greater electrification of transportation or more aggressive fuel switching to hydrogen (although there are currently technical issues with practical hydrogen storage in personal vehicles, and there is currently no hydrogen supply network).

2.4. Additional measures and deeper pathways

The Canadian decarbonization pathway was developed by using a technology-rich stock turnover simulation model, which includes and evaluates both currently available technologies and those still under development but with the potential for future commercial availability. The Canadian pathway is extremely aggressive and ambitious, reducing emissions by nearly 90% between 2010 and 2050. As a result, few additional measures and deeper pathways are available. One emission reduction option that is currently being investigated in Canada is accelerated weathering of mine wastes. Some mine tailings mineralize atmospheric carbon dioxide, and researchers are working on accelerating this process, both abiotically and microbially. This could offset the GHG emissions from mining projects and has the theoretical potential to sequester much larger quantities of emissions, turning mine wastes into a significant carbon sinks.¹⁹ Another known decarbonization pathway not included in this version of the analysis is the full suite of potential options for switching from pyro metallurgy (using heat) to hydro metallurgy (using acid solutions and electricity) in the metal smelting sectors. Finally, another pathway that may allow deeper reductions is the use of biomass with CCS in electricity generation to create net sequestration electricity production; we have not considered this option due to potential feedstock limitation issues.

2.5. Challenges, opportunities and enabling conditions

Challenges

The fossil fuel production and mineral extraction sectors play a major role in the Canadian economy. However, their export-oriented nature is a challenge, since they create significant production emissions in Canada even though the outputs are consumed in other countries. The commercial availability of CCS will be essential to economically address these emissions.

More broadly, many of the major changes described in the Canadian decarbonization pathway will not occur without strong policy signals, which will require public support and in many cases will be driven by public pressure, whether domestically or indirectly through external market-access pressures. Technological innovation and deployment is a critical component of the Canadian pathway, but large-scale deployment of new technologies is dependent on public acceptance, which must be earned through continued engagement and dialogue and cannot be assumed.

Knowledge Gaps

A significant knowledge gap in the Canadian decarbonization pathway is how global decarbonization efforts will change demand for products and services that support low-carbon development and in which Canada has a competitive advantage. **Changing global demand patterns could lead to the expansion of existing industries or the development of new industries, dampening adverse decarbonization impacts and supporting continued economic development.**

¹⁹ Dipple, G. et al. 2012. Carbon Mineralization in Mine Waste. Available online at <http://www.cmc-nce.ca/wp-content/uploads/2012/06/Greg-Dipple.pdf>

Enabling Conditions

International cooperation is required to support research, development, and deployment of critical decarbonization technologies, as well as to implement a global equimarginal abatement effort through GHG reduction sales and purchases. Technical constraints make the marginal cost of emissions abatement based on currently available technologies very high in the heavy industrial and energy extraction and processing sectors, compared to other Canadian decarbonization options and to the cost of reducing emissions in many other countries. A focus on global (rather than purely national) emission reductions is the most efficient way to address this challenge. While the current phase of the DDPP project focused on identifying national technological pathways, this topic will be key in the next phase of the DDPP's work.

2.6. Near-term priorities

The Canadian deep decarbonization scenario depends on significant technological innovation and deployment. This requires both domestic investment and innovation and global research cooperation and technology spillovers. To remain on the path toward deep decarbonization, increased investment and accelerated research, development, and deployment efforts will be required in the following priority areas:

- Improving post-combustion CCS, for both electricity generation and industrial process applications;
- Development and commercialization of solid oxide fuel cells and other technologies, including pre-combustion capture, that either reduce GHG intensity or reduce the cost of CCS by producing a pure CO₂ waste stream;
- Enhanced transmission grid flexibility and energy storage technologies to allow more electricity generation from intermittent renewables;
- Development and commercialization of cellulosic ethanol and advanced biofuels derived from woody biomass, algae or other feedstocks; and
- Development and commercialization of batteries and hydrogen storage to enable electrification and fuel switching to hydrogen in the transportation sector.

In parallel with efforts to collaborate on the deployment of critical enabling technologies, addressing the significant differential in abatement opportunities and marginal abatement costs across countries and sectors must be an international priority. While challenging to implement, a global equimarginal abatement effort through GHG reduction sales and purchases has the potential to be the most efficient way to achieve the global target while maintaining strong economic growth.

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1. Country profile

1.1. The national context for deep decarbonization and sustainable development

Despite fast growth over the last decade (with an average GDP growth rate of 10% over 2000-2012), China is still a developing country with a low level of economic development. In 2010, its GDP was 5,930 billion US\$, and per capita GDP was just 4,433 US\$. China's has a very significant secondary sector of the economy, which contributed 48.3% to GDP in 2013, but this sector's contribution has declined by 12.5 percentage points since 2000, while the tertiary sector of the economy increased by 12 percentage points. Due to economic and social development, China's level of urbanization has risen from 26.4% in 1990 to 53.7% in 2013. With a 1% increase in urbanization rate, 13 million Chinese inhabitants move to cities every year to pursue a higher standard of living. China is also the most populous country in the world; by the end of 2013, China's population was 1.36 billion, about 20% of the world total.

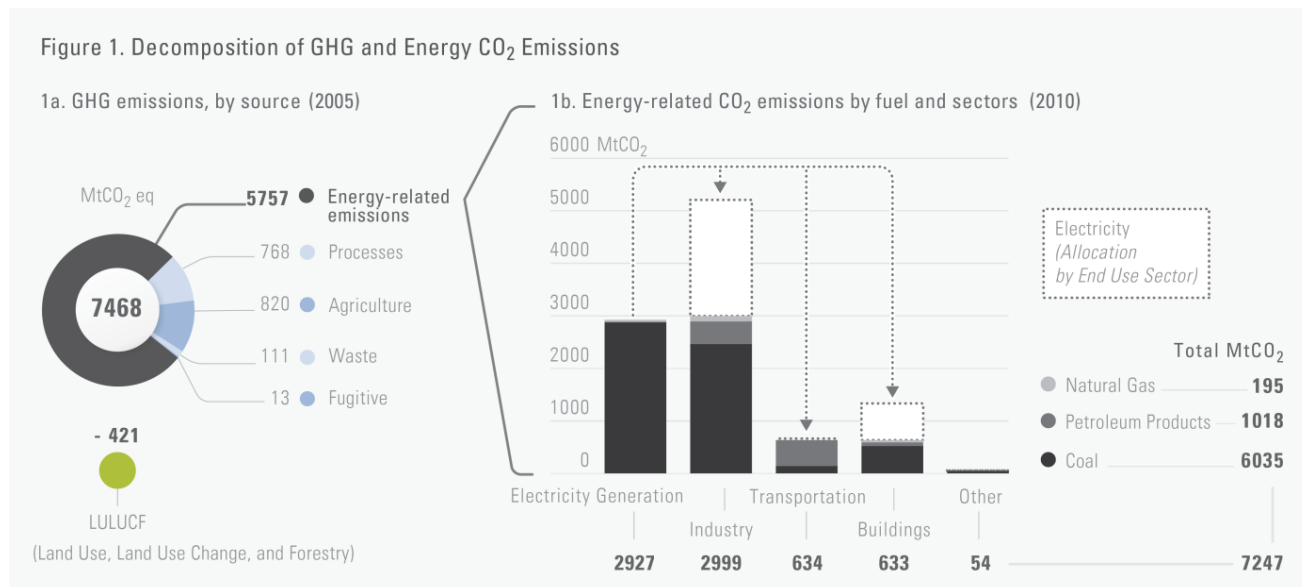
Although China has made remarkable progress, it is under heavy pressure to improve environmental protection due its resource-intensive development. Xi Jinping, China's President, has described the country's recent model of economic development as "unsustainable," not least because pollution is harming lives and livelihoods, particularly in cities. China recognizes the problems created by pollution, both from greenhouse gases (GHGs) that cause climate change and from other gases and particles. China is also facing growing constraints due to the limited availability of natural resources other than coal. China's leadership has signaled its intention to accelerate the transformation of China's growth model, to make China an innovative country, and to promote more efficient, equal and, sustainable economic development.

1.2. GHG emissions: current levels, drivers, and past trends

According to "Second National Communication on Climate Change" in 2005, China's total GHG emissions were approximately 7.5 Gt CO₂eq of which carbon dioxide accounted for 80%, methane for 13%, nitrous oxide for 5%, and fluorinated gases for 2%. The total net GHG removals through land use change and forestry was about 421 Mt CO₂ eq.

Of total GHG emissions, energy activities represent 77% in 2010 (7.2 GtCO₂) with direct emissions from electricity, industry, transportation, and buildings at 2,929 MtCO₂, 2,999 MtCO₂, 634 MtCO₂, and 633

MtCO₂ respectively (Figure 1a). The major emitting energy activities are the coal-intensive power generation and industrial sectors (Figure 1b). Notably, as the main sector driving economic growth, the industry sector accounts for 68% of total final energy consumption and almost 71% of total energy-related CO₂ emissions in 2010. This is essentially from a few energy-intensive industries, which consume about 50% of energy use in the industry sector (iron and steel, cement, synthesis ammonia, and ethylene production).



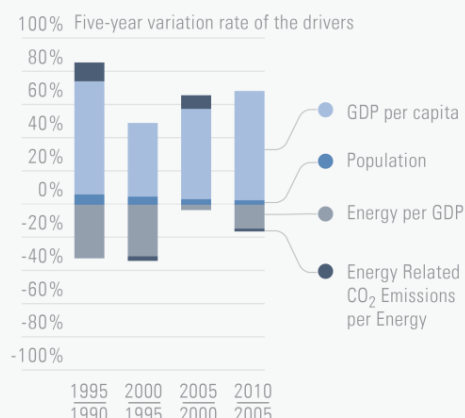
Source: Second National Communication on Climate Change (2005)

The growth of China's economy has been the major driver of increasing emissions in the past three decades. The structure of this growth has had opposite dynamics over the last decades with direct consequences on emissions. During the first ten years of China's openness policies (1980-1990), structural change favored lower-emission activities and helped to decouple emissions from aggregate growth. This was followed by a rapid process of industrialization, which saw a double digit growth rate in the heavy industries. This industrialization accelerated growth in emissions faster than GDP, though this was tempered in the 11th Five-Year Plan. This shows the crucial impact of economic structure on China's future emission rates.

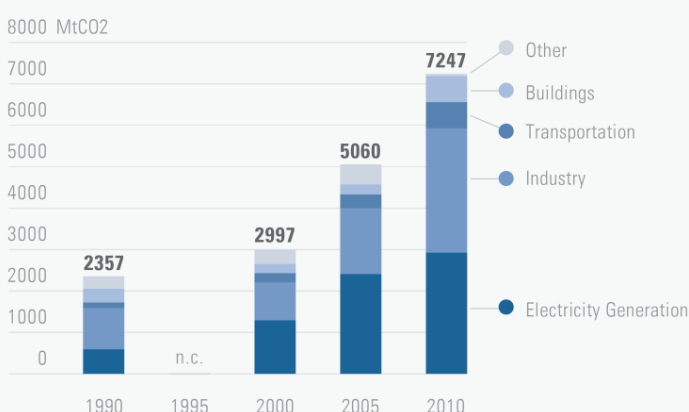
Coal has dominated China's energy mix over the past decades, supporting economic growth with a high carbon intensity fuel. The only factor that has significantly contributed to slow the rate of growth in emissions has been energy efficiency, as seen in the reduction of China's energy intensity per unit of GDP (Figure 2a). Electricity generation has been the major driver of the increase in carbon emissions, since the growing needs for electricity have been satisfied by the fast development of coal-based power units.

Figure 2. Decomposition of historical energy-related CO₂ Emissions, 1990 to 2010

2a. Energy-related CO₂ emissions drivers



2b. Energy-related CO₂ emissions by sectors



Although China is now the country with the highest emission levels, current and historical per capita emissions are still lower than IPCC Annex I country levels, whether on an annual (5.4tCO₂e/cap) or cumulative (95 tCO₂e/cap over 1850-2009) basis. Given these recent trends, continuously increasing emissions can be expected in the future with business as usual economic growth.

2. National deep decarbonization pathways

2.1. Illustrative deep decarbonization pathway

2.1.1. High-level characterization

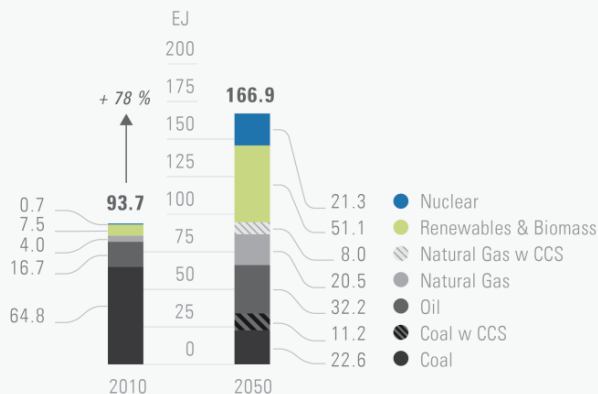
The illustrative deep decarbonization pathway combines an acceleration of the evolution of economic structure, reductions in energy intensity and the promotion of non-fossil fuel energy to control emissions in a context of continued economic growth. GDP per capita is assumed to increase by more than 6 times from 2010 to 2050 to satisfy development needs, but energy trends are significantly decoupled from this growth with an increase of primary and final energy of 78% (from 93.7 EJ in 2010 to 166.9 EJ in 2050) and 71% (from 66.9 EJ in 2010 to 114.4 EJ in 2050) respectively (Figure 3). This increase is mainly triggered by the industrial sector (+28%), buildings sector (+141%), and transportation sector (+204%), along with changes in economic structure, an increase in urbanization rate, and the completion of the industrialization process. In particular, the share of coal in primary energy consumption falls to 20% in 2050, while the use of natural gas and non-fossil fuels increase, contributing 17% and 43% respectively.

Table 1. The development indicators and energy service demand drivers in China

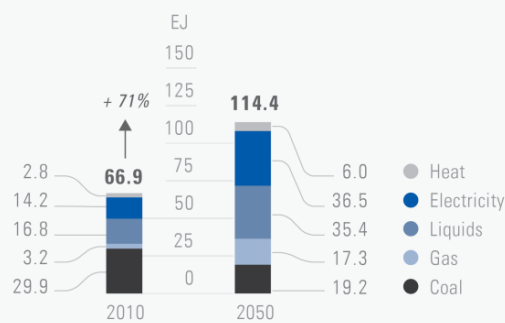
	2010	2020	2030	2040	2050
Population [Millions]	1360	1433	1453	1435	1385
GDP per capita [\$ /capita, 2010 price]	4455	8708	14666	20945	27789

Figure 3. Energy Pathways, by source

3a. Primary Energy



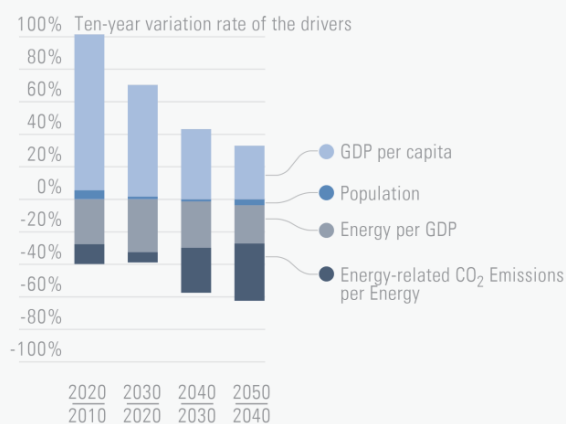
3b. Final Energy



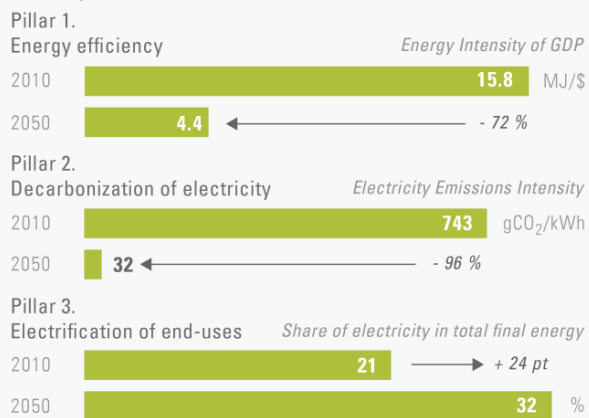
In the illustrative deep decarbonization pathway, energy-related CO₂ emissions decrease by 34%, from 7.25 GtCO₂ in 2010 to 4.77 GtCO₂ in 2050, essentially due to a decrease of both the primary energy per unit of GDP by 73% and of energy-related CO₂ emissions per unit of energy by 61% (Figure 4a). The former is largely explained by structural change with a large decrease of the share of energy-intensive sectors of the economy and improvement of economy-wide energy efficiency. The latter mainly comes from decarbonizing the power sector and the electrification of end-uses (from 21% in 2010 to 32% 2050) while increasing living standards and modernizing energy use patterns (Figure 4b). The application of CCS technologies in power generation and the industrial sector is also a crucial feature of this illustrative pathway, contributing 1.3 GtCO₂ and 0.8 GtCO₂ respectively.

Figure 4. Energy-related CO₂ Emissions Drivers, 2010 to 2050

4a. Energy-related CO₂ emissions drivers

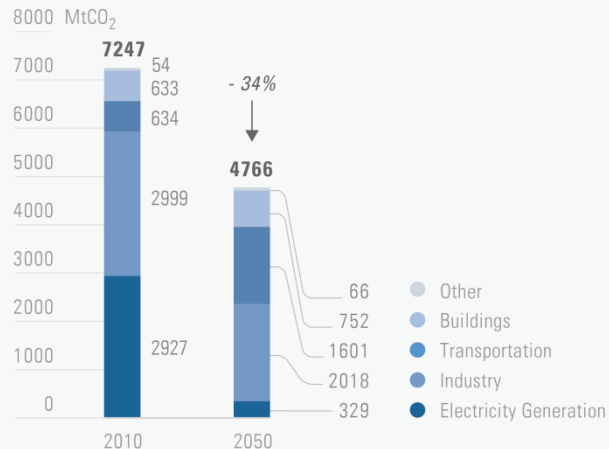


4b. The pillars of decarbonization



At the sectoral level, the industry sector emissions remain the largest, but buildings and transportation increase in share, from 17% in 2010 to 49% of 2050 emissions (Figure 5).

Figure 5. Energy-related CO₂ Emissions Pathway, by Sector, 2010 to 2050



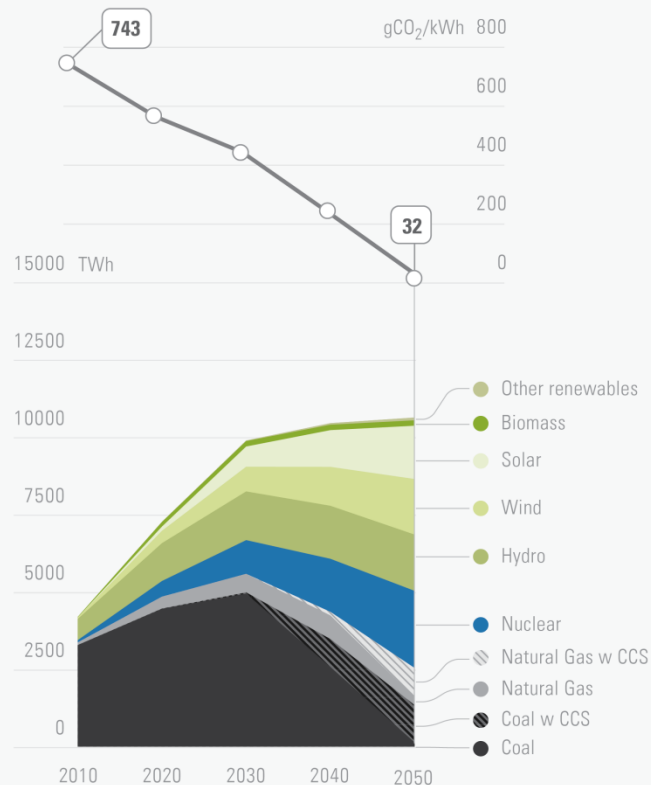
2.1.2. Sectoral characterization

Power sector

Electrification is an important indicator of economic and social development, and electricity consumption in the illustrative deep decarbonization scenario is projected to reach 10,143 TWh in 2050, or 7,300 kWh per capita (around 2.5 times the 2010 level).

Since thermal power, especially from coal, is an important source of local pollutants and GHGs, the decarbonization of power sector is of significance for the achievement of low-carbon development. The carbon emission intensity of power generation in 2050 will decrease from 743 gCO₂/kwh in 2010 to 32 gCO₂/kwh in 2050 (Figure 6a). This is permitted by the large-scale use of nuclear (which reaches 25% of electricity production in 2050), intermittent renewables (installed capacity of wind and solar respectively equal 900 GW and 1,000 GW in 2050, contributing 18% and 17% of electricity generation respectively), and hydro (which accounts for an additional 18%). Fossil-fuel power generation units still represent 24% of electricity generation in 2050 (notably because natural gas power generation technologies act as an important back-up technology for intermittent generation technologies). Fossil-based emissions are reduced by a large percentage due to the deployment of efficient technology options (notably, all new coal power plants after 2020 will be supercritical, ultra- supercritical, or IGCC power generation technologies) and CCS facilities on 90% of coal power plants and 80% of natural gas power plants. This diffusion supposes that CCS technology will become commercialized after 2030.

Figure 6. Energy Supply Pathway for Electricity Generation, by Source



Industry

Energy efficiency could be improved by a large degree through technological innovation in industrial sectors²⁰. This would permit a reduction of energy consumption per value added of the industry sector by 74% from 2010 to 2050, limiting the rise of final energy consumption to 28% (from 46 EJ in 2010 to 58 EJ in 2050). By promoting the transformation of coal-fired boilers to gas-fired boilers and enhancing the use of electricity, the illustrative pathway reduces the share of coal from 56% in 2010 to 30% in 2050, while increasing that of gas and electricity in final energy use. Since it's hard to change feed composition in some industries, it is not expected that further significant changes in energy structure are possible.

In addition, structural changes in industry could be achieved through developing strategic industries, controlling overcapacity of main industry outputs, and eliminating backward production capacity. Notably, many high-energy-intensive industry sectors will experience a slower growth, and the output of some high-energy-intensive industry products (notably, cement and crude steel) are anticipated peak by 2020.

²⁰ E.g., replacing converter with electric furnace or using waste heat of low temperature flue gas in sintering and pelletizing in iron and steel industry and replacing vertical shaft kilns with new dry production process and enforcing low-temperature cogeneration in cement industry.

These different options lead a 57% decrease of CO₂ emissions in the industry sector, particularly due to the contribution of CCS technology. If CCS is deployed appropriately on a commercialized scale after 2030 in key industry sectors, it is expected to sequester 28% of total CO₂ emissions in the industry sector in 2050 (Figure 7a).

Buildings

Total floor area will continue to grow (from 45.2 billion m² in 2010 to 80.3 billion m² in 2050), and the urban and rural residential building floor areas per capita will increase (reaching around 36 m² and 47 m² respectively) in parallel with the process of urbanization. This pushes total energy consumption up by 140% (from 11 EJ to 27 EJ) in line with a 33% increase of energy consumption per capita. Energy efficiency measures play an important role in limiting this rise of energy demand, where performance improves by 25%, 22% and 10% from 2010 to 2050 for commercial, urban residential and rural residential units respectively and appliance energy efficiency increases (e.g. 66% and 75% for regular and central air conditioners).

The proportion of coal in energy use decreases gradually (from 39% in 2010 to 5% in 2050), as electricity and gas rise (reaching 50.5% and 33.2% in 2050 respectively). This triggers a decrease of the average carbon emission intensity from 119.8 gCO₂/MJ in 2010 to 32.7 gCO₂/MJ in 2050. That ensures a 34% lower emissions level in 2050 compared to 2010 (Figure 7b).

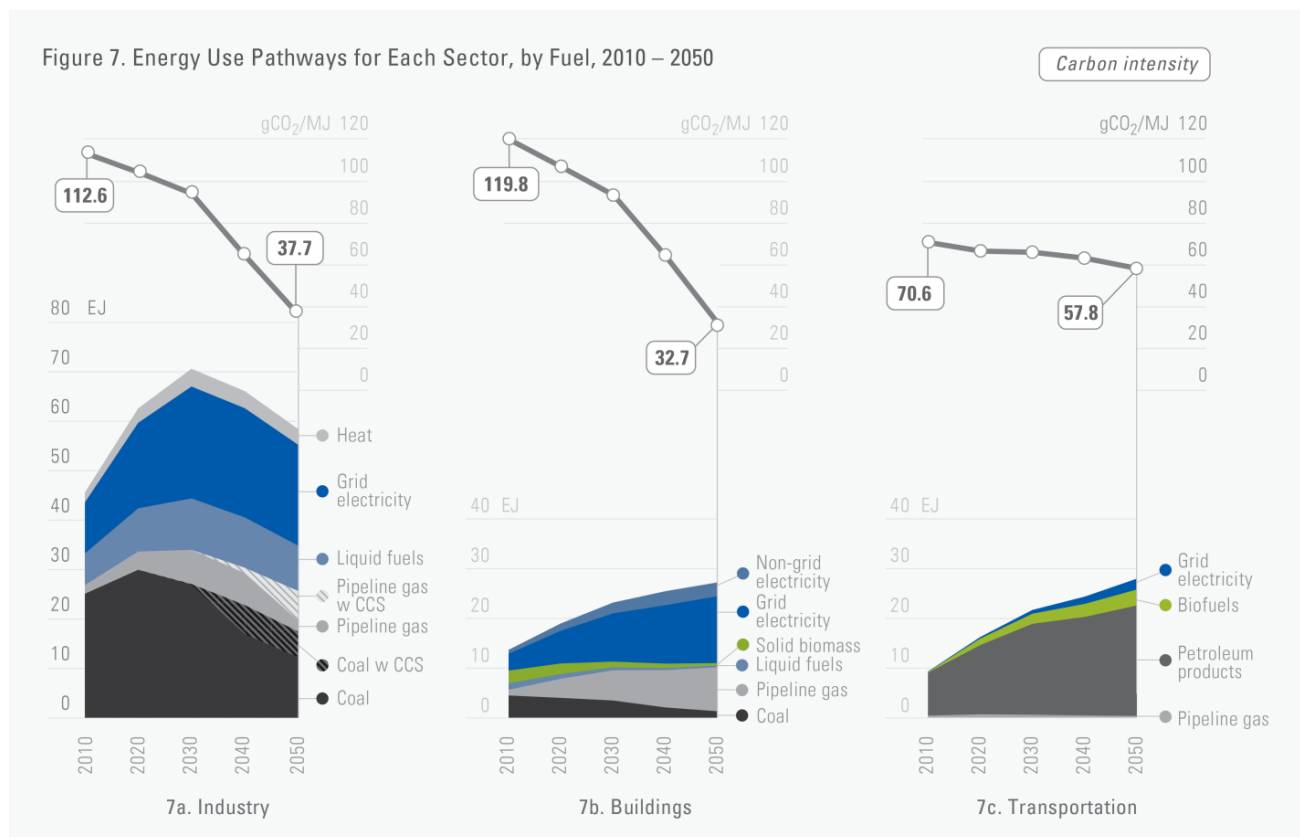
Transport

Pushed by rising mobility demand along with wealth increase (a ten-fold increase of kilometers per capita to reach 20,000 km/cap in 2050), energy consumption in transport will almost triple, from 9.3 EJ in 2010 to 28.1 EJ in 2050, representing a rising share of total energy consumption, from 14% in 2010 to 24% in 2050. A partial decoupling will allow the carbon emissions to rise by only 149% (from 652 MtCO₂ in 2010 to 1,621 MtCO₂ in 2050) due to transport mode shifts, an increase of vehicle fuel economy, and the promotion of electricity and biofuel use (Figure 7c).

The primary mode shift encompasses a transition from on-road to off-road modes of transport, where rail and water transport grow over time. In freight transportation, road transportation is limited to 32% in 2050, water transportation maintains the highest share (about 42% in 2050) and railway grows to 24%. Within the passenger transportation, road transportation will be kept at 35% in 2050 and railway transportation will remain the main transportation mode (45% of total passenger mobility in 2050) notably due to the development of high-speed railway and rail-based transit systems in cities (attaining 50,000 km by 2050, 36 times higher than in 2010).

For the on-road transportation, improvement of transportation management is an important option to control the rapid growth of demand. An increase in fuel economy is also crucial, with a 70% improvement of light duty vehicles' energy intensity and the deployment of high efficiency diesel vehicles in freight transportation. And, even more importantly, the share of gasoline and diesel vehicles sold significantly decreases by 2050 because of the adoption of alternative fuel vehicles. In intra-city transportation low-carbon vehicles gradually play a more dominant role with the adoption of pure electric vehicles, plug-in hybrid electric vehicle (PHEV), biofuels and fuel-cell vehicles (FCV). A reduction in gasoline and diesel use also occurs because of railway electrification, which will play a dominant role in the railway energy mix by 2050.

Figure 7. Energy Use Pathways for Each Sector, by Fuel, 2010 – 2050



Note: Carbon intensity shown in Figure 7 for each sector includes both direct end-use emissions and indirect emissions related to electricity production.

2.2. Assumptions

Emphasizing technology development and innovation is vital for the achievement of the Illustrative Deep Decarbonization Pathway. Sufficient input on technology R&D and incentives for technology deployment are necessary. In order to achieve the decarbonization pathway, significant technological and economic effort needs to be made in different sectors, and low-carbon technologies must be distributed across the country. The most important low-carbon options, especially energy saving technologies in end use sectors, in the illustrative pathway are discussed below:

- Transport: high-efficiency diesel vehicle or gasoline cars, electricity vehicles, plug-in hybrid vehicles, and fuel cell vehicles in passenger transport; a 30% improvement of fuel economy for conventional high duty vehicles; fully electrified rail-based transit for both long-distance and short-distance by 2050.
- Buildings: increasing energy efficiency for both existing and new buildings through innovative technologies (like advanced, low-carbon buildings, which will increase their share in urban regions from 2% in 2012 to 50% in 2020 and help to reduce the heating and cooling demand); to substitute for coal boilers, the application of advanced heating facilities, such as ground source heat pumps and decentralized solar heating systems as well as natural gas boilers and CHP for centralized heating; development of high-energy-efficiency cooling systems, lighting system and appliances; the large-scale use of renewable energy, such as solar water heaters in residential buildings.
- Industry: high-efficiency waste heat recycling technologies, high efficiency boilers and motors across all sectors; energy saving technologies in high-energy-intensive industries permitting a

fall from 2010 to 2050 of the energy consumption per unit of product output of crude steel, cement, ammonia and ethylene by 48%, 32%, 26%, and 26%, respectively.

- Electricity generation: an increased reliance on non-fossil fuel power generation technologies is the major contributor to the reduction in the carbon intensity of electricity generation. Hydro power production of 500 GW approaches its potential by 2050; wind power reaches 1,000 GW in 2050 (70% off-shore); solar energy power generation experiences a fast development, where solar PV and solar thermal reach approximately 1,000GW and 150GW respectively in 2050; biomass-fired power generation and other renewables will be limited due to resource constraints and high relative cost; nuclear power generation technologies will be developed (due to learning from foreign advanced technologies and domestic research and demonstration) and exceed 300GW by 2050.
- CCS technologies will be another important technology and will be deployed in both the power and industry sectors at scale in 2050. It is expected that CCS is developed and demonstrated from 2020 and deployed at a commercialized scale from 2030. Both CO₂ utilization and geologic storage have great potential compared to the amount of CO₂ captured in the illustrative pathway (0.1 to 1 billion ton per year for the former, more than 1 billion ton annually for the latter).

2.3. Alternative pathways and pathway robustness

In order to achieve the illustrative decarbonization pathway, there are key measures that must deviate significantly from current trends. This includes a low-carbon transition in electricity generation even as electricity demand increases faster than gains in end-use energy efficiency. The former dimension depends on the development and deployment of non-fossil fuel power generation; the improvement in energy efficiency concerns key industrial sectors, vehicles, urban buildings, and residential appliances. There are still uncertainties with some key measures and technologies that might affect the achievement of this pathway, such as the integration of intermittent renewable power into the power system, application of CCS facilities, supply of natural gases, and penetration of electric vehicles.

In case the magnitude of the measures discussed above is less than assumed, some alternative approaches could be envisioned, leading to different emissions scenarios. For example, the proportion of non-fossil fuel electricity is 41% in 2050 in the illustrative deep decarbonization pathway, of which nuclear power represents a share of 31%. However, if the nuclear development is hindered in the future, coal power (with CCS) or renewable power might grow in its place. Increase reliance on wind and solar energy in the power sector is possible, though it largely depends on the possibility of developing new energy storage solutions or enough natural gas power units to manage the resource intermittency.

2.4. Additional measures and deeper pathways

Dematerialization

A large portion of China's emissions are linked to the process of urbanization since large quantities of construction materials will be required to build and maintain urban infrastructure, especially cement and steel. Measures to decrease the demolition of buildings and transportation infrastructures will contribute to further deeper decarbonization by combining a reduction of material consumption intensity and reuse of waste construction materials.

Technology innovation

The early deployment of key mitigation technologies can help China follow a deeper decarbonization pathway that will also contribute to the growth of China's economy in other ways. Notably, the large scale of the Chinese market, production economies of scale, and learning-by-doing can help accelerate cost reductions and diffusion of low-carbon energy options, in line with China's development strategy to grow "strategic emerging industries."

Structural change

China's growth has been characterized by a high saving and investment rate in the past three decades. In the future, China will maintain its growth rate around 7%, reduce its saving and investment rate, and increase the share of consumption in its GDP. To maintain the growth rate at a relatively high level while reducing the investment rate, China needs to increase the productivity of its investment. Deep decarbonization strategies can contribute to this gain in productivity through: 1) shifting the structure of the economy towards less capital intensive sectors (e.g. from industrial sectors to service sectors); 2) improving the efficiency of capital investment to produce output, especially through energy saving; and 3) increase the productivity of other factors, especially labor and energy.

2.5. Challenges, opportunities, and enabling conditions

China's future development is the source of much uncertainty when examining potential emission reduction pathways.

First, the level of economic growth is largely uncertain. The average Chinese growth rate has been a little more than 10% in the past twenty years. The 18th CPC National Congress has projected that the GDP growth rate will be around 7.2% in the next decade. This reduction of 3 to 4 percentage points is more than the typical growth rate of developed countries. China's economy will continue to develop at a relatively high speed, varying from 5% to 10%. This expected variation will have a significant impact on the actual level of energy demand.

The second aspect is future adjustments to industrial structure and changes in the mode of development. China's energy consumption per unit of GDP is twice the average level of the world, which means there is a significant opportunity for reductions in energy intensity. However, the decline cannot depend on incremental technology change, because China's power plants are newly-built with efficient supercritical and ultra-supercritical units, and for energy-intensive industries the efficiency gap compared to developed countries is low (10%-20%). Therefore, the focal point in China is to adjust the industrial structure and change the mode of development towards less heavy and chemical industry as well as less production of energy-consuming products like steel and cement. Nevertheless, the issues of how to adjust and how to identify the degree and intensity of the adjustment have great uncertainties.

The third aspect is urbanization, triggered by the demand of social development. The demand for steel and cement is very large in the process of urbanization. According to estimates, there may be an increase of 1 percentage point in the urbanization rate each year.

Finally, exports are an important factor in the economy, production of which significantly contributes to total emissions. Currently, 25% of energy is used for the production of export products in China, and given that adjustments of the structure of exports is not an easy task, manufacturing exports (and

associated emissions) are expected to remain important in the long run. This area of potential emission reductions would benefit from further investigation.

2.6. Near-term priorities

The reduction of CO₂ emissions is not only a response to climate change, but it also addresses the urgent demand of developing the national economy. If the coordination works well, the strategy of climate change mitigation and sustainable development will lead to a win-win situation.

Change the concept of development

The guiding ideology and the concept of development must be changed among all cadres. The central government should understand the trade-off between GDP growth highly dependent on resource industry and the cost paid for resources losses. The central and western regions need to be redesigned and readjusted so as to draw more attention to climate change. At the same time, the evaluation mechanism of officials must be revised. The promotion of a position should not only rely on the growth rate of GDP but should also look at a comprehensive analysis of gain and loss.

Deepen the energy reform

The reform of the energy sector needs to be promoted, including the reform of the price system and fiscal taxation system. Although China's energy price remains high in developing countries, the price structure and pricing system is very reasonable, especially that of coal and electricity. The current price of coal and electricity does not include the environmental cost, and so the exploitation of resources does great damage to the environment. The reform of resource taxes and the proposal of a carbon tax must be considered in energy policy, along with the price system and fiscal and financial field.

Pricing Carbon

China has established 7 pilot emissions trading schemes (ETSs) at provincial and city levels with a view to establish a national ETS around 2020. The future development of China's ETS should build upon the experience gained in regional pilots and resemble the approach taken in the EU ETS and the Australian and Californian schemes. A careful design is key for the success of China's ETS, especially in the electricity sector, as is practical and reliable company-level measurements, reporting, and verification of emissions. An early stage of harmonization with design of other international ETSs will facilitate the linkage with these ETSs in the future.

Reduce coal consumption

Methods for reducing the use of coal have many synergistic effects. The main way to improve the domestic environment is to reduce coal mining. Substantial coal mining not only consumes a large amount of water, but it also leads to slag penetration and deposition, resulting in the serious pollution of groundwater resources. In addition, coal mining causes the collapse of areas that have been mined. The area of subsidence in China has reached 10,000 km². Furthermore, conventional pollutants, such as sulfur dioxide, nitrogen oxides, and dust (including the thick fog and haze weather in Beijing and Tianjin) are partly caused by burning coal. Therefore, the reduction of coal consumption is essential for China to improve domestic environmental quality.

France

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1. Country profile

1.1. The national context for deep decarbonization and sustainable development

France has a low endowment of domestic fossil resources (domestic production represents less than 2% of primary consumption) and energy imports, mostly oil and gas, are a substantial source of total external trade deficit (these imports represent around 70 billion US\$ (2012), a deficit close to the total external trade deficit in 2012). Faced with this situation, France has developed a specific energy security strategy resorting notably to the launching of an important nuclear energy program in the 1970s. Today, France is in particular equipped with 63 GWe of installed nuclear capacity, which supplies 77% of the electricity produced and 24% of total final energy. As a result, France is today already a relatively low energy consumption country (2.6 toe/cap) and has GHG emission intensities at the lowest end of OECD countries (5.7 tCO₂/cap).

In the French policy debate, decarbonization was first introduced in 2005 with the adoption of a Factor 4 emission reduction target for 2050, compared with 1990. More recently the discussion on carbon taxation has given rise to several commissions and reports (Quinet 2009, Quinet 2013; Rocard 2009). The experts who drafted the Quinet report in 2009 recommended a carbon tax set at a rate of €32 per ton of CO₂ in 2010, rising to €200 (150-350) in 2050 as the implicit value of the constraints for reducing CO₂ emissions entailed by the targets for 2020 and 2050. In 2009, France was therefore on the verge of adopting a carbon tax for diffuse emissions (transport and building) that, combined with the ETS for large industries and electricity, would have provided a comprehensive system of economic incentives through carbon prices in all sectors. However, the constitutional council dismissed the law on the eve of its enforcement, while it had already been voted upon by the parliament. More recently, decarbonization has been an important component of the Energy Transition, which has been set as a priority by President François Hollande. To investigate this issue, the National Debate on Energy Transition took place in 2013 as a deliberative process between different groups of stakeholders (NGOs, Trade Unions, Business, MPs, Mayors) aiming at identifying and assessing the consequences of different scenarios.

Three policy commitments structure the decarbonization scenarios (or “energy transition trajectories”) for France:

- European targets to be translated into domestic objectives: EU 3x20 for 2020 targets (20% reduction in EU GHG from 1990 levels; raising the share of EU energy consumption produced from renewable resources to 20%; 20% improvement in the EU's energy efficiency)
- Factor 4 reduction of emissions in 2050 compared to 1990 (-75%)
- The reduction of the share of nuclear in power generation, down to 50% by 2025, target set in 2012 by President François Hollande

Key challenges for the French economy and society that are directly or indirectly related to the purpose of decarbonization include:

- i. the rebuild of industrial competitiveness to counterbalance the de-industrialization observed over the last 40 years (industry's share in the economy has been steadily falling during the last 30 years from 25% in the 1980s to 19% in the 2010s), and the 2.6 million fall of employment in industry.
- ii. the reduction of energy poverty, which is has become a crucial issue as, in 2010, more than 6% of the French population is below the threshold defining fuel poverty (expenditures on fuel and heating represent more than 10% of income); in particular, low-income households living mostly in rural areas or in small towns spend on average 15% of their income on energy, for housing and transport.
- iii. a long term effort in directing land and urban planning towards more sustainable patterns through ambitious infrastructure deployment. This is in particular crucial to control mobility needs in a relatively low-density country.
- iv. the highly controversial issue of nuclear energy beyond 2025. France's nuclear power plants are, on average, nearly 30-year old and an intense debate concerns the choice between upgrading them with new nuclear plants, extending their service life in some cases, or replacing them altogether with other technologies.

1.2. GHG emissions: current levels, drivers, and past trends

GHG emissions in France amounted to 549MtCO₂eq and 392MtCO₂ in 1990 (excluding LULUCF). In 2010 they were down to 501MtCO₂eq and 366MtCO₂, respectively a 9% and 7% decrease. LULUCF induce negative emissions (-24MtCO₂eq in 1990 and -37MtCO₂eq in 2010). Between 70% and 75% of the GHG emissions are CO₂ emissions (Figure 1 and Figure 2).

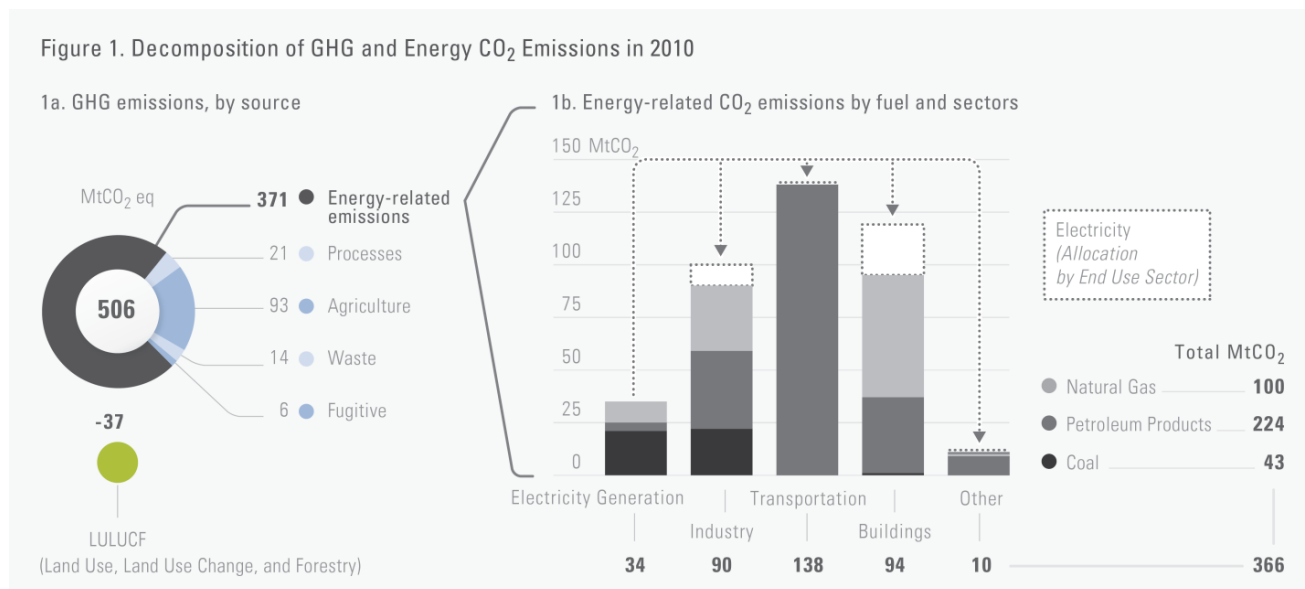
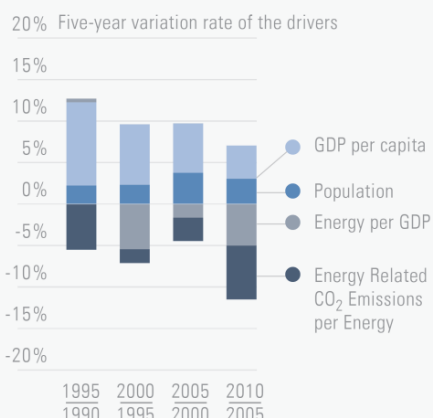
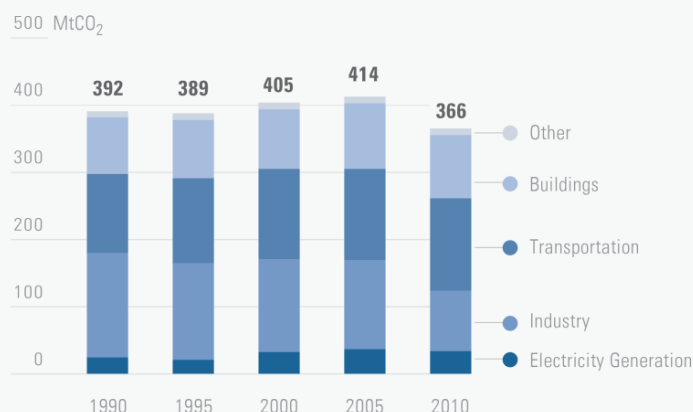


Figure 2. Decomposition of historical energy-related CO₂ Emissions, 1990 to 2010

2a. Energy-related CO₂ emissions drivers



2b. Energy-related CO₂ emissions by sectors



Transport

The main sector for GHG emissions is the transport sector with 138MtCO_e representing 27% of GHG emissions and 38% of CO₂ emissions (excluding LULUCF). The 17% increase since 1990 has been mostly triggered by road transport, which represents almost all the emissions from this sector.

In the passenger transport sector, the rise of mobility, notably driven by a rise of the distance per capita, has been the main source of sectoral emissions increases, notably because modal breakdown has remained stable at an 80% share for individual cars. Energy efficiency improvements have also been significant, particularly in the last decade, but not sufficient to compensate for the rise of activity levels.

In the freight transport sector, the rise of emissions has been driven by a continuous rise of activity levels; indeed, demand for freight transport has increased very fast over the 1990-2008 period (+57%), at an even faster rate than GDP, and the partial decoupling observed since the 2008 economic crisis has only moderated this rise without reversing it. The evolution of the modal breakdown has also played an important role in the increase of carbon emissions, with a continuous decline of rail share (from 27% in 1984 to 8% in 2010) and the domination of road (84% of freight transport in 2010) that were only partially compensated by energy efficiency. According to the government's targets, rail and water transport modal share has to reach 25% in 2022 compared to 14% in 2007.

Buildings

The residential and tertiary sector represents 19% of GHG emissions, and its increase has been driven by demographic trends and a steady increase in the per capita surface. Important decarbonization of the energy consumption happened in the 1980s because of the electrification associated with the nuclear program, and nowadays electricity is one of the main carriers used for heating, which is a French peculiarity. Energy efficiency improvements developed during the 1980s and have been reinforced between 2000 and 2010 notably thanks to the implementation of successive thermal regulations for new buildings and to the introduction of fiscal incentives for thermal retrofitting.

Industry

Industry represented 18% of GHG emissions in 2010, a 42% fall since 1990, half of it being due to the drop of industrial production over the last three years. The main drivers for the significant decrease in emissions between 1990 and 2010 are the overall decarbonization of the energy used in industry and further improvements in energy efficiency, notably triggered by the European Emission Trading Scheme. In particular, structural evolutions have gone towards a decrease of energy-intensive industries (e.g. -17% and -27% for steel and cement production respectively), and technical progress has permitted significant reductions of the CO₂ content of production (e.g. the diffusion of electric arc furnace for steel production driving the emission rate from 1.78tCO₂/t steel in 1990 to 1.32tCO₂/t steel in 2010).

Agriculture

Agriculture represents 18% of total GHG emissions, N₂O, and methane being major contributors (51% and 41% respectively) while CO₂ from energy consumption represents only 8%. Major sources of emissions include land fertilization (46%) and enteric fermentation (27%). Between 1990 and 2010 GHG emissions have decreased by 8%, particularly because of the decrease in mineral fertilizing uses, in milk production intensification and in the size of cow livestock.

Power

France is characterized by low emissions in the power sector because of the contribution of nuclear (77%) and hydro (11%) energies. On average, current emissions in the power sector amount to 62 gCO₂/kWh; this is to be compared with the European average 347 gCO₂/kWh. However, due to the weight of nuclear, renewable electricity (excluding hydro) currently represents only 2% of electricity production.

2. National deep decarbonization pathways

2.1. Illustrative deep decarbonization pathway

2.1.1. High-level characterization

The assessment of the Illustrative Deep Decarbonization Pathway for France is based on the results obtained with the IMACLIM-France model, developed at CIRED.²¹ This Illustrative Deep Decarbonization Pathway combines an overall ambitious energy efficiency improvement program and a diversification of low-carbon energy carriers mobilizing electricity penetration, bioenergy and renewables, or waste heat.

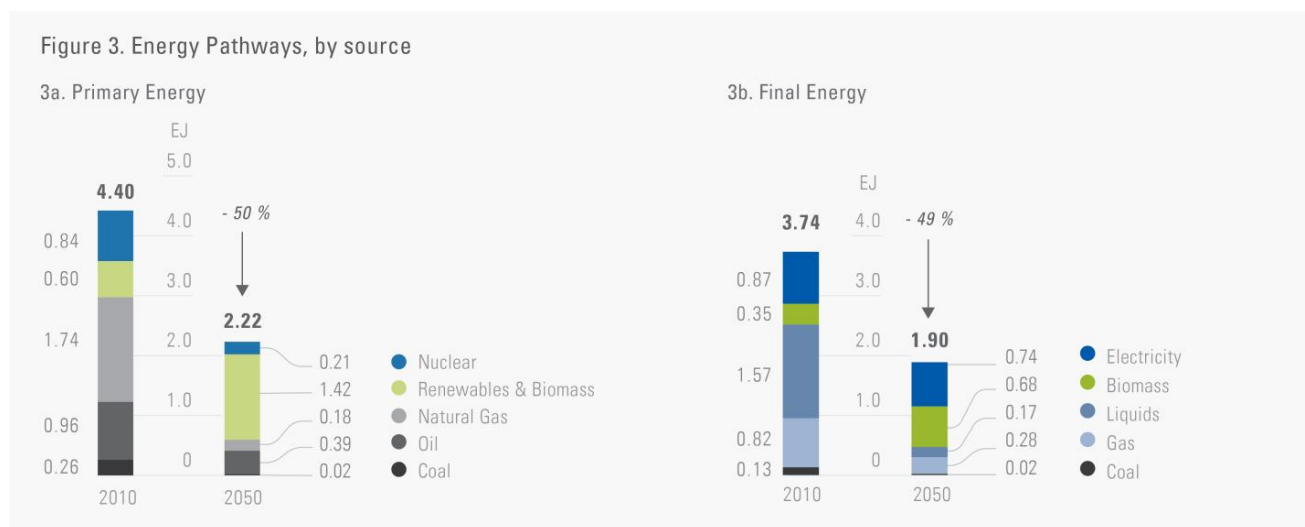
Table1. The development indicators and energy service demand drivers in France

	2010	2020	2030	2040	2050
Population [Millions]	65	66	69	71	72
GDP per capita [\$/capita]	33400	39400	45400	52500	61500

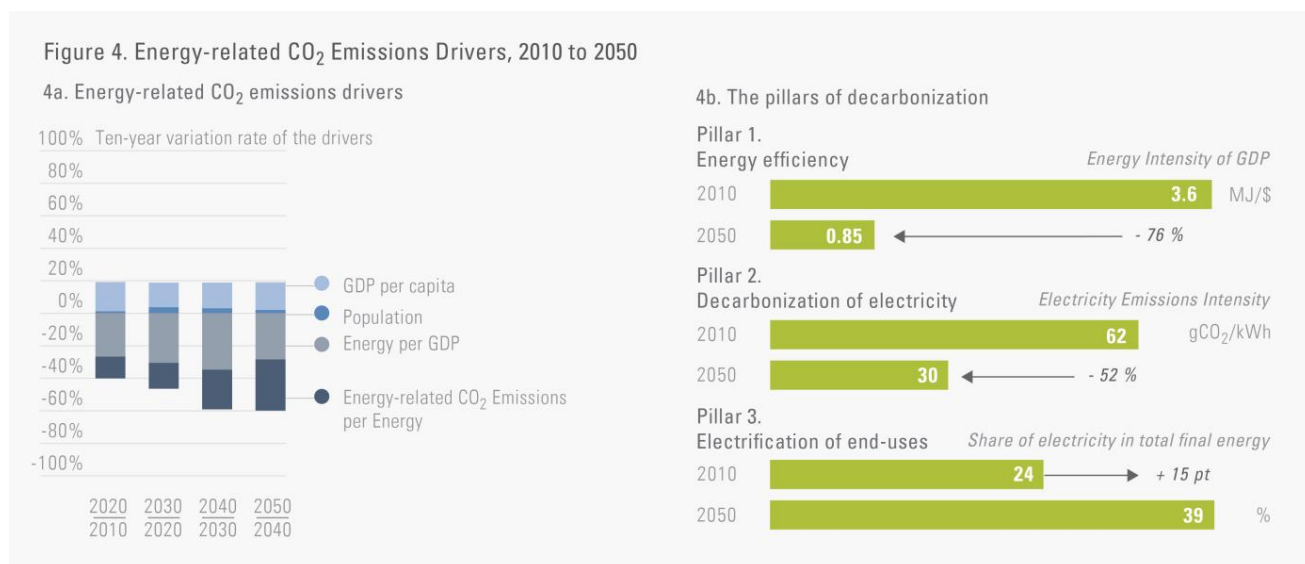
Between 2010 and 2050, economic projections for France anticipate an average annual growth of 1.8%, population is expected to increase by 11%, and the structure of the economy is supposed to be

²¹ For more information on the IMACLIM modelling platform, see <http://www.imaclim.centre-cired.fr/?lang=en>

stabilized during the next decades. The deep efficiency measures would reduce final energy consumption by nearly 50 percent in 2050 compared to 2010, and electricity, although decreasing by 20% in absolute terms, sees its share increasing from 24% to 39% in 2050.

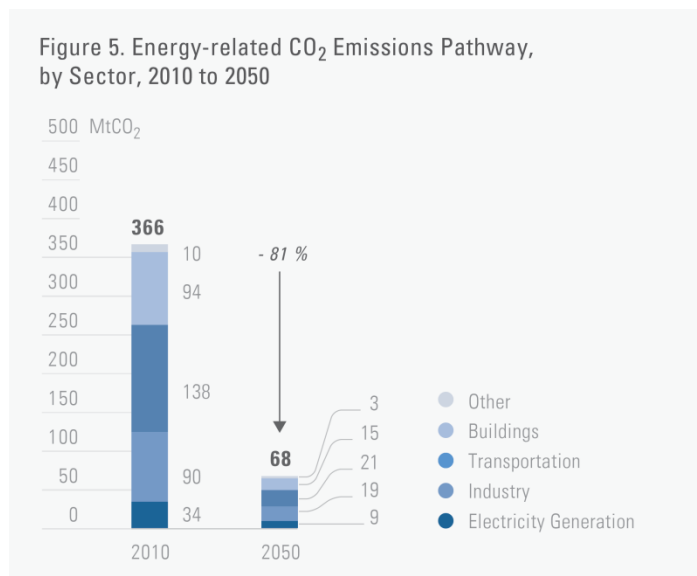


The decrease of the carbon intensity of fuels in end-use sectors is allowed by a division by three of coal consumption and, even more crucial for the transport sector, by a massive substitution of oil by gaseous fuels and biomass. On the supply side, the decrease of the share of nuclear (from 77% in 2010 to 50% in 2025 and 25% in 2050) does not create a rise of carbon emissions because it is accompanied by deep diffusion of renewable electricity—mostly hydro, wind and PV—which increases from 17% in 2010 to 71% in 2050.



Under this pathway, buildings and electricity emissions are deeply decarbonized and the core of emissions remaining in 2050 comes from the transport and industry sectors. As for transport, very important reductions are obtained over the 2010-2050 period, but given the high initial emission level transport still represents 30% of 2050 CO₂ emissions. Industry becomes the second major emission

contributor in 2050 (26%); this is notably because of the assumption of constant structure of the economy which assumes in particular a constant share of energy-intensive industries.



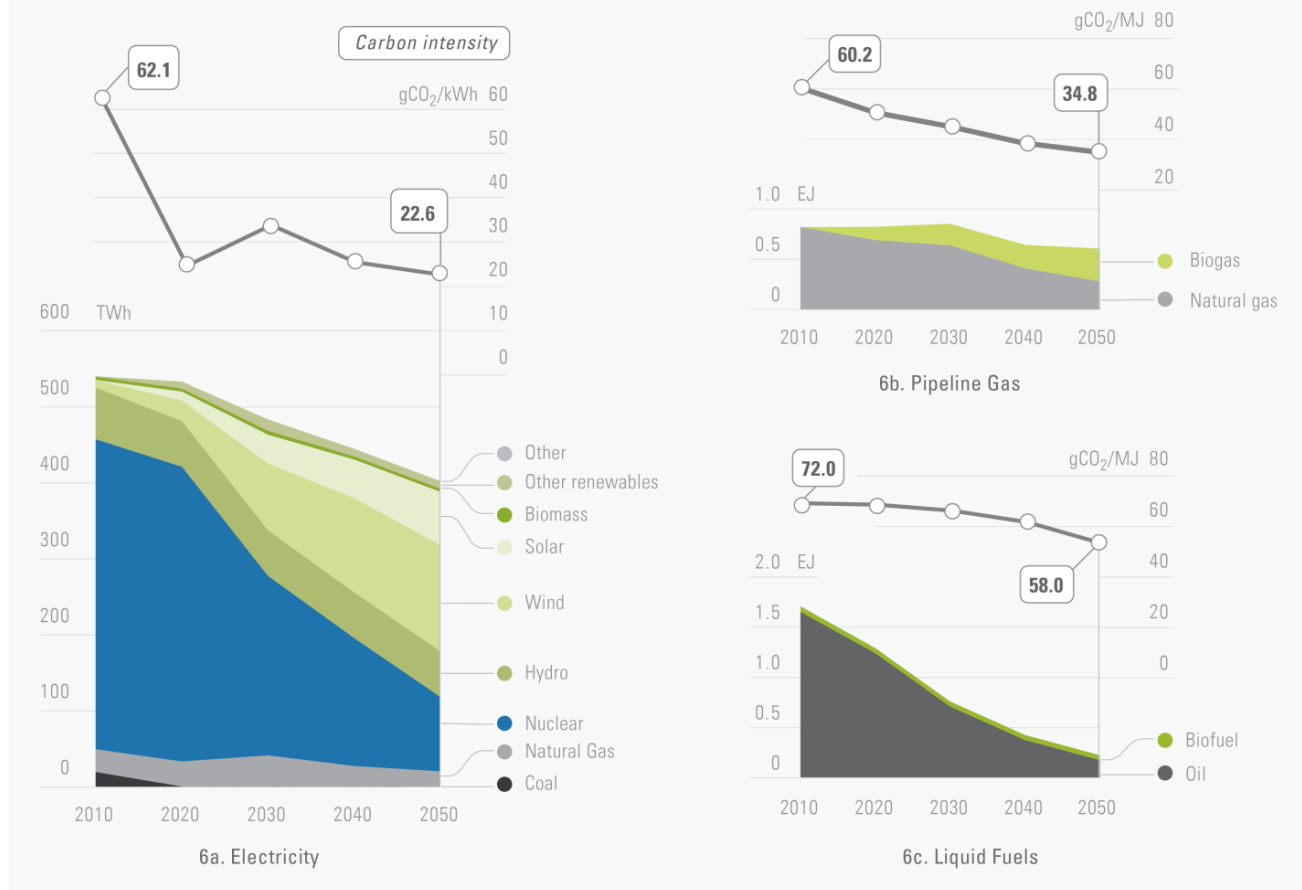
2.1.2. Sectoral characterization

Energy supply

Despite the deep electrification of energy consumption, electricity demand slightly decreases over 2010-2050 as a result of strong efficiency gains in the energy system and a convergence of net exports (30TWh in 2010) to zero by 2050. Power-generation technologies are deeply modified over the period towards a diversification of energy carriers with, in particular, a significant long-term decrease in nuclear share in the mix, a significant increase of renewable energy: in 2050, nuclear represents 25% of production, while wind, photovoltaic, and other non-hydro renewables produce 140TWh, 70TWh and 14TWh respectively. Due to environmental constraints, and in spite of an important technical potential, hydro production is considered to remain stable around 60TWh. Combined-cycle gas turbines are needed to ensure both the transition between the decrease of nuclear and the full deployment of renewables and the balancing of the network with high intermittent sources in the long term.

Other energy carriers are also deeply decarbonized thanks to the diffusion of bioenergy: in 2050, second generation biofuels and biogas represent, respectively, 22% of liquid fuels and 53% of gas.

Figure 6. Energy Supply Pathways, by Resource



Transportation

In the transport sector, total passenger mobility is stabilized over the period notably thanks to a limitation of urban sprawling, combined with the development of new services for the reduction of mobility (remote working) and the deployment of a functionality economy (car sharing systems), which decrease the global demand for mobility particularly at local level. In parallel, a 30% increase of the modal share of collective transport and soft modes alternatives (bicycles) is permitted by i) organizational measures and infrastructure deployment for urban and local mobility and ii) new investments in rail infrastructures and the retrofitting of existing rail infrastructures. On the technology side, motorization types are diversified to adjust to specific mobility segments (hybrid electric and full electric vehicles) and offer more flexibility in uses (range extender and plug-in hybrid electric vehicles). Significant energy efficiency improvements are assumed: +50% for cars (2,5l/100km on average), +20% for buses, +40% for planes.

A decoupling of freight volumes and economic activity driving a stabilization of freight demand in the medium and long term is obtained through better logistics and the development of eco-conception or new technologies such as 3D printing. Rail transport reaches 25% of freight transportation in 2050 and water transport is developed. Concerning trucks, major evolutions are energy efficiency improvements (reaching 30% in 2050) and the switch to natural gas.

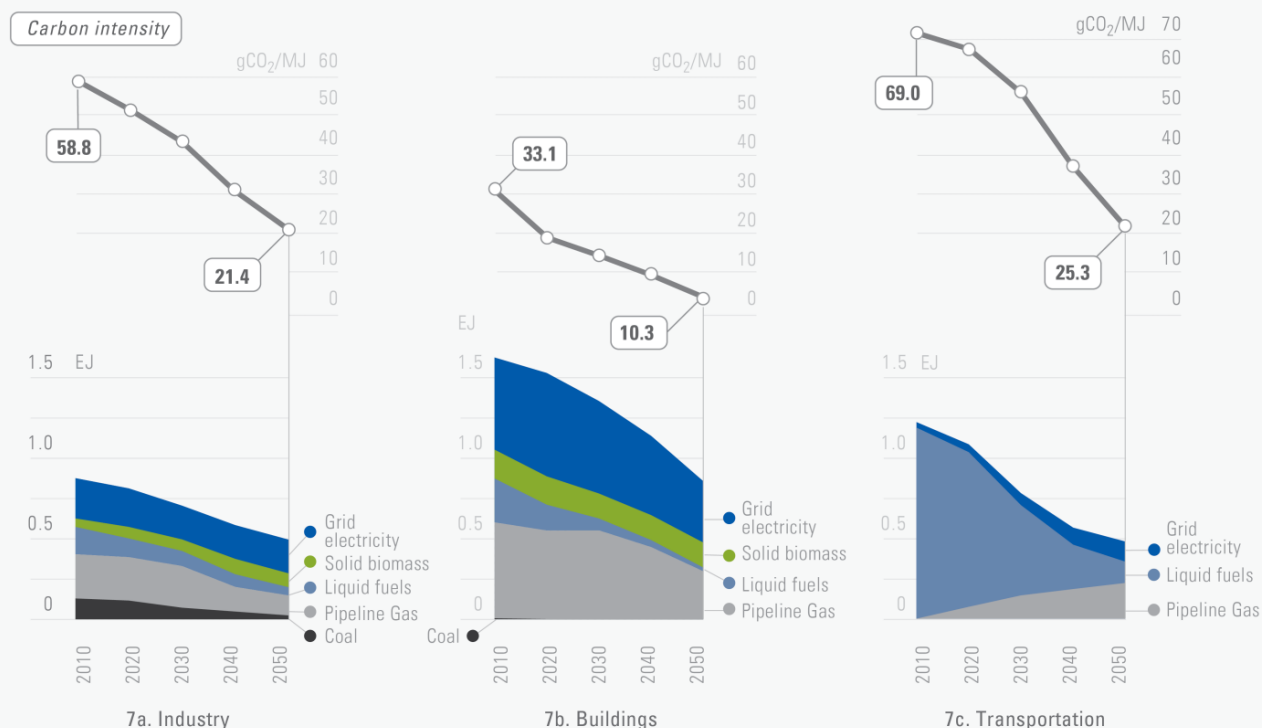
Buildings

More than two thirds of the dwellings that will exist in 2050 are already built so that efficiency improvement through the thermal retrofitting of existing buildings is a crucial component of the decarbonization strategy. A proactive strategy is necessary to address nearly all existing building (600,000 retrofitting per year after 2020 in the residential sector and 21 Mm² in the commercial sector) and ambitious improvements per unit are considered (-55% in the commercial sector and -65% in the residential). Additionally and consistently with the measures from the *“Grenelle de l’Environnement,”* standards impose new buildings to consume less than 50 kWh/m² in 2020 and to reach zero energy consumption after 2020. In parallel, the share of multi-dwelling buildings should increase, inducing only a small increase in the per capita surface. Electricity and off-grid renewables become dominant heating fuels and specific electricity consumption is controlled by a 30% performance improvement for all appliances, corresponding to a pervasive penetration of the most energy efficient appliances currently available.

Industry

The Illustrative Decarbonization Pathway considers no major change on the structure of production, industry remaining at a constant 20% share in GDP, neither on final industrial energy mix, the decrease of the carbon intensity being essentially due to the development of biogas and of renewable energy. The major breakthrough specific to the industrial sector is a significant reduction of energy consumption, which is obtained by the diffusion of optimized industrial processes (circular economy and industrial ecology principles), combined with 30% energy efficiency gains.

Figure 7. Energy Use Pathways for Each Sector, by Fuel, 2010 – 2050



2.2. Assumptions

While low or zero energy solutions may be relatively easily implemented in new buildings, the retrofitting of existing buildings will have to be implemented at a very large scale, in the range of 600,000 units per year. This will require a combination of technical advancements (incremental innovations in the building practices and radical innovations in materials and control instruments), capacity building in the industry, and specific policy measures to overcome legal and regulatory barriers.

The transport pathway is supported by a combination of land and urban planning, organizational innovations, and behavioral changes. Technological innovation is also decisive to promote smart logistics and support the diffusion of alternative motorization types (hybrid electric, plug-in hybrid electric, full electric, and natural gas vehicles). In particular, the development of natural gas vehicles in France could be facilitated by its development in neighboring countries, which are already adopting this technology, and by the progressive deployment of biogas combined with the decrease in gas consumption for heating.

In industry, technological breakthroughs are not central to the Illustrative Decarbonization Pathway; the optimization of industrial practices (circular economy and industrial ecology principles) is the key option to decouple energy use and carbon emissions from production.

Finally, energy production is highly decarbonized essentially thanks to power-generation renewables, biogas and biofuels, the development of all these sources being in line with available assessments of their potentials for 2030 (Tanguy & Vidalenc, 2012).

2.3. Alternative pathways and pathway robustness

After consideration of 16 pre-existing energy scenarios (from NGOs, or academic research, or public agencies), the National Debate on Energy Transition in 2013 identified four families of possible pathways: SOB for sobriety, EFF for efficiency, DIV for diversity, and DEC for decarbonization (Ardity et al., 2012). Each describes contrasted but consistent alternatives for the deep decarbonization of the French energy system along two dividing lines: the level of demand and the energy mix (between a priority to nuclear, to renewables, or to a diversified set of energy carriers).

All these trajectories describe a plausible deep decarbonization pathway, since they all reach the Factor 4 emission reduction target (SOB and EFF even reach more ambitious reductions of carbon to leave more flexibility on other GHG gases) and the Illustrative Deep Decarbonization Pathway belongs to the EFF family.

The common features among these four pathways are numerous, although each supposes different ambition levels for sector by sector developments, and define a set of minimum requirements to reach the Factor 4 overall target. This concerns in particular:

- In the building sector: a deep retrofit of buildings with important efficiency improvements (at least 300,000 units in the residential and 15Mm² of commercial surface with an average energy efficiency gains of 45%), a phase out of oil product uses for heating and systematic improvements of appliances' energy efficiency

- In the transport sector, a switch from individual cars and trucks to rail and collective transport and important efficiency gains in vehicles (at least 50%)
- In industry, energy efficiency improvements (at least 20%) and optimization of industrial processes

These common features provide a robust identification of the key dimensions of the decarbonization strategies for France. However, the intensity of some actions driving the pace and ultimate potentials of energy demand reduction and of energy decarbonization in the Illustrative Pathway may be questioned. This concerns particularly the retrofit of the whole building stock by 2050 implying 600,000 annual retrofits, the role of biogas as an important combustion fuel, the mix of new technologies, including biofuels, replacing the conventional car (electric vehicles, hybrid vehicles, and NGV) and the rapid scaling-up as well as high final level for renewable electricity.

Should these targets prove to be too difficult to attain, then the decarbonization strategy should integrate the constraints and be adjusted in due time. To compensate for weaker reduction in final energy consumption, a higher level of decarbonization could be sought with more nuclear and more of other decarbonized sources, particularly biomass and waste heat, and finally the introduction of carbon capture and storage, particularly in industry. A DIV – i.e. diversified mix – trajectory would provide such an alternative pathway resorting to less ambitious assumptions on efficiency but still reaching deep emission reductions thanks to more low-carbon supply in due time. It is worth noting that the a DIV-type trajectory can be considered as a “second-best” pathway, in the sense that it is not the most robust given its dependence upon the availability of a vast set of not currently commercially available technological options (notably CCS); such pathway then offers a solution if it appears that the implementation of an EFF-type trajectory does not allow to reach the deep decarbonization trajectory because of unexpected barriers and difficulties in mobilizing energy efficiency potentials.

The Illustrative Deep Decarbonization Pathway relies on the assumption of an economic competitive nuclear in the future. If this assumption proves to be optimistic for future nuclear development, more renewable energies can be mobilized for electricity production reorienting the scenario in a SOB-type trajectory.

2.4. Additional measures and deeper pathways

Some technical options are not considered in the Illustrative Pathway, but play a central role in alternative scenarios presented above, notably:

- Methanation: synthetic methane from a recombination of carbon dioxide (from fuel combustion), hydrogen (from renewable electricity), heat and a catalyzer can be used as storage capacity in gas network and as a non-carbon energy for transportation.
- Carbon capture and storage: significant storage capacity in the North of France could store 40 MtCO₂/year from 2040 mainly for industry.
- Nuclear cogeneration, although a sensitive issue, can be used to supply heat for buildings and industry.

2.5. Challenges, opportunities, and enabling conditions

Bio-energy supply

A crucial challenge for the Illustrative Pathway is associated with the capacity of the agricultural sector to develop an important bio-energy supply with second generation biofuels and biogas for energy substitution.

Implementation of a carbon tax

One of the most important instruments to trigger the necessary changes in technologies and behaviors for the energy transition is the implementation of a price signal through carbon taxation, which could be used to lower taxation on labor, to finance energy efficiency and renewable energy development, or be transferred as a lump sum to households, particularly the more vulnerable ones.

Financing the energy transition

Whatever the energy pathway, the energy transition would require very large investments amounting to around 2,000 bn€ over the period (the building retrofitting program only would require between 20 bn€ and 30 bn€ each year). Even if the energy transition will more than compensate the extra investment by decreases in the energy bills of households and industries, one of the main barriers to finance the energy transition is the lack of short-term profitability of energy transition investments for private agents: the difference between private discount rates (typically 10-15% p.a. or more) and social discount rates (2-6% p.a.) has since a long time been identified everywhere as the major cause of the “efficiency gap.” Several proposals for triggering the financing capabilities exist: orienting household savings, such as saving accounts (1,300 bn€), in low-carbon investments, creating a public bank such as the KfW in Germany for the thermal retrofitting of buildings, creating an entity for the financing of the energy transition (focusing on the retrofitting program, and on the development of renewable energies) with a guarantee from the State.

Professional transitions and formation

Employment has become a very central issue of the energy transition debate. Quantitative studies of the energy transition in France conclude to a positive assessment with massive job creation potentials in renewable energy, construction, infrastructures, and collective transports. New skills will have to be developed (for thermal retrofitting for instance) at a very large scale and as rapidly as possible. On the other hand, occupational retraining programs will be needed for jobs in activities such as road freight transport, car industry, or in nuclear energy. With around 10% of active population currently unemployed, the acceptability of energy transition is conditioned upon credible answers for professional transitions in these sectors.

Local authorities, governance, and social feasibility

Concrete examples of energy transition actions such as building retrofitting, optimizing local renewable resources in function of specific uses, developing networks for heat or for gas, show that concrete actions already happen at local level. Energy issues are indeed directly linked to many other local policies: urban planning, local transports, wastes, housing, and also social policies at the urban or municipality levels. Regional authorities are already in charge of transportation, land planning, economic development and training. Participatory processes are also an element of acceptability of energy transition. Further, by empowering local governance systems, national policies could leverage existing

local experiments, accelerate policy responses, foster resource mobilization, and engage local stakeholders.

Stability in climate policy orientations

The long term Factor 4 objective that became a legal target in 2005 is an important catalyst for climate policies by stabilizing expectations of consumers and economic agents in their low-carbon investment decisions; a medium to long-term stability of climate policies is needed. Although this target has been unopposed by any stakeholder group since its very first introduction by the *Mission Interministérielle pour l'Effet de Serre* in 2003, some governmental decisions apparently contradictory to official objectives have been observed notably for wind and photovoltaic policies: administrative decisions impose new constraints on wind development and, since 2011, the feed-in tariffs for photovoltaic are revised every 3 months. As a result, wind and PV development have significantly slowed down and the 20% target for renewable energy development in 2020 may become unattainable. The implementation a pre-established increasing carbon price would be central for a full environmental and economic efficiency of public policies.

Ambitious EU and international climate energy objectives

Ambitious EU and international climate energy objectives are also of paramount importance for numerous reasons: leverage effect of EU objectives and induced directives on national policies, credibility and acceptability of national policies, industrial strategies for low carbon technologies and economic competitiveness issues.

2.6. Near-term priorities

Near-term sectoral priorities should focus on renewable energy development and the implementation of the building retrofitting plan. These two actions are crucial for any deep decarbonization pathway in France, but face strong inertias (both because they are associated to long-lived infrastructure and require the development of specific skills that are not currently available), which make early development crucial. In addition, these actions have strong potential positive effects on employment that can increase the social and political desirability of these measures.

In addition, specific financing mechanisms must be conceived to support in particular the massive retrofitting program and a carbon price has to be rapidly implemented, even at a low level during the first years, but with a pre-established increasing rate (in the range of 4-5% p.a., the level of the social discount rate), in order to reach a level near to the 100 €/tCO₂ in 2030 that has been already identified as consistent with the policy targets.

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INDONESIA

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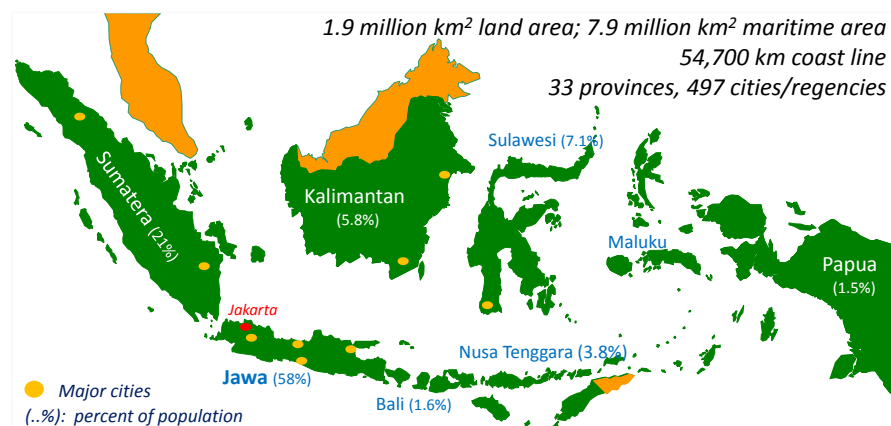
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1. Country profile

1.1. The national context for deep decarbonization and sustainable development

Indonesia is the largest archipelago in the world. Located between the Pacific and the Indian Oceans, it bridges two continents: Asia and Oceania. It consists of approximately 17,000 islands with a population of 234 million. The majority (almost 80%) of Indonesians live in the Western part of Indonesia on the islands of Jawa and Sumatera (see Figure 1).

Figure 1. Map of Indonesia with basic statistics



Fossil fuels have historically been the major source of energy in Indonesia. Out of the 189 Mtoe of primary energy supply in 2011, oil accounts for almost half at 46.3%. The remainder is provided by coal (26.1%), natural gas (20.4%), commercial biomass (3.4%), hydro (2.4%), and geothermal (1.3%). In addition to this commercial energy, traditional biomass is still used for cooking in rural areas. The major energy consumers in Indonesia are industry (46.1%) and transport (35.6%). The remaining 18.3% is shared by residential (11%), commercial (4.2%), and agriculture, mining and construction (3.2%). The majority of final energy consumption is in the form of fuels (oil, coal, gas, and biomass comprise 88%), and the remaining 12% of final energy is provided as electricity. Indonesia's electrification rate (the percent of the population with access to electricity) is around 78%, with a low per capita annual consumption of 660 kWh/capita. Given that the country is an archipelago with many islands and remote rural communities, a large number of Indonesians do not have access to electricity. Fossil fuels are the dominant source of energy for electricity generation; coal, natural gas, and oil respectively represent

42%, 32%, and 12% of the generation mix. The remaining 13% is provided by hydropower (8%) and geothermal (5%). Indonesia developed with this dependency on fossil fuels in part because of the country's energy resource endowment, which includes 120 billion tons of coal, 8 billion barrels of oil, and 150 Trillion Standard Cubic Feet (TSCF) of natural gas. In addition to fossil energy, Indonesia is also endowed with renewable energy resources, including 75 GW of hydro,²² 29 GW of geothermal, 50 GW of biomass, and solar energy potential of 4.5 kWh/m²/day.

Indonesia is a developing nation with a GDP of 847 billion US\$ (2012). The per capita GDP in 2012 was 3,592 US\$. Over the past 5 years, the country's annual economic growth fluctuated between 4.3% and 5.9%. The Indonesian economy has shifted from one that was highly dependent on agriculture to one that is more industry and service-based. In 2012, the composition of the economy was: 47% industry, 38% service, and 15% agriculture. It is expected that the Indonesian economy will move further toward a service-based economy in the future. Despite continuous economic growth, many Indonesians are still poor, with approximately 11% of the population living below the poverty line. In the next three decades, the Indonesian population is expected to grow at approximately 1% each year, and employment for this additional population is critical. To lift the population out of poverty, the government plans to promote economic growth that averages at least 5% per year and has set a goal of reducing the poverty rate to below 4% by 2025.

Historically, energy has not been used efficiently in Indonesia because prices were kept artificially low through government subsidies. These subsidies have helped fuel an increase in energy use; average annual growth of energy consumption has been larger than average annual GDP growth. Through efficiency measures, the government hopes to reverse this trend by 2025. It is also expected that remote, rural communities will be electrified using local renewable resources such as microhydro power and solar photovoltaic (PV) technology. The government has set a goal that all households will have access to electricity by 2025, and plans for energy efficiency and the increased use of renewable energy resources have put Indonesia on a deep decarbonization pathway.

1.2. GHG emissions: current levels, drivers, and past trends

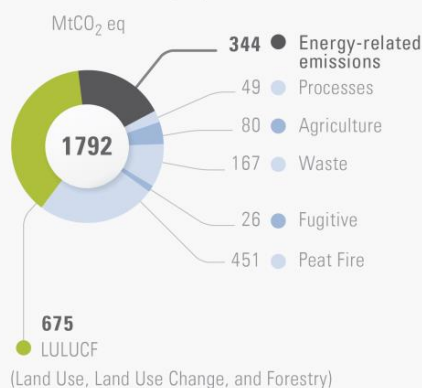
According to the Indonesian Second National Communication (which reports the latest official figures concerning the country's emissions), Indonesian GHG emissions were around 1,800 MtCO₂e in 2005 (see Figure 1). This represents an increase of 400 MtCO₂e compared to 2000. Most emissions (63%) come from land use change and peat fire, and combustion of fossil fuels contributes around 19% of the emissions.

In the fuel combustion category, coal is the major emission source (see Figure 2). The second major source is oil combustion. Coal is the main fuel in power generation as well as a major energy source for industrial activities. Oil is used in the transport and building sectors. In the end-use sector, one-half of the direct combustion emissions are from fuel burning in industrial activities. Emissions from power generation come from the building (60%) and industry (40%) sectors.

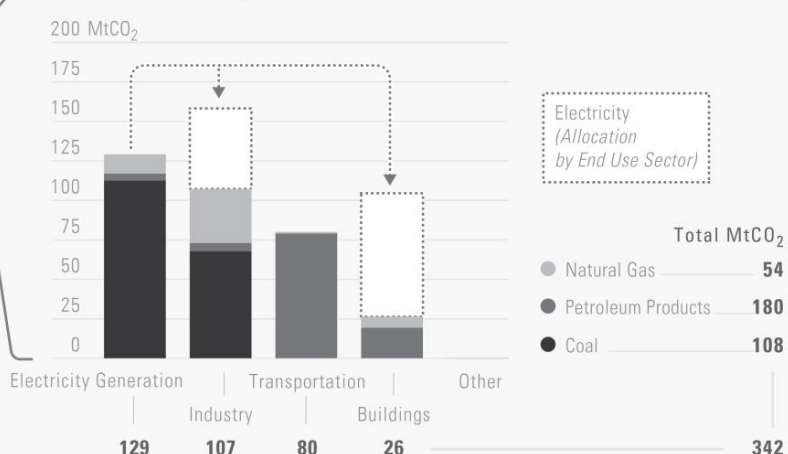
²²This is a resource potential, based on preliminary resource surveys. Assuming this could be converted into technical potentials and with capacity factor of 40%, then this resource will generate 263 TWh per year. As comparison, in 2010 the generation of hydropower was 16 TWh. Many of the hydro resources are located in Eastern Indonesia, far from electric demand center in the West. Transmission from East to West requires construction of undersea cables.

Figure 2. Decomposition of GHG and Energy CO₂ Emissions in 2005

2a. GHG emissions, by source



2b. Energy-related CO₂ emissions by fuel and sectors

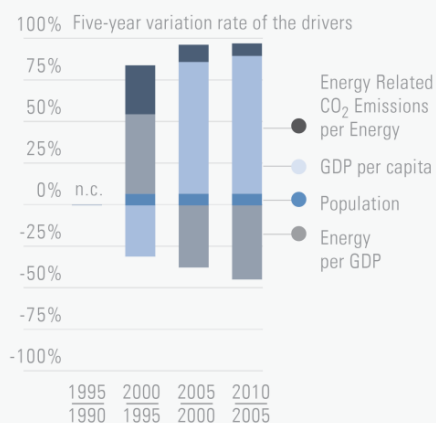


Source: Second National Communication Indonesia

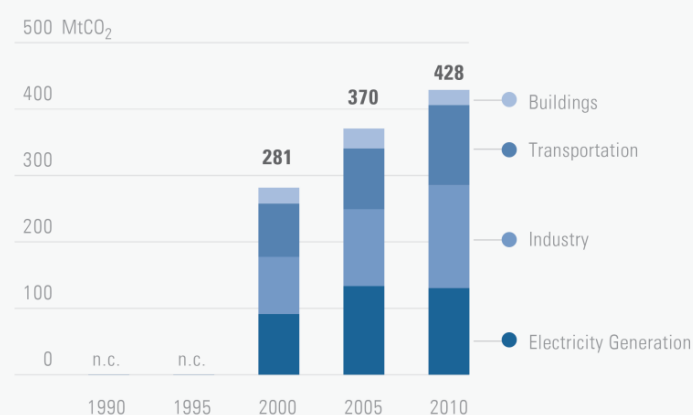
As shown in Figure 3, the main driver of GHG emissions over the past decade has been economic activity, which increased at a rate of 5% to 6% per year. Increasing energy use per unit of GDP also contributed to the increase in emissions, showing that the economy simultaneously grew more energy-intensive.

Figure 3. Decomposition of historical energy-related CO₂ Emissions, 1990 to 2010

3a. Energy-related CO₂ emissions drivers



3b. Energy-related CO₂ emissions by sectors



2. National deep decarbonization pathways

2.1. Illustrative deep decarbonization pathway

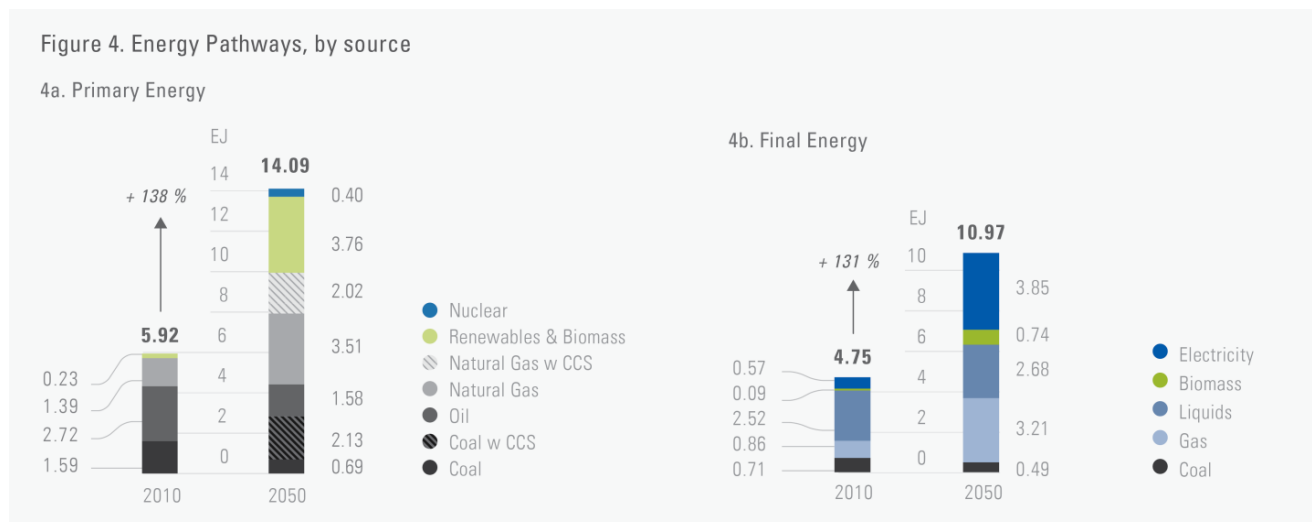
2.1.1. High-level characterization

As a developing nation, the Indonesian economy and population are projected to grow significantly in the next four decades. The projections for these energy service demand drivers and other relevant development indicators are shown in Table 1.

Table 1. Development Indicators and Energy Service Demand Drivers

	2010	2020	2030	2040	2050
Population [Millions]	234	252	271	289	307
GDP per capita [\$/capita]	2,306	3,655	5,823	9,319	14,974
Access to Electricity	70%	85%	99%	99%	99%
Poverty indicator	12%	8%	3%	3%	2%

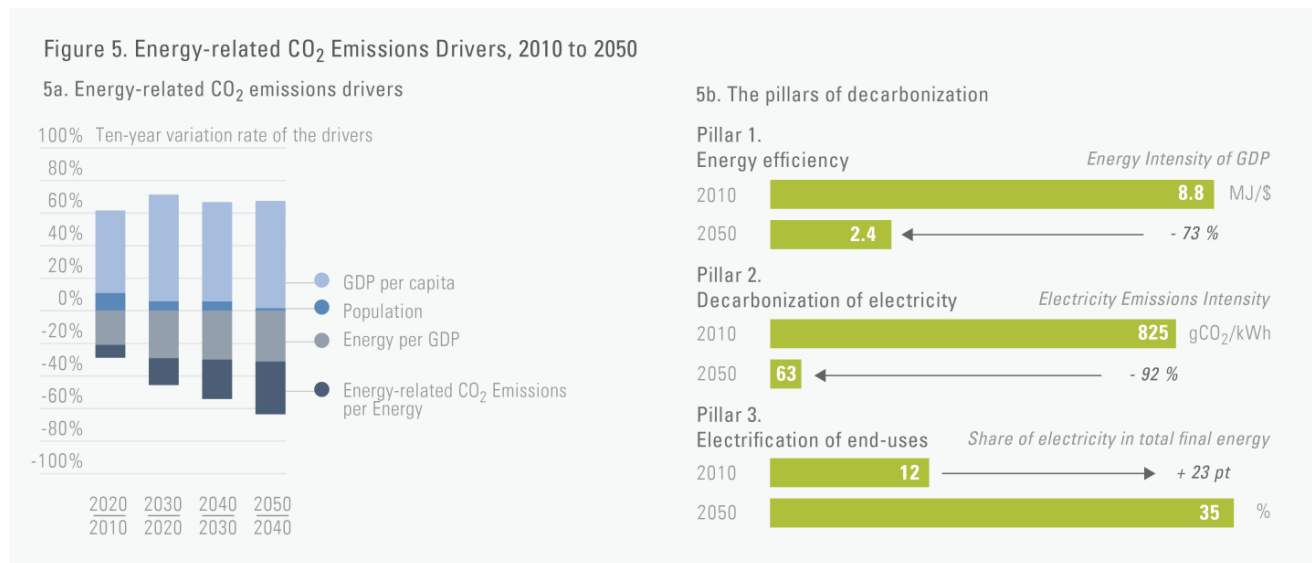
To achieve significant decarbonization, Indonesia has to drastically change its energy supply and demand mix (see Figure 4). The following are the important features of decarbonization in primary energy: reduce oil consumption, reduce coal share and equip most of the remaining coal plants with CCS, increase the share of natural gas and equip a significant fraction of gas plants with CCS, significantly increase the share of renewables, and begin to use nuclear power. The important features of decarbonization in final energy are: significantly decrease use of coal, increase the share of natural gas, significantly reduce oil consumption, and significantly increase share of electricity.



The drastic change of the primary as well as the final energy mix is the result of many measures. As shown in Figure 5, the illustrative Indonesian decarbonization pathway is a combination of energy

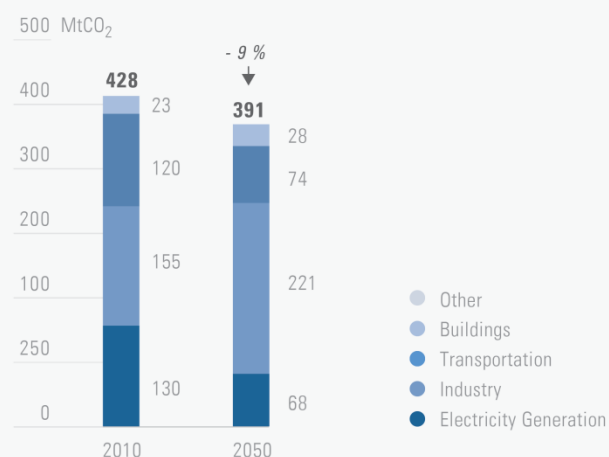
efficiency, low- and zero-carbon emitting technologies, and structural changes in the economy. The key elements of the pathway are as follows:

- Energy efficiency improvements would be deployed in all sectors.
- The deployment of lower-carbon emitting energy sources would be realized in part through fuel switching from coal to gas, oil to gas, and a switch from onsite fuel combustion to use of electricity. The remaining large energy systems that burn fossil fuels would be equipped with CCS technology.
- Further fuel switching to renewable resources is a critical component of the scenario in all sectors: solar, hydro, and geothermal for power generation, biofuels in transport, and biomass, biofuels, and biogas in industry.
- Structural changes in the economy (*i.e.* decreased role of industry in the formation of national GDP through service sector substitution) are expected to contribute to the decarbonization of the energy sector.



By implementing these strategies, the energy-related Indonesian CO₂ emissions will change in a sustainable manner by realizing deep decarbonization by 2050. As shown in Figure 6, industry and power generation remain the major sources of emissions in 2050. Significant decarbonization will occur in the power sector, from 130 MtCO₂ in 2010 to 68 MtCO₂ in 2050. Despite decarbonization efforts, emissions from industrial sector will continue to increase, from 155 MtCO₂ in 2010 to 221 MtCO₂ in 2050.

Figure 6. Energy-related CO₂ Emissions Pathway, by Sector, 2010 to 2050



As shown in Figure 2, land use change and forestry are the main sources of GHG emissions, and they will continue to be so without new strategies in these areas. Therefore these sources have been targeted for reduction as part of the national emissions reduction commitment. The emissions from this sector mainly come from deforestation, forest degradation, and peat emissions. A decrease in emissions can be accomplished through six strategies: (i) the acceleration of establishment of a forest management unit (FMU) in all forest areas to ensure the improvement of forest management, (ii) the introduction of mandatory forest certification systems to reduce illegal logging and increase the application of sustainable management practices, (iii) a reduced dependency on natural forests in meeting wood demands by increasing the use of low-carbon stock lands or degraded lands for the development of timber plantation and enhancement of carbon sequestration by increasing forest regeneration and land rehabilitation, (iv) the reduction of forest conversion in meeting land demand for agriculture by increasing the productivity of the existing agricultural land and planting intensity as well as optimizing the cultivation of unproductive lands, (v) a restriction on the use of peat land for agricultural development and the implementation of low-emission technologies in peat land, and (vi) the issuance of financing/incentive policies and the development of a financing system to support the implementation of the first five strategies.

The implementation of the above strategies could significantly reduce GHG emissions in these sectors from about 3.42tCO₂e/capita (about 800 MtCO₂e) in 2010 to about -1.08tCO₂e/cap (about -330 MTCO₂e) in 2050. These sources could become a net-sink of CO₂ emissions by 2030 at a rate of about -0.29tCO₂e/cap (about 80 MtCO₂e).²³

²³ It is assumed that all government targets on wood, palm oil, and rice production are met. The government target for wood production from natural forest will be stable at about 18.54 million m³/year (starting from 2020-2050), and timber plantation will reach 360 million m³ by 2050. The area for palm oil plantation, which is now about 9.27 million ha, will increase to 15 million ha by 2050, and rice production will meet domestic demand (self sufficiency). The land demand for settlement and commercial building will increase following the population growth.

2.1.2. Sectoral characterization

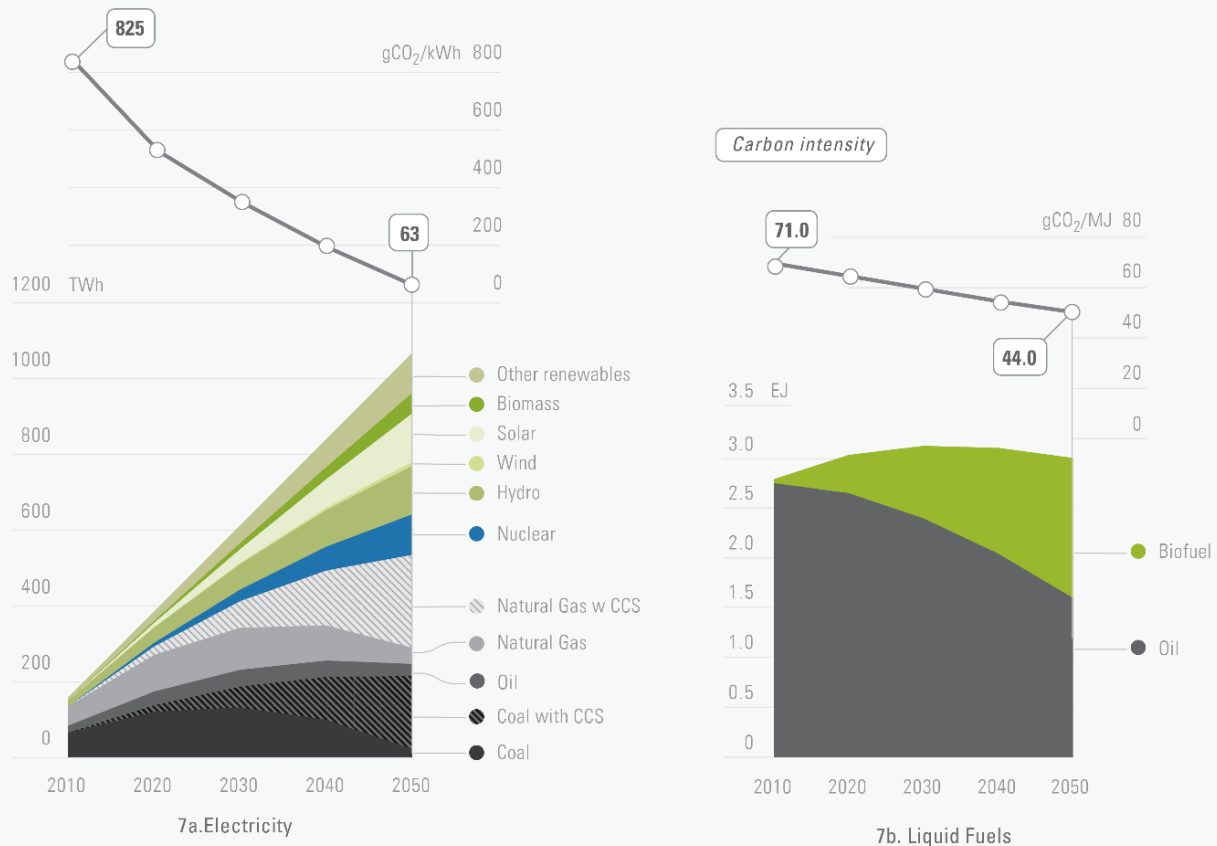
As mentioned above, Indonesia's primary energy mix is currently dominated by fossil fuels. Oil, coal and gas together account for 93% of the energy supply, and the remaining 7% comes from renewable energy resources (biomass, hydropower, and geothermal). The end users of the energy are the industrial sector (50%), transport (34%), and building (16%). The breakdown of types of energy on the end user side is as follows: liquids (54%), gas (18%), coal (15%), and electricity (11%). To achieve decarbonization, a major transformation will take place in the energy system, including the electrification of transport and industry and deployment of renewables and application of CCS.

Another important element of the decarbonization pathway is a significant increase in the share of biofuels in transportation, industry, and power generation. To ensure sustainability, the feedstock of biofuels would be planted in unused land (without disturbing forest stock), and as time progresses and new technology is developed, the feedstock will come from waste biomass.

Electricity Generation

Electricity demand will increase significantly with economic development and a shift of energy use in residential, industrial, and transport toward electricity. In the power sector, the decarbonization strategy includes fuel switching to lower-carbon emitting fuels (coal to gas, oil to gas), massive deployment of CCS for remaining coal and gas power plants, and extensive deployment of renewables (solar, geothermal, hydropower, and biofuels). Deep decarbonization in power generation will also require deployment of nuclear power plants and efficiency improvements in existing power plants. A summary of this decarbonization pathway is shown in Figure 7. Electricity demand will grow 5% per annum on average, from 158 TWh in 2010 to 1,083 TWh in 2050. Decarbonization in this sector will result in a decrease in the average CO₂ emission factor, from 825 gCO₂/kWh in 2010 to 63 gCO₂/kWh in 2050, and the CO₂ emissions of the electricity generation will decrease from 130 MtCO₂ in 2010 to 68 MtCO₂ in 2050.

Figure 7. Energy Supply Pathways, by Resource



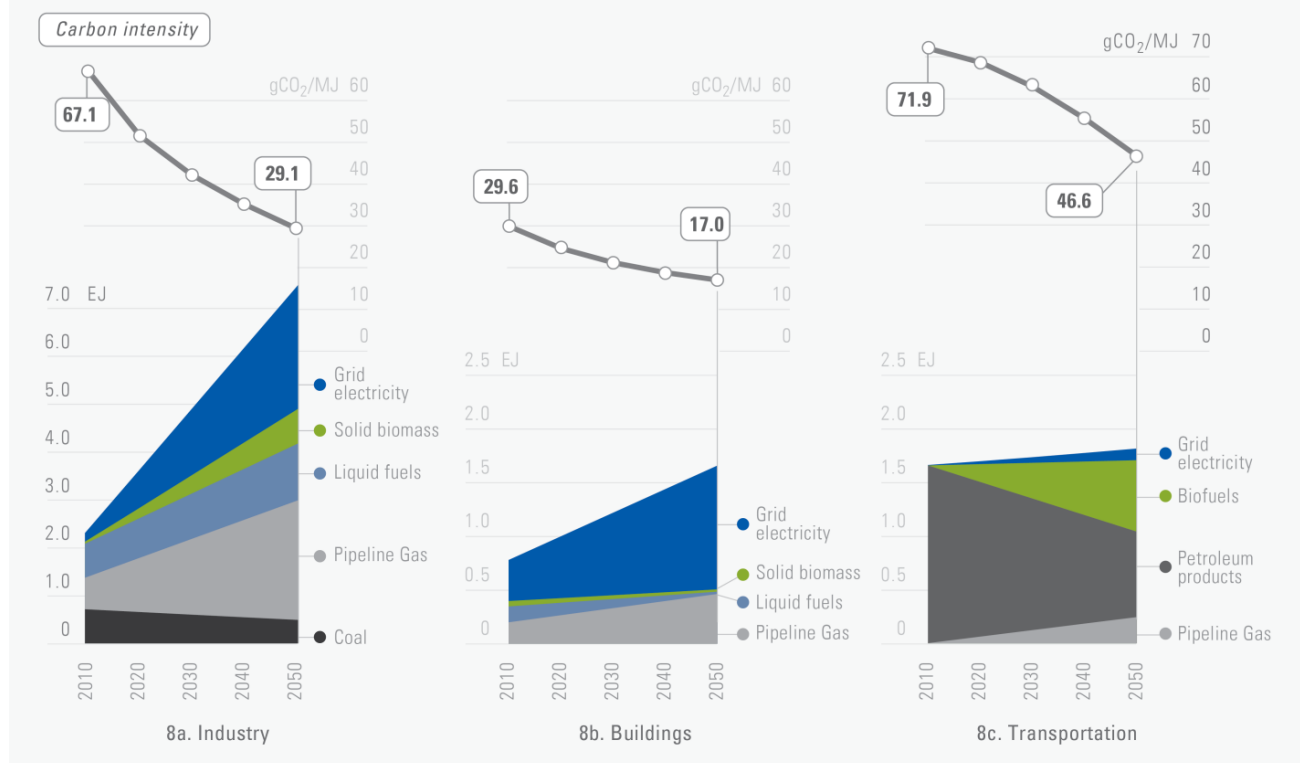
Liquid Fuels

To achieve deep decarbonization, it is assumed that there would need to be a significant switch from petroleum fuels to biofuels. Figure 7b shows the trajectory of the total liquid fuels used in transport, industry, and power generation and their associated carbon intensity.

Industry

Fuel switching to lower-carbon fuels and bioenergy (solid biomass wastes and biofuels) is the dominant strategy for decarbonization in the industrial sector. In addition, CO₂ emission reductions are also realized through industrial efficiency improvement (decreasing energy intensity) and CCS for coal and gas in heavy industry. These decarbonization measures would reduce the emission intensity of fuels in industry sector from 3.81 tCO₂/toe in 2010 to 1.88 tCO₂/toe in 2050. The trajectory of industrial energy use and the associated emission intensities are shown in Figure 8a. A decreased share of industry and heavy industry in the national economy would also contribute to the emission reductions. It is expected that the share of industry in GDP will decrease from 27.8% in 2010 to 17% in 2050. Improvements in efficiency are expected to reduce industrial energy intensity from 365 toe/M\$ in 2010 to 229 toe/M\$ in 2050.

Figure 8. Energy Use Pathways for Each Sector, by Fuel, 2010 – 2050



Note: Carbon intensity for each sector includes only direct end-use emissions and excludes indirect emissions related to electricity or hydrogen production.

Transport Sector

The energy demand in the transport sector is expected to increase significantly with economic development and population growth. In the passenger transport sector the decarbonization strategy includes modal shift to mass transport, electrification of vehicles, fuel switching to less-carbon emitting fuels (oil to gas), use of more energy-efficient vehicles, and extensive use of biofuels. Similar strategies are also applied to freight transport. A shift of freight transport from road to railway is expected to decrease CO₂ emissions. As a result of modal shift, it is expected that the share of personal vehicles decreases from 60% in 2010 to 40% in 2050. In 2050, it is expected that 30% of personal cars are electric vehicles. Decarbonization of this sector is expected to reduce the emission intensity from 3.02 tCO₂/toe in 2010 to 1.73 tCO₂/toe in 2050. Figure 8b shows the trajectory of energy use and the associated emission intensities of transport sector.

Building Sector

Decarbonization in the building sector would result primarily from fuel switching from oil to gas/LPG and from fuels to electricity along with more efficient electric equipment. Switching from on-site fuel combustion to electricity would reduce direct emissions from buildings, and with a decarbonized electricity generation sector, this switch would lead to emission reductions. For the residential sector, increasing per capita income will increase energy consumption, but this will be balanced by more efficient equipment and the expectation that homes will remain relatively small. The trajectory of buildings energy use is shown in Figure 8c.

2.2. Assumptions

The deep decarbonization of energy activities in Indonesia can only be achieved through a combination of measures: efficiency, fuel switching (including to electricity), deployment of renewable, nuclear, and CCS and structural change of the economy, especially in the industrial sector. The success of the country's decarbonization pathway is obviously dependent on the realization of many assumptions used in its development.

Indonesian hydropower plants under the illustrative scenario would generate around 37 GW in 2050, which is approximately half of the total hydro resources (75 GW). Indonesian geothermal resources would amount to around 29 GW, which supports the 25 GW of geothermal power assumed in the scenario. As a tropical country with an average radiation of 1.45 kWh/m²/day, it is reasonable for Indonesia to envisage a scenario where 75 GW solar power is used in 2050.

For energy security reasons, Indonesia will most likely continue to use its abundant coal resources for electricity generation. However, most of the plants will be equipped with CCS facilities to capture CO₂ and store it in geological formation. Given the need for deep decarbonization, CCS will also be used to reduce emissions from natural gas power plants. The total CO₂ that would need to be stored by 2050 equals about 3,300 Mton (with an annual value of 286 Mton). The storage is assumed to take place in the abandoned and depleted oil and gas reservoirs in Indonesia. It is estimated that the volume of Indonesian depleted reservoirs could store around 11,000 Mton, which is more than three times the space required by the CCS scenario.

Deep decarbonization also includes the massive use of biofuels for transport, industry, and power generation. In 2050, the total biofuel demand would be around 85 Mton per year. Based on current technological standards, to meet this biofuel demand domestically, around 18 million ha of land are needed to grow the biofuel feedstock. Indonesia currently has around 8 million ha of land devoted to crude palm oil (CPO) production, which could be used as biofuel feedstock. The additional 10 million ha of land needed to support biofuel for decarbonization would be available from unused non-forest land, which is estimated to be around 50 million ha.

2.3. Alternative pathways and pathway robustness

Power generation is one of the major contributors of CO₂ emissions. Under the current pathway, the main tool of decarbonization is coal and gas CCS. Therefore, the uncertainty of the pathway lies in the uncertainty of CCS deployment. There is only a limited amount of research into the scale of geological formation for CCS in Indonesia. The suitability of the CCS scenario is based on the assumption that the CO₂ will be injected in depleted gas and oil reservoirs. If all of this storage does not become available, the alternatives to CCS include: more hydropower, biomass, and solar. An increase in the use of hydropower would require the construction of long subsea cables, as the location of large hydro resource is in Eastern Indonesia, while the demand center is in Western Indonesia. If half of the CCS envisaged in the illustrative scenario could not be realized, hydro would need to be increased from 30 GW to 61 GW, and biomass would need to increase from 15 GW to 20 GW. The increase in solar power would eventually be constrained by concerns for grid reliability associated with resource intermittency. Under the illustrative scenario, the share of intermittent renewables is only around 14%. If

the use of hydropower were limited below what is assumed in this scenario, solar could be substantially increased before reaching reliability limits, which are estimated to occur above a 25% threshold.

2.4. Additional measures and deeper pathways

More aggressive efforts to substitute internal combustion engine cars with electric vehicles (EVs) would help further reduce direct emissions in the transportation sector. Under the illustrative pathway, the share of EVs in personal cars is 30% in 2050. It may be further increased to 50% in 2050. Also, more electrification in the light industry will reduce direct emissions. Under the current pathway, the light duty fleet is 35% EVs in 2050. This level of electrification could conceivably be increased to 50%. The feasibility of this increase, however, requires further research. An increase in electrified transportation and industry will create more emissions in the power sector; the low-electric emission factor must therefore be maintained. As mentioned above, additional hydropower and geothermal power could be harnessed to support this increased load. To utilize the remaining large hydropower resource, it would be necessary to construct a subsea electricity transmission line, given that the resource is located far away from the demand center.

2.5. Challenges, opportunities, and enabling conditions

The Indonesian illustrative decarbonization pathway is primarily composed of technological changes that are very different from the current mix of energy technologies. Many of the technologies are still in their infancy (*e.g.* CCS, electric vehicles, high efficiency power plants, etc.). The realization of the pathway is highly dependent on the development and maturation of these technologies in the coming years, and the technological approach would require massive development of new infrastructure (*e.g.* infrastructure for enabling mass public transport, new railways, gas transmission, subsea electrical transmissions, and CCS facilities). As a result, one of the main challenges of the pathway is how to finance the infrastructure investment.

Some of the commercially available technologies, such as solar, biofuel and geothermal power, are currently more expensive than conventional fossil fuel technologies. Wide-scale deployment of these low-carbon resources would therefore require further technology development to lower costs, making them competitive with conventional resources.

Deployment of nuclear power also poses a special challenge: social acceptability. It is therefore necessary to explore how to convince Indonesians that nuclear power is a necessary part of the future energy mix.

In 2009, the Indonesian Government announced a non-binding commitment to reduce its emissions 26% by 2020 (compared to business as usual development). However, being a non-Annex I country, concern for climate change is not yet fully internalized in Indonesian development agenda. To embrace a deep decarbonization pathway, the government has to first adopt climate change as a key component of its national development agenda.

In summary, significant efforts are necessary for a deep decarbonization pathway to be realized: internalizing climate change into the national agenda, financing for investments in infrastructure, technology development, technology transfer, a social campaign for nuclear, and the right energy

pricing policy for renewables. To overcome some of these challenges, international cooperation is needed, especially for infrastructure financing and technology transfer.

2.6. Near-term priorities

Deep decarbonization is a long-term development objective, and the incorporation of climate change in the Indonesian national agenda has just begun. To embrace deep decarbonization, Indonesia must continue to internalize climate change in the political sphere. Nevertheless, there are a number of near-term actions that need to be taken now to begin implementing a decarbonization pathway:

- The modal shift to public transport was initiated decades ago, but the success of these efforts has been limited. One of the barriers is that investment in public transport has been limited. As a result, new efforts to explore financing options for the transportation sector are needed.
- Biofuels were introduced into the Indonesian energy system in 2005. However, the use of this fuel is currently limited. One of the barriers is that biofuels have to compete with subsidized petroleum diesel and gasoline. Though recently the government has subsidized biofuels, increased policies to promote biofuel development are needed. Currently biofuel production uses traditional feedstocks that are also needed for the food sector, *i.e.* crude palm oil and molasses. Research and development into other biofuel feedstocks must be emphasized.
- Some technologies that are envisaged in the pathway, such as electric vehicles and CCS, are new to Indonesia. Research, development, and demonstration of these technologies needs to be conducted over a number of years in order to make progress.
- The key challenge of deep decarbonization is the financing of low-carbon infrastructure. The government, therefore, has to begin to look for international cooperation and find assistance for infrastructure development. In addition, the government must seek international partners for the technology transfer of technologies necessary for deep decarbonization.

JAPAN

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1. Country profile

1.1. The national context for deep decarbonization and sustainable development

The Japanese economy is characterized by low domestic reserves of fossil fuels, which makes it highly dependent upon importations. This situation has raised important energy security issues since the 1950s when Japan has turned from domestic coal and hydro to imported oil to fuel its fast economic growth. After the first oil shock in the 1970s, Japan's energy policy priorities have shifted to be framed around the three pillars of energy security, environment protection, and economic efficiency, with in particular the development of nuclear, liquefied natural gas (LNG), and imported coal to limit the dependency on oil. The focus on energy security and climate change has favored the development of renewables and the domination of nuclear power, which has been the most important energy source until the Daiichi Nuclear Power plant accident in March 2011.

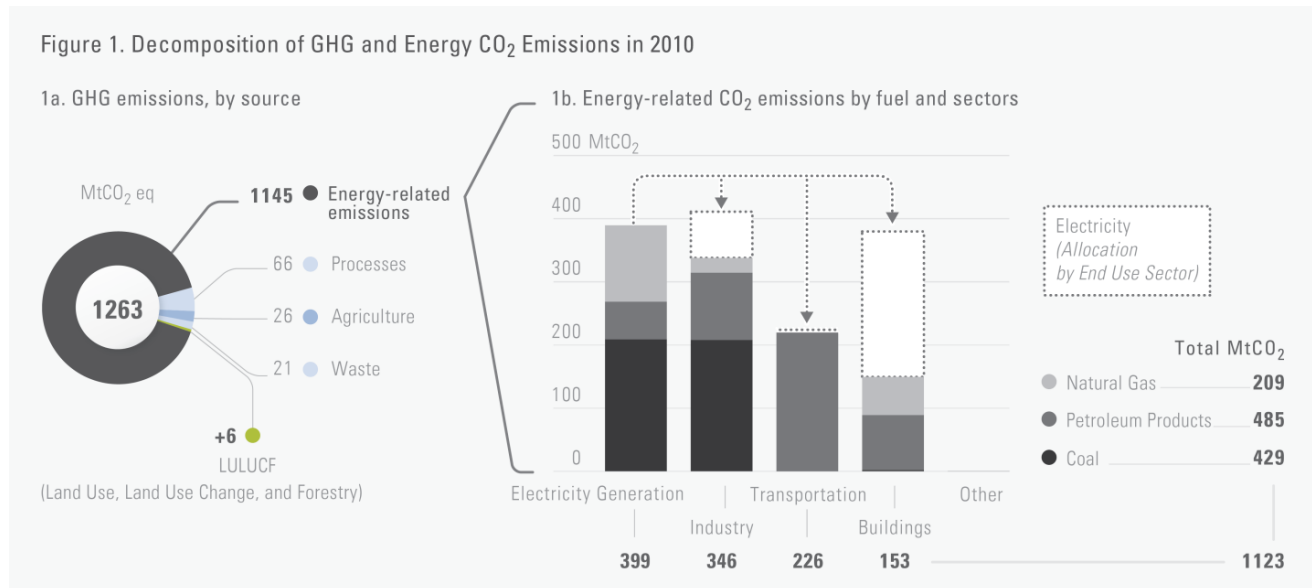
Energy strategies have changed after the 2011 accident. The Innovative Strategy for Energy and the Environment (2012) and the comments on Basic Energy Plan by Advisory Committee for Natural Resources and Energy (ACNRE, 2013) concluded that the dependency on nuclear power should be decreased; consequently, the power generation from nuclear power decreased substantially in 2012 from its level in 2010 and import of fossil fuels, especially LNG, increased in spite of energy efficiency improvement in end-use sector.

To achieve the political GHG mitigation target of reducing 80% emissions compared to the 1990 level by 2050 with lower nuclear dependence, it is utmostly necessary to reduce energy consumption by reducing energy service demands and by increasing the use of energy saving technologies, and to increase the share of renewable energies. As the potential of renewable energies is unevenly distributed, regional electricity exchange is required. The major renewable energy capacity is not located in the major electricity demand regions such as Kanto area but in the rural regions such as Hokkaido and Tohoku areas. However current electricity interconnection capacity between regions is not high in Japan and strengthening interconnections is therefore a crucial issue.

1.2. GHG emissions: current levels, drivers, and past trends

Total GHG emissions in 2010 (excluding LULUCF) amounted to 1,256 MtCO₂eq in Japan of which CO₂ represented a large majority (1,191 MtCO₂ or 94.8%) (Figure 1a). The sectoral decomposition shows that three activities were dominantly responsible for these CO₂ emissions at this date (Figure 1b): power generation, notably because the power sector was largely fueled by imported coal and LNG (even in 2010 before nuclear was partly removed from the power generation mix); industry, because the

industrial sector plays a very important role in the Japanese economy notably for exports; and transport sector, because the vehicle transports of both passenger and freight traffic were increased. Moreover, although shares of commercial and residential sectors are not large, the emissions from these sectors have increased because of increasing distribution of electrical appliances. At the same time, the emissions from the industry sector have reduced continuously since 1990, and those from the transport sector have reduced since 2000. The trends demonstrate a continuous but moderate increase of total CO₂ emissions over 1990-2007 (+14%) before recent drastic changes (-8% between 2008 and 2010 after the economic crisis and +7% between 2010 and 2012 because the closure of nuclear plants after Fukushima triggered a temporary increase of fossil importations).



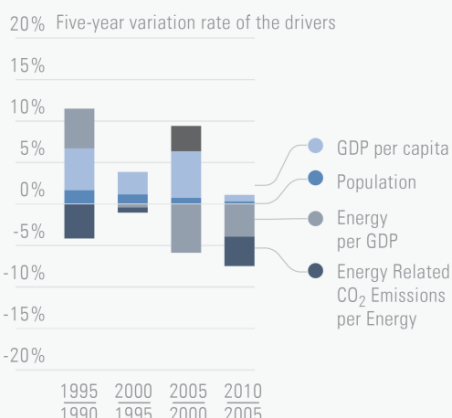
Source: Greenhouse Inventory Office of Japan²⁴

2007 saw the most GHG emissions for the 1990 to 2010 period, which was a 15% increase from base year under the Kyoto Protocol (KPB). The total GHG emissions in 2010 decreased by 0.4% compared to the emissions in the base year under KPB (excluding LULUCF). Since 2010, GHG emissions have resumed to increase and accounted for 1,343 MtCO₂eq in 2012. They increased by 6.5% compared to KPB. During the 1st commitment period, GHG emissions increased by 1.4% compared to KPB. On the other hand, if the carbon sink of LULUCF and credit of Kyoto Mechanism are counted, the GHG emissions during the 1st commitment period amount to 1,156 MtCO₂eq, a 8.4% decrease from KPB.

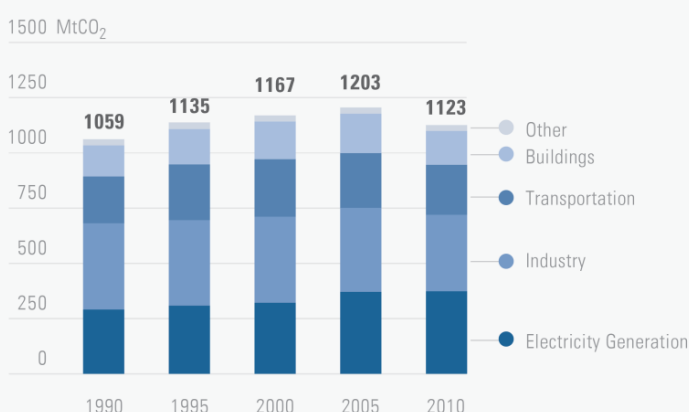
²⁴ <http://www-gio.nies.go.jp/aboutghg/nir/nir-e.html>

Figure 2. Decomposition of historical energy-related CO₂ Emissions, 1990 to 2010

2a. Energy-related CO₂ emissions drivers



2b. Energy-related CO₂ emissions by sectors



In Figure 2, the decomposition of drivers of changes in CO₂ emission from fuel combustion over 1990-2012 demonstrates that the Japanese economy has experienced a continuous diffusion of energy efficiency permitting an average 0.7% annual rate of production energy intensity decrease. The other Kaya drivers did not have such a consistent effect in that period. Until 2007, growth of GDP per capita has been the major driver of CO₂ emission increase, while there was a substantial decrease in 2008 and 2009 due to the global economic recession. In 2011 and 2012, the contribution of improvement of energy efficiency was neutralized by the increase of carbon intensity due mainly to the suspension of nuclear plants after the Great East Japan Earthquake in 2011 and the resulting comeback of fossil fuels.

2. National Pathways to Deep Decarbonization

2.1. Illustrative Deep Decarbonization Pathway

2.1.1. High-level characterization

In line with declining birthrate and growing proportion of elderly people, both total and active Japanese populations are expected to experience a significant decrease between 2010 and 2050, by 24% and 39% respectively as shown in Table 1. Despite the decline in population, the continuous rise of GDP per capita is projected to be sufficient to ensure a steady rise of total GDP (from about 5.38 trillion USD in 2010 to 8.37 trillion USD in 2050).

The deep decarbonization pathways in Japan are assessed using AIM/Enduse model.²⁵ Table 1 summarizes the major socio-economic indicators used in the estimation of deep decarbonization pathways in Japan. The indicators are taken from the assumption by Working Group of Technology

²⁵ AIM/Enduse model is a dynamic recursive, technology selection model for the mid- to long-term mitigation policy assessment, developed by the National Institute for Environmental Studies, Kyoto University and Mizuho Information Research Institute. This model has already been applied to assess the mitigation target in Japan. The model applied for the deep decarbonization pathways is a multi-region version of AIM/Enduse model of Japan, that is to say, the model is composed of 10 regions and considers the regional differences in renewable energy potential and energy demand characteristics. The 10 regions almost coincide with the business areas of 10 public power supply firms.

Perspective of Central Environmental Council in Japan and the estimation of population by National Institute of Population and Social Security Research.

Table 2. Major socio-economic indicators

	2010	2050	Variation 2010/2050
GDP (trillion JPY₂₀₀₀)	538	837	+56%
Population (million)	128	97	-24%
Active population (Million)	82	50	-39%
GDP per capita (US\$/cap)	38003	82116	+116%

Source: Central Environmental Council, 2012. Report on measures and policies after 2013.

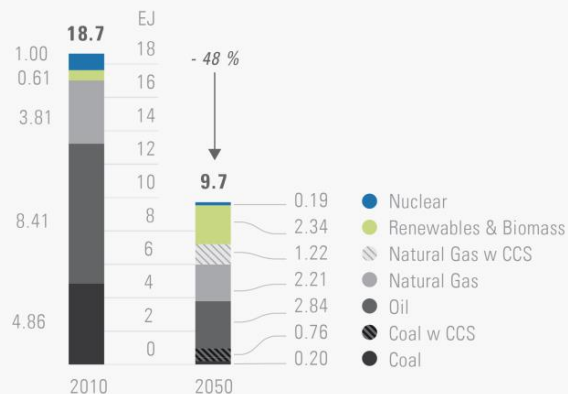
In Japan's illustrative deep decarbonization scenario, the long-term GHG emission reduction target is achieved by large scale energy demand reduction in end-use sector and decarbonization in power generation sector including deployment of CCS.

In parallel with continuous growth in GDP per capita, improvements of both energy efficiency and carbon intensity become the major drivers to substantial CO₂ emissions reductions in the mid and long terms. Total final energy consumption in 2050 decreases substantially and accounts for approximately 50% of the 2010 level (Figure 3, right panel). Particularly in transport sector, the pace of energy demand reduction is the most rapid in the mid- to long terms, followed by residential, commercial, and industrial sectors. The shift to public transport, fuel efficiency improvement, and efficiency improvement of transportation service will promote the reduction of CO₂ emissions in the transportation sector.

Dependency on fossil fuel is reduced substantially compared to the 2010 level due to reduction in energy demand and deployment of renewable energy. In 2050, fossil fuel consumption falls by approximately 60% compared to the 2010 level with an approximate 35% decrease of total primary energy supply and increase in share of renewable energy which accounts for approximately 40% (including hydropower) of total primary energy supply in 2050 despite almost complete phase out of nuclear power (Figure 3, left panel). Among the fossil fuels, natural gas and oil (including non-energy use) exist in 2050 while coal is almost phased out because of its high carbon intensity. Natural gas supply increases in the mid term in place of oil and coal because of its lower carbon intensity, but falls to the 2010 level by 2050 along with energy demand reduction and large-scale deployment of renewable energy. Hence, natural gas without CCS acts as a bridge technology.

Figure 3. Energy Pathways, by source

3a. Primary Energy



3b. Final Energy

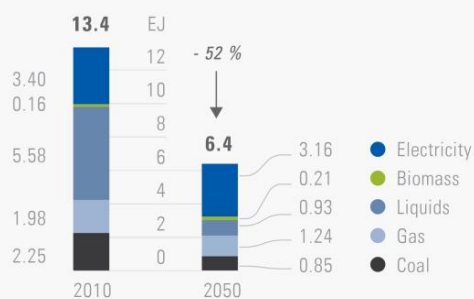
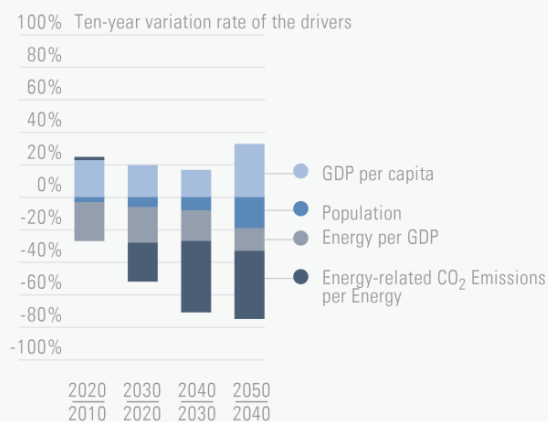


Figure 4. Energy-related CO₂ Emissions Drivers, 2010 to 2050

4a. Energy-related CO₂ emissions drivers



4b. The pillars of decarbonization

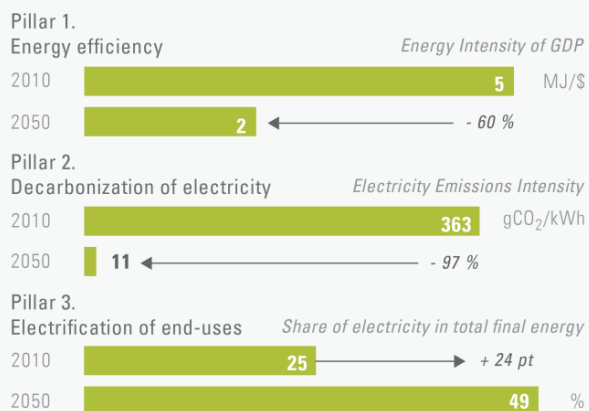
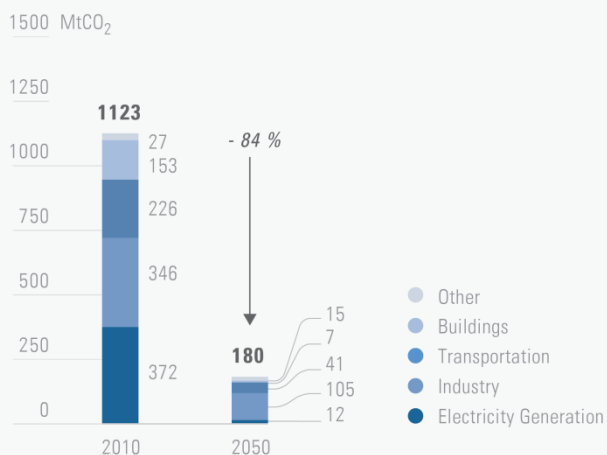


Figure 5. Energy-related CO₂ Emissions Pathway, by Sector, 2010 to 2050

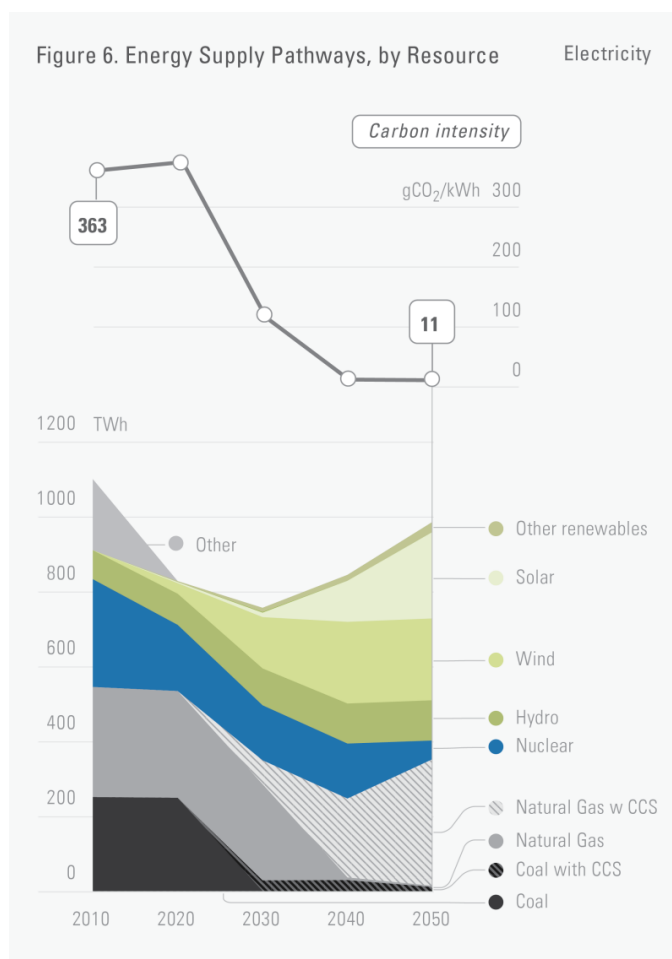


2.1.2. Sectoral characterization

Power sector

The nuclear power is assumed to be phased out gradually (see next section for more extensive discussion) and electricity generation from coal without CCS is entirely phased out by 2050. Renewable energy is developed over the mid to long terms and reaches approximately 59% of total electricity generation through large-scale deployments of solar PV and wind power (Figure 6). In addition, natural gas (equipped with CCS) is developed to ensure balancing of the network and reaches about a third of total electricity generation in 2050. Due to large-scale deployment of renewable energy and natural gas equipped with CCS, carbon intensity of electricity falls to nearly zero in 2050.

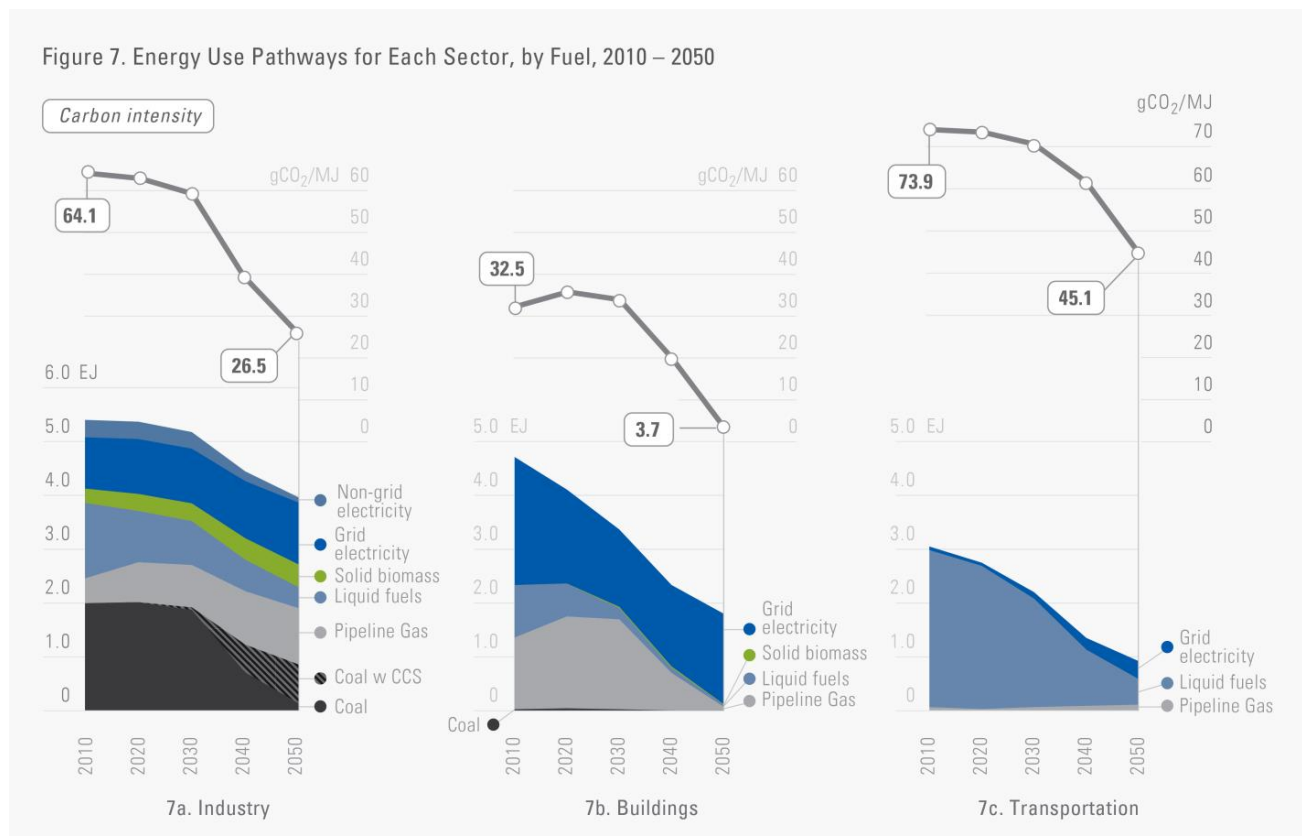
In 2050, approximately 199 MtCO₂ is captured by CCS technologies and cumulative captured CO₂ reaches about 3,096 MtCO₂. This represents about 60% of the potential of CO₂ storage in an anticlinal structure (the well and seismic exploration data for Japan is estimated by RITE)²⁶.



²⁶ The potential storage of CO₂ in an anticlinal structure where well and seismic exploration data accounts for about 5.2 Gt. In addition, the potential storage in existing oil/gas fields represents about 3.5 Gt. Moreover, the total potential storage capacity can be 146 Gt including the storage in geological structure with stratigraphic trapping, etc. (<http://www.rite.or.jp/English/lab/geological/survey.html>). According to the report by Central Environmental Council in Japan, it is suggested that about a half of the potential capacity can be economically attractive by 2050 (<http://www.env.go.jp/council/06earth/r064-03/ccs.pdf> (in Japanese)).

Industrial sector

The industrial sector is the largest emitter: its CO₂ emissions represent about 40% of total GHG emission in 2050 because fuel demand for high temperature heat is hardly replaced by low-carbon sources. Activity levels demonstrate a moderation of activity in energy-intensive sectors in line with restructuring of the Japanese industry: -23% for crude steel production (from 111 Mt in 2010 to 85 Mt in 2050) and -11% for cement (from 56Mt in 2010 to 50 Mt in 2050). Combined with energy efficiency, this ensures a reduction of final energy consumption by more than 30%. Fuel switching, and notably the phase-out of coal without CCS, contributes to improve significantly the carbon intensity of energy in the mid to long terms (Figure 7a).



Note: Carbon intensity shown in Figure 7 for each sector includes only direct end-use emissions and excludes indirect emissions related to electricity or hydrogen production.

Building sector

In residential and commercial sectors, final energy demand is reduced by approximately 60%, in line with a stability of commercial floor space (+3% only, from 18,3 Mm² in 2010 to 19 Mm² in 2050) and a 17% decrease of the number of households, hence reducing energy service needs in the residential sector. It is worth noting that fossil fuels (notably gas) remain important in the transition (until 2030), thus explaining a temporary rise of the carbon intensity before electricity becomes the dominant energy over the long term, hence ensuring a significant decrease of the carbon intensity in this sector in 2050.

Transport sector

In the transportation sector, CO₂ emissions in 2050 reduce by almost 80% compared to the 1990 level and account for about 17% of Japan's GHG emissions, as shown in Figure 4. In a context of a reduction of passenger total mobility (-10% of passenger transport demand) corresponding to an increase of

mobility per person, the 18% decoupling of freight transport relative to production is made possible by a combination of energy efficiency, electrification of the fleet, as well as hydrogen and a small diffusion of gas-fueled vehicles (for freight), reaching in total almost 50% of energy consumed, substitute for oil-based fuels and ensuring a continuous decrease of the carbon intensity of fuels in 2050 (Figure 7c).

2.2. Assumptions

Low-carbon technology options

A wide range of low-carbon technologies is taken into account in Japan's illustrative scenario, and include:

- In electricity supply: efficiency improvement of power generation, coal and gas with CCS, reduced T&D (Transmission & Distribution) line losses, wind power, solar PV, geothermal, bioenergy.
- In industry: energy efficiency improvement, electrification wherever feasible in industrial processes, natural gas use, CCS for iron making and cement lime, fuel economy improvement of agricultural machine, bioenergy use, nitrogen fertilizer management.
- In buildings: improvement of the energy efficiency performance of buildings, high-efficiency equipment and appliances, electric heat pump water heaters, energy management system.
- In transport: energy efficiency improvement, gas-powered heavy duty vehicles (HDVs), vehicle electrification, hydrogen vehicles.

Nuclear power

As future availability of nuclear power is still uncertain in Japan, electricity generation from nuclear plants and availability of nuclear power is based on the premises of *New Policies Scenario* of *World Energy Outlook 2013* published by International Energy Agency. According to the illustrative scenario, nuclear plants' lifetime is limited to 40 years for plants built up to 1990 and 50 years for all other plants, and during 2013 to 2035 an additional 3 GW nuclear plants capacity is included. Subject to these assumptions and maximum capacity factor of 70% for all plants, electricity generation from nuclear plants represents about 50 TWh in 2050.

Geologic carbon storage potential

Complying with previous studies, CCS technologies are assumed to be available from 2025 and annual CO₂ storage volume is assumed to increase up to 200 MtCO₂/year in 2050. The potential of storage of CO₂ is set to be around 5 GtCO₂. CCS technology can be applied to both power generation and industrial sectors. In the power generation sector, both coal plants and natural gas plants can be equipped with CCS technology, but bioenergy with CCS (BECCS) is excluded in this analysis. For industrial use, CCS technologies are available in iron and steel and cement sectors. In 2050, the amount of captured CO₂ in the iron and steel sector and the cement sector reaches about 60 MtCO₂ and 20 MtCO₂, respectively. A maximum capture rate of CO₂ by CCS technologies is assumed to be 90% for all CCS technologies.

Electricity interconnection

In Japan, as the regions with large potential of renewable energy are different from the ones with large electricity consumption, reinforcement of interconnection capacity would be helpful to facilitate more effective use of local renewable sources. In the illustrative scenario, due to reinforcement of electricity interconnection, carbon price to achieve 80% reduction target is reduced by about 9% because power

generation from renewable energy in Hokkaido and Tohoku regions becomes available in Tokyo region, the largest electricity consumer in Japan. The capacity of interconnection between Tohoku and Tokyo region is tripled during 2010 to 2050.

Demand-side management

Deployment of battery electric vehicle (BEV), heat pump water heater, and converting electricity into hydrogen can provide flexibility to electricity system through implementation of demand side management. In 2050, electricity peak demand in daytime becomes higher relative to off-peak demand, and this necessitates integration of substantial solar PV into electricity system.

2.3. Alternative pathways and pathway robustness

Decarbonization pathway without nuclear power

The Illustrative Pathway considers a gradual phase-out of nuclear but it still represents 19% of electricity generation in 2030 and 5% in 2050. However, no nuclear plant has been in operation since the end of 2013, though some nuclear plants have been put under safety inspection by the Nuclear Regulation Authority, and it is possible that a complete phase-out is decided. Therefore, it is worth considering a pathway that would consider a complete phase-out of nuclear to assess robustness of deep decarbonization pathways. In this scenario, no nuclear plant is assumed to restart in the entire period of estimation after 2014.

In such an alternative pathway, higher carbon intensity is experienced during the transition period where coal and gas without CCS compensates the gap caused by the phase-out of nuclear. But the impact of nuclear phase-out as compared to the illustrative scenario is relatively small in the long term, given the small share of nuclear in 2050 in any case. An 80% emission reduction in 2050 is still feasible with additional deployment of renewable energy and natural gas equipped with CCS.

Decarbonization pathway with less deployment of CCS

As the feasibility of deep decarbonization pathways crucially depends on the availability of CCS, a Limited CCS Scenario is prepared to assess further robustness. In this scenario, CO₂ storage volume is limited to 100 MtCO₂/year (half of the volume assumed in the Illustrative Scenario) and cumulative captured CO₂ reach about 1,550 MtCO₂.

Achieving long-term emission reduction target proves to be still feasible with substantial increase of renewable energy, particularly solar PV and wind power, in the long-term electricity supply, in place of natural gas equipped with CCS. In the scenario, the share of renewable energy in electricity supply reaches approximately 85% in 2050 and intermittent renewable energies account for about 63% in electricity generation in 2050, hence imposing a further challenge for integration into the electricity system. The utilization of the technologies that provide the desired flexibility, such as pumped hydro plants and demand side management using battery electric vehicles can be helpful to integrate large amount of variable renewable energies (VREs).

2.4. Additional measures and deeper pathways

The following measures should be considered for deeper decarbonization.

Further development and diffusion of innovative low-carbon technologies

The technologies listed in Table 2 are proven energy-saving technologies up to 2050. On the other hand, further improvement in energy efficiency of low-carbon technology beyond the levels assumed in the scenario analysis and development of innovative technology provide additional potential to reduce emission, especially in the industrial sector. In addition, system technologies such as reinforcement of electricity interconnection and demand side management system would be helpful for effective deeper decarbonization.

Change of lifestyle to reduce energy service demand while maintaining standard of living

Both in the illustrative scenario and in alternative pathways, substantial change in lifestyle and reduction of energy service demand is not considered. However, behavioral change has further potential to reduce energy demand affordably while maintaining the standard of living. For example, the material stock in developed countries is likely to saturate, and developing countries will also catch up with the developed countries in the future. The enhancement of service economy or stock economy will be able to reduce the material demand, and as a result, energy demand will reduce. Analyzing these effects could help with more refined assessment of deeper pathways.

Change of material demand and its energy service demand

Both in the illustrative scenario and in alternative pathways, substantial change in material production is not considered. However, with existing stock level of infrastructure and decline in future population, a small amount of material production to maintain the stock level is likely to be sufficient. For example, stock of steel in developed countries is estimated to be 4.9-10.6 ton per capita. If the quantities of material production are controlled, the energy service demand in industrial sector could be reduced further, and as a result, CO₂ emissions also could reduce.

Redevelopment of cities designed to consume less energy

Further reduction in emission and energy demand in cities can be achieved by change in urban form favoring even more important shift from private vehicles to public transport and reuse of waste heat. In addition, mitigation actions in cities often provide multiple co-benefits.

Relocation of industrial firms where unused energies are easily available

Though reinforcement of electricity interconnection is taken into account as an option in the scenario analysis, relocation of industrial firms would contribute to more effective use of heat from renewable sources and waste heat. Especially, at present most of the low temperature heat is disposed of. Though the locations of various industries and locations between industries and residential areas are well organized, there is a potential to improve energy efficiency and utilization of heat by reorganizing the locations, thereby further reducing CO₂ emissions.

2.5. Challenges, opportunities, and enabling conditions

Energy system transformation

Deep decarbonization in Japan requires a large scale transformation in the energy system. In particular, there is a huge challenge to integrate VRE, such as solar PV and wind power, into the electricity system. Additional plants that can provide flexibility, such as pumped hydro storage, are built to complement large-scale deployment of VREs in the scenario analysis. In addition, demand side management would

be an effective option but may not be implemented by a market mechanism alone, therefore, additional policy instruments such as dynamic pricing of electricity would be needed.

Promoting public acceptance of deep decarbonization pathways

The pace of deploying low-carbon technology is strongly influenced by public acceptance. In general, higher discount rates provide further opportunity to diffuse low-carbon technologies. Public acceptance of technologies may also involve social issues as well as economic barriers, because there are a wide range of possible co-benefits and adverse side effects that can be caused by diffusion of low-carbon technologies.

2.6. Near-term priorities

Avoiding lock-in of high carbon intensity infrastructure

Some infrastructures such as power plants and buildings entail considerable lock-in risks because the majority of those introduced in the near term would remain in 2050. As some gas combined-cycle plants as well as coal plants have to be equipped with CCS in 2050, newly built plants should be CCS-ready in addition to the introduction of the best available technology.

Continuation of electricity saving

After the Great East Japan Earthquake in 2011, electricity use had been reduced in order to avoid blackouts due to the Fukushima accident and the suspension of other damaged power plants. Continuing these actions could be helpful for deep decarbonization.

Reducing near-term impact of energy import price

Since 2011, fossil fuel import values have increased in Japan due to the rise in global crude oil price, the depreciation of Japanese Yen, and the suspension of nuclear plants. Immediate actions for deep decarbonization that decrease fossil fuel demand can contribute to reducing the impact on the economy in the near term.

Mexico

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1. Country profile

1.1. The national context for deep decarbonization and sustainable development

GHG emissions in Mexico are rising due to an increasing use of fossil fuels. As the population slowly stabilizes (projected to be 151 million by 2050)¹ and continued economic growth is expected, it is crucial to design a deep decarbonization strategy before new infrastructure is built. Many actions to mitigate climate change have valuable co-benefits (local health improvement, economic savings, and greater productivity, among others), and some are also linked to poverty reduction and social inclusion (for example food and energy security).

Proven reserves of oil in Mexico are estimated to be around 1,340 million tons of oil equivalent (toe), while gas reserves represent an additional 430 million toe.² The national energy reform approved recently is expected to boost investments in oil and gas production. Electricity generation is mainly produced from natural gas (50%), oil (11%), hydro (15%), and coal (13%); energy-intensive industry accounts for 23% of GDP.

Urban population reached 72% in 2010, and it is expected to be close to 83% by 2030. Around 98% of households have access to electricity to date, and there are 210 vehicles per 1,000 people. In some rural areas, wood is still used as the main fuel for heating and cooking.

The majority of future economic growth is expected to be driven by tertiary activities (services), which could account for nearly 70% of national GDP by 2050; in 2010 they represented around 60% of the total GDP. As this sector is less intensive both in energy and in CO₂ than other economic activities in Mexico, this shift is expected to decrease GHG emissions.

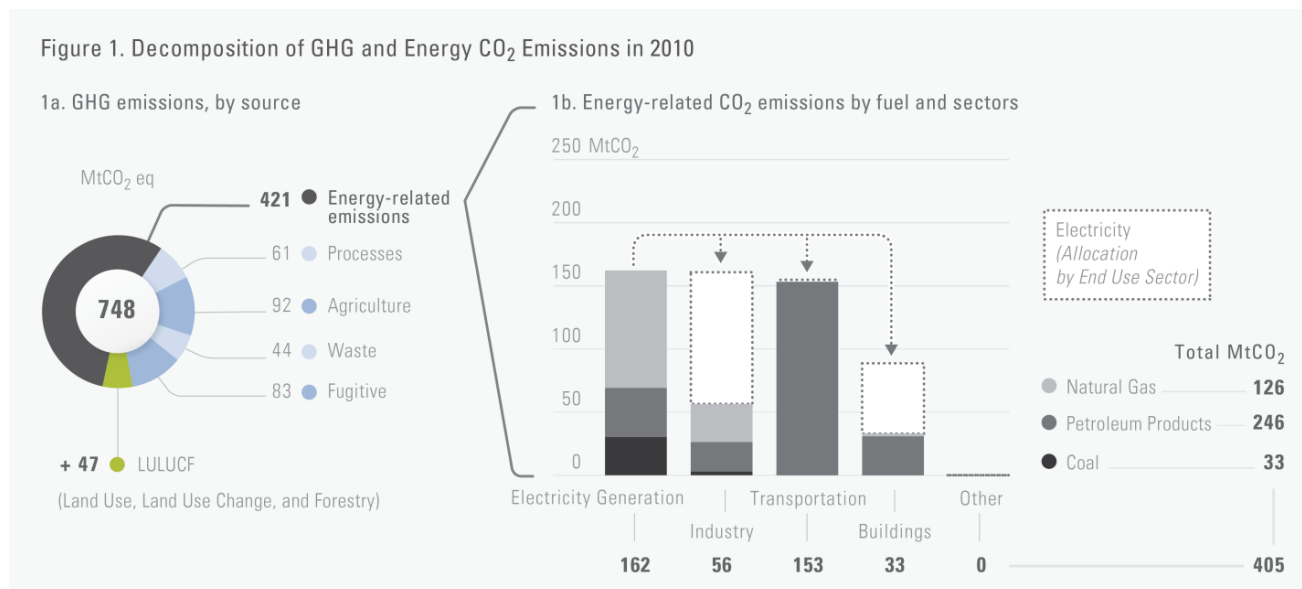
As GDP per capita increases, medium-sized cities are expected to grow. Historic trends show that urban centers expand in patterns that increase energy consumption and land use change. Smart urban development has been identified as a key way to transition towards more efficient and sustainable green growth schemes in Mexico.

¹ Comisión Nacional de Población (CONAPO), at: <http://www.conapo.gob.mx>

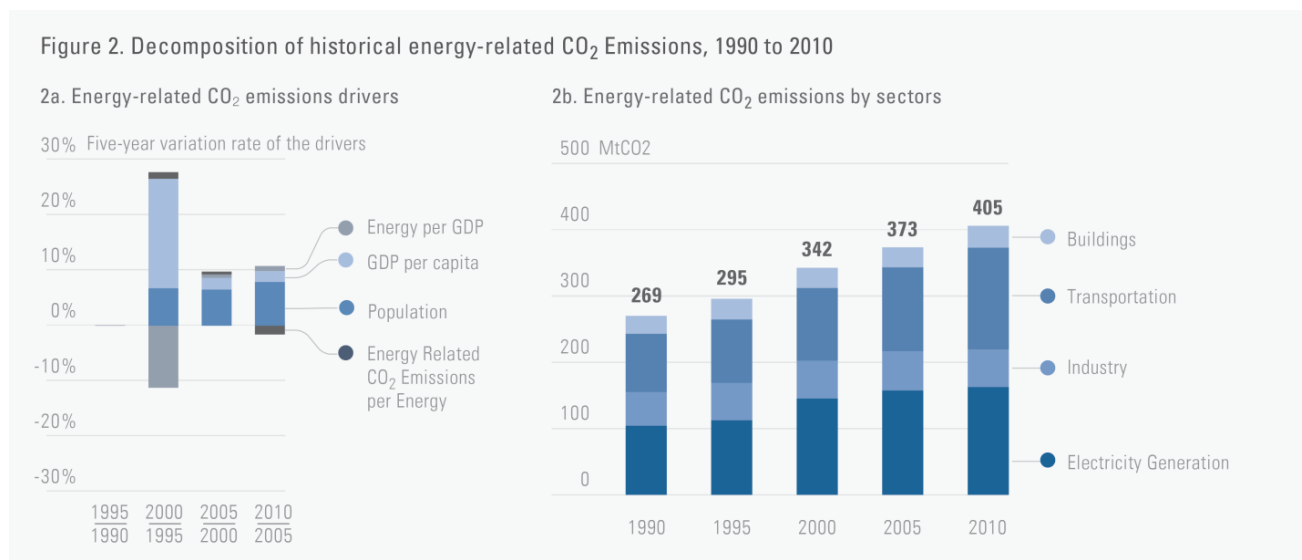
² Data reported for January 2014. SENER, 2014, at: <http://egob2.energia.gob.mx/SNIH/Reportes/Portal.swf?ProgGuid=FCAF8F9D-21D6-4661-98B5-55D84B9C1D85>

1.2. GHG emissions: current levels, drivers, and past trends

Total GHG emissions in Mexico reached 748 MtCO₂e in 2010.³ The largest source of emissions is the combustion of fossil fuels (56%), and the greatest contributors to this category are the transport sector and electricity generation (Figure 1).



Historically, GHG emissions in Mexico have been driven by increases in both population and in GDP per capita (Figure 2a).⁴ Energy use per capita has increased as well, at an average rate of about 1% per year between 1995 and 2010.



³ Inventario Nacional de Emisiones de Gases de Efecto Invernadero 1990-2010, INECC-SEMARNAT, 2013.

⁴ GDP increased 28% from 1995 to 2000 causing final energy per dollar of GDP to decrease noticeably in the same period. The significant increase in GDP reflects a recovery from the economic crisis of 1995, so only a limited amount of information can be gained from an examination of the 1995 to 2000 time period.

Total energy consumption reached around 176 million toe in 2010, including all consumption by final users (transport, industry, buildings), energy industries, and transmission losses.⁵ The distribution of final energy use was spread over the following fuels: gasoline (32%), electricity (16%), diesel (16%), natural gas (11%), LPG (10%), and wood (5%). Approximately 30% of all energy use is dedicated to transportation, and close to 70% of that energy is consumed by passenger transport alone. This trend reflects the increase in vehicle ownership, which doubled from 2000 to 2010 to approximately 207 vehicles per thousand people. This increased ownership and use has caused GHG emissions from the transport sector to increase at an annual rate of 3.2% between 1990 and 2010.

2. National deep decarbonization pathways

2.1. Illustrative deep decarbonization pathway

2.1.1. High-level characterization

The illustrative deep decarbonization scenario described in this report has been devised to achieve reductions of CO₂ emissions as a result of changes in energy use and production towards less emission-intensive alternatives. As shown in Table 1, this analysis assumes a GDP growth rate of approximately 3% every year,⁶ from around 950 billion USD (at 2008 prices) in 2010 to some 3,100 billion USD in 2050. GDP per capita would reach approximately \$20,425 USD/person by 2050.

Table 1. Development Indicators and Energy Service Demand Drivers

	2010	2020	2030	2040	2050
Population [Millions]	113	127	137	145	151
GDP per capita [\$ /capita]	8,339	9,987	12,407	15,764	20,425

Much of projected reduction in CO₂ emissions across sectors relies on reducing the carbon intensity of electricity generation coupled with a switch from the combustion of fossil fuels to use of electricity in those final uses of energy where it is possible to do so. Although some assumptions were made regarding the future energy consumption of some appliances, the deep decarbonization scenario modeled does not include the effects of dedicated schemes to *accelerate* improvement of energy efficiency faster than historical trends.

Non-electric fuel switches include a shift to natural gas from petroleum coke, coking coal, diesel, and residual fuel oil used in industry, as well as partial use of ethanol, natural gas, and biodiesel in transport to reduce gasoline and diesel consumption.

This exploratory deep decarbonization scenario to 2050 assumes that primary energy systems in Mexico migrate from a heavy dependence on oil to pipeline gas, renewables, and nuclear power and that end-use energy will be provided mainly by electricity and natural gas (Figure 3). However, it is

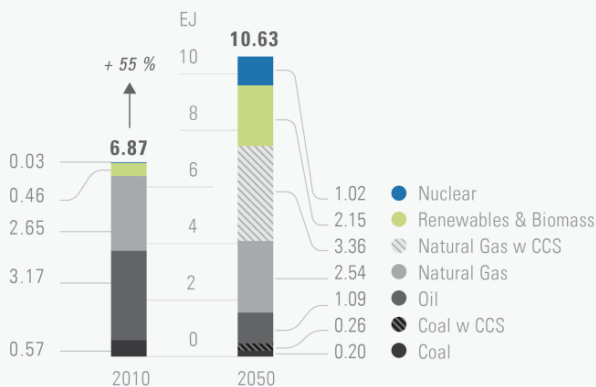
⁵ Balance Nacional de Energía, Sistema de Información Energética, SENER, 2014.

⁶ Official estimates for annual GDP growth in 2014 have been recently adjusted from 3.1% to 2.8% (Banco de México, communiqué: <http://www.banxico.org.mx/informacion-para-la-prensa/comunicados/resultados-de-encuestas/expectativas-de-los-especialistas/%7BB22F53FD-4129-ECE1-85E3-BCA42D652B16%7D.pdf>). In this study we assume 3% annual growth as illustrative of a modest constant growth in the long term.

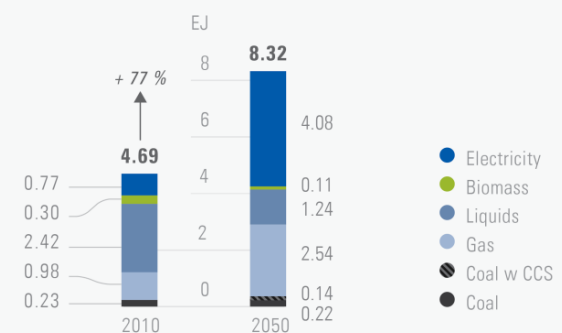
important to emphasize that a number of factors make it impossible to anticipate what specific technology choices will be made in Mexico, including the fact that the country is undergoing a major reform of its energy sector, which will affect regulation, planning, and the presence of private sector providers. As a result, this scenario in no way represents an expected or recommended pathway, and is neither government policy nor an official document of planning or intent. It merely seeks to lay out what a potential scenario could look like, in order to explore possible interplays between technologies and their feasibility considerations.

Figure 3. Energy Pathways, by source

3a. Primary Energy



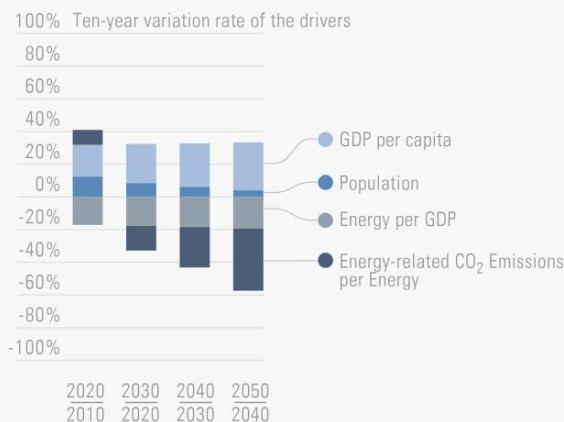
3b. Final Energy



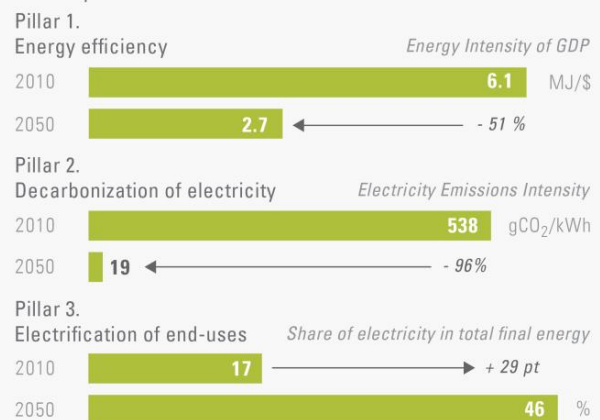
This deep decarbonization scenario shows a substantial (96%) reduction in the GHG emissions released per unit of energy produced from 2010 and 2050 (Figure 4). Energy intensity of GDP also decreases, at a less aggressive rate of 2% each year to yield an overall reduction of 55% from 2010 to 2050. Finally, there is a substantial increase in the share of electricity in final energy use from 17% in 2010 to 46% by 2050.

Figure 4. Energy-related CO₂ Emissions Drivers, 2010 to 2050

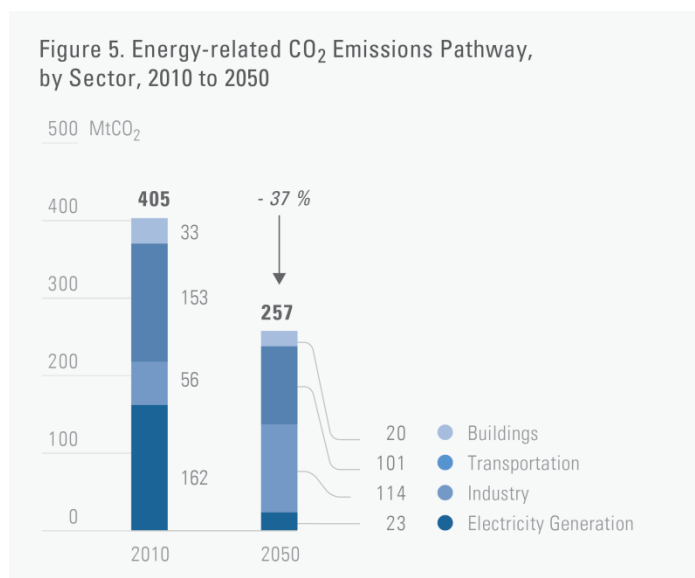
4a. Energy-related CO₂ emissions drivers



4b. The pillars of decarbonization



The scenario assumes drastic reductions in the GHG emissions from electricity generation and transportation and lower reductions in buildings when comparing emission levels from 2050 to 2010 (Figure 5).



2.1.2. Sectoral characterization

The prominent role of electrification as a decarbonization strategy prioritizes a reduction of GHG emissions intensity in the electricity generation sector.

Electricity generation

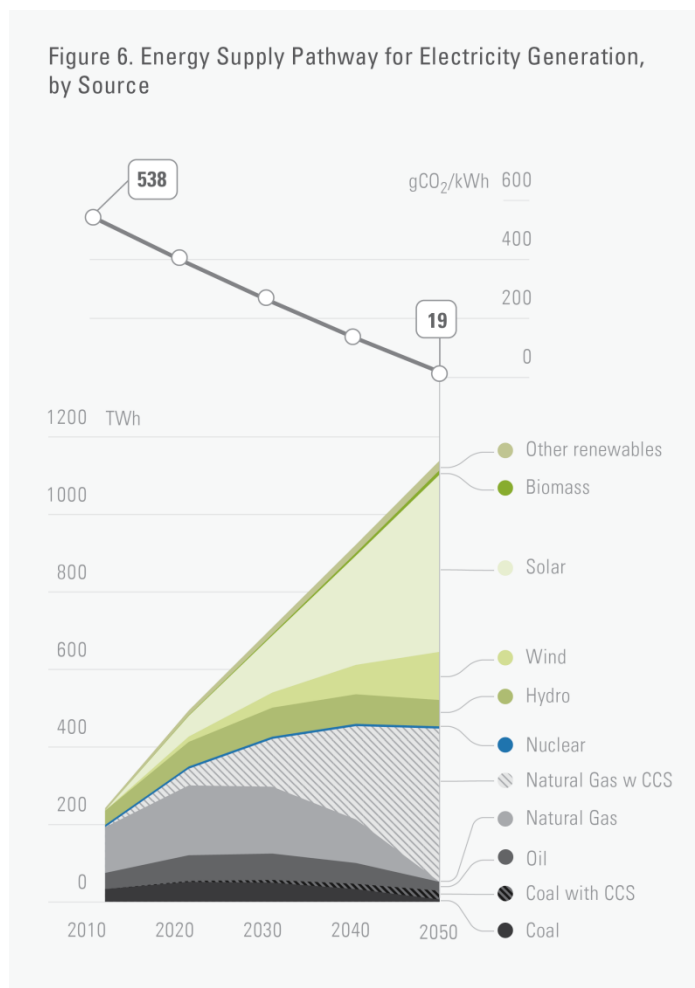
In 2010, electricity generation was associated with a CO₂ emissions intensity of 538 gCO₂ per kWh. Results of an initial analysis show that in order to be consistent with the deep decarbonization objective, carbon intensity would need to fall to around 20 gCO₂ per kWh by 2050. To accomplish this, the illustrative deep decarbonization scenario assumes electricity in Mexico will be generated from a larger share of renewables (especially solar), and natural gas with CCS.

The additional electrical power required to enable the electrification of energy demand is substantial at nearly 1,100 TWh by 2050. To meet this electricity generation need, the full potential for renewable energy resources identified to date has been taken into account⁷, which includes 6,500 TWh/year of solar, 88 TWh/year of wind, 77 TWh/year of geothermal, 70 TWh/year of hydro,⁸ and 11 TWh/year of biomass. Assuming that technological advances make it feasible to incorporate high levels of intermittency into the grid by 2050 (by developing energy storage capabilities, for example) a balanced mix was composed with the two main energy sources: solar (40%) and natural gas (35%). It is assumed that the rest of the supply is provided by wind (11%), hydro (6%), geothermal (2%), coal (2%), oil (2%) and nuclear (1%). Electricity generation from all fossil fuels (450 TWh) will require CCS in all generation plants (+60 GW) to comply with the stringent CO₂ emission intensity discussed above. Such a

⁷ Inventario Nacional de Energías Renovables, SENER, 2014, in <http://iner.energia.gob.mx/publica/version2.0/>

⁸ Includes estimates for large and small scale hydropower.

generation mix would have a share of intermittent renewable power of 51%⁹ and an average emission factor of only 19 g of CO₂ per kWh produced (Figure 6).



Energy consumption

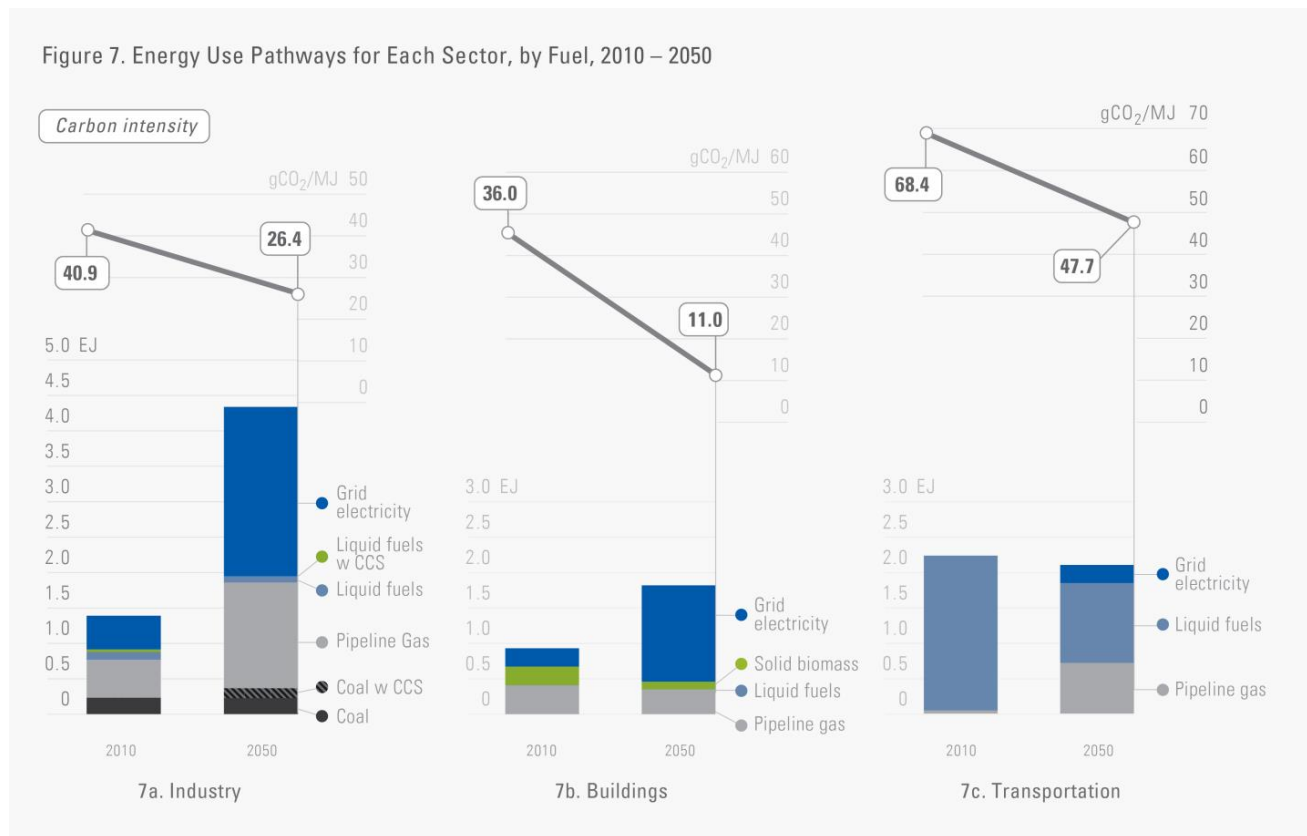
Under the deep decarbonization scenario illustrated here, final energy consumption would amount to approximately 200 million toe by 2050 (from industry, transport, and buildings). In this exercise, the reduction in carbon intensity of the industrial activity is achieved by the massive substitution of oil products (residual fuel oil, coke and, diesel) by largely decarbonized electricity (to around 55% of energy demand projected by 2050) and natural gas (35%). The resulting carbon intensity after such measures would be about two-thirds less than it is today (Figure 7a).

Due to the low energy requirements in households and Mexico's relatively mild weather, GHG emissions from buildings (residential and commercial sectors) have not historically been increasing at high rates. However, steps must be taken to ensure household energy consumption does not emulate North American trends. To reduce the building-related direct energy emissions, the scenario explores the substitution of gas (both LPG and natural gas) by electricity in final energy uses (figure 7b).

⁹ Hydro power is considered as part of intermittent technologies for two reasons: highly variable mini-hydro

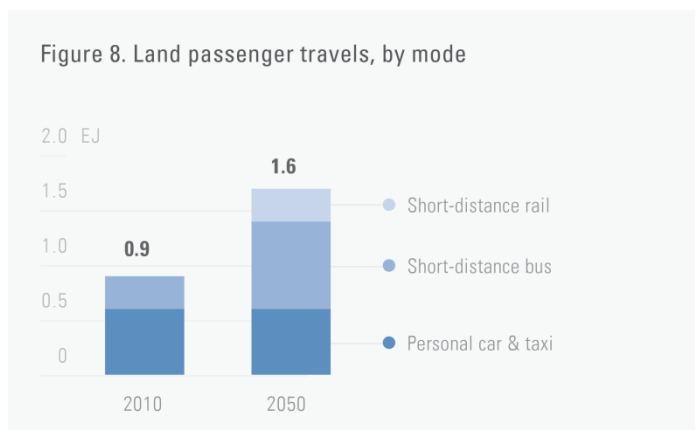
In the transport sector, a massive fuel shift from gasoline and diesel to electricity and natural gas has been considered as an illustrative decarbonization approach (Figure 7c and Figure 8), using three exploratory assumptions:

- 1) A passenger modal shift to mass-public electric transportation systems to satisfy the increasing travel demand;
- 2) Freight shift to electric trains and gas powered trucks; and
- 3) 60% of light vehicles (private cars and taxis) would switch to electricity, and 65% of freight would switch to natural gas and biodiesel by 2050.



Note: Carbon intensity for each sector includes only direct end-use emissions and excludes indirect emissions related to electricity or hydrogen production.

potential is an important part of future potential and the vulnerability of hydrologic systems to climate change.



2.2. Assumptions

The preliminary deep decarbonization scenario outlined in this report relies heavily on the complementarity between the electrification of energy usage across sectors and the simultaneous abatement of GHG emissions in the power sector. In order to do this the implementation of large infrastructure and investments for clean energy are required. In this scenario, we have emphasized the role of solar energy, together with extensive use of CCS techniques at gas power plants.

Achieving this very ambitious solar target (≈ 260 TWh/year, assuming a capacity factor of 20%) requires an aggressive cost reduction strategy that allows massive roll-out of said technology, both as dedicated solar power plants feeding the grid, as well as distributed production for households and industries, and investment in transmission lines. Further advances in energy storage technology and smart grids will also be required to integrate so much intermittent resource into the grid, and would help limit demand on the grid and the need for even more generation and transmission infrastructure.

Given the large share of gas-fueled electricity projected in this scenario, Mexico would need the potential capacity to store approximately 200 million tons of CO₂ every year. A theoretical storage potential of 100 GtCO₂ has been identified in a preliminary study.¹⁰

Increasing the amount of electricity produced from renewable sources other than solar would require further exploration and technological development to exploit lower-yield potentials in wind, geothermal, and biomass resources.

The preliminary approach followed to deeply decarbonize the transport sector assumes the feasibility of implementation of extensive electric inter-modal mass transport systems. For this to be true at the required scale it would be necessary to change the present urban growth patterns. Today's medium-sized cities are expected to drive most of the future growth and would need to adopt and enforce best smart growth practices. This scenario also assumed that by 2050 electric vehicles will be widely available, and that it will be possible to divert freight from the road to electric trains without major technical issues.

¹⁰ The North American Carbon Storage Atlas (NACSA), 1st Edition, 2012. www.nacsap.org

2.3. Alternative pathways and pathway robustness

Given the dependence of this approach on the decarbonization of the electricity generation sector, it is important to explore alternative technological scenarios for this sector. In this analysis we assume the presence of competitive energy storage systems that enable grids to include a high share of intermittent sources (solar or wind power) and are valuable to manage overall demand. However, if such a solar plan is unfeasible, an alternative pathway must be devised, perhaps by increasing the share of nuclear power or natural gas with CCS.

2.4. Additional measures and deeper pathways

The projected GHG emissions resulting from measures considered in the illustrative deep decarbonization scenario could be further reduced by additional actions that have not been yet evaluated.

Other options that have not been explored at full capacity in the present study and that may have interesting potential are: additional renewables (wind, geothermal, and marine power), industrial processes redesigned to decrease energy intensity and byproduct GHG emissions, large-scale CCS in industrial facilities, massive adoption of hybrid vehicles, large-scale production of bio-fuels for transport, and partially substituting the natural gas in the pipeline network with lower-carbon alternatives.

Municipal and agricultural waste can be a source of biogas, rather than GHG emissions. Utilizing biogas from landfills and water treatment operations might help lower future consumption of natural gas for electricity generation.

2.5. Challenges, opportunities and enabling conditions

Major challenges that may deter realization of this scenario include current energy subsidies (both for fossil fuels and electricity), economic potential, lack of resources to fund the transition, and the technological availability of cost-effective options for CCS, electric vehicles, solar power harvesting, and biofuels production.

Amongst the enabling conditions that require international cooperation, we identify technology development for energy storage and energy management (smart demand and smart grids), carbon taxes to imports and exports of fossil fuels, and the development of zero carbon or carbon negative agriculture and forestry techniques to support production of sustainable bioenergy crops and reduce emissions from these sectors.

2.6. Near-term priorities

Although this is an initial exploration of deep decarbonization in Mexico, some conclusions can be drawn from the magnitude of the challenge at hand. Adoption of better practices in urbanization and territorial planning could prove crucial to lower future energy consumption per capita and simultaneously improve quality of life. Better-organized cities could induce the behavioral changes needed for mode shifts in transportation.

A robust low-carbon electricity generation policy is required to evaluate different future alternatives, increase certainty over governmental plans, and provide an economically feasible route for future development.

Energy efficiency programs coupled with appropriate energy price signals could help decrease the financial burden of the transformation needed by reducing energy demand and thus reducing the amount of funds needed to transition towards a deep decarbonization development pathway.

Russia

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1. Country profile

1.1. The national context for deep decarbonization and sustainable development

With the largest territory of the world (17 billion km², of which 67% are on permafrost), the Russian Federation has a very low population density (8.4 person per km²). It is endowed with large fossil fuel reserves representing 34% of world reserves of natural gas, 12% of crude oil, and 20% of coal. The energy sector is logically dominated by fossils fuels, which are importantly used for exports (around 40% of the 1.7 billion tons of coal equivalent (tce) extracted natural gas, coal, and crude oil is exported).

The forest area covers 1.2 billion hectares, most of which is owned by the State (97%). The agricultural land occupies 220 mln hectares and is used mainly for plowing, crops, forage production, and livestock pastures. The total waste production is approximately 4 billion tons per year, less than half of which is utilized or treated.

National production is structured around industrial production (30%), trade (19%), services (12%), transport and communication (8%), agriculture (4%), and construction (7%). An important characteristic of the industrial sector is the rather high overall depreciation of industrial capital. Since more than 80% of assets are more than 20 years old across all carbon-intensive industries and sectors, industrial modernization is one of the high priorities for the national government. Similarly, the overall capacity structure of the power generation sector is quite old, as the main investments were made in the 1960-1980s, and almost all large units will exceed their expected service life and become obsolete in 10-20 years. Notably, in 2010, out of the 146GW thermal power and combined heat and power (CHP) plants, 91 GW were more than 30 years old, and 46 were more that 40 years old. Another important specificity over recent years is the intense rise of the transportation sector, notably for private cars which have reached 38.8 millions units or 257 cars per 1,000 people in 2013.

The long-term strategic goals of economic development are stipulated in various official documents, such as the Concept of Socio-Economic Development by 2020,¹¹ Energy strategy – 2030,¹² General

¹¹<http://www.economy.gov.ru/minec/activity/sections/strategicplanning/concept/>

Scheme of Electricity Units Allocation – 2030,¹³ and others. The specific climate change mitigation policy objectives are provided in the Russian Climate Doctrine (2009),¹⁴ Presidential Decree “On greenhouse gas emission reduction” (2013)¹⁵ and its Implementation Plan adopted by Government (2014),¹⁶ as well as the sectoral and industrial plans and programs (*e.g.* the energy efficiency improvement program, environmental policy, forestry, agricultural, and many others).

The main focus on longer-term development goals in Russia deals with the economic growth, diversification of the economy, modernization of its technological base and infrastructure, increase of the share of innovative, knowledge-based sectors, improvement of environmental quality, and population wellbeing. The long-term targets for carbon emissions by 2050 have not been identified as yet, and the deep decarbonization strategy is still to be developed and adopted by Russia.

1.2. GHG emissions: current levels, drivers, and past trends

The structure of domestic energy consumption is centered on fossil fuels, where natural gas, coal, and petroleum represent respectively 52%, 12%, and 35% of total demand. Electricity generation is mainly based on thermal power plants (68% of total production), and major alternatives include hydropower with 15% and nuclear with 16%. The share of renewable sources is negligible (below 1% of total primary energy production).

In 2011, Russia’s GHG emissions were dominated by CO₂ emissions, contributing to 73% of total GHG emissions essentially from fossil fuel combustion, which account for 1,502 MtCO₂e or 65% of total emissions (2011). Other major sources of emissions include fugitive emissions from the energy sector (418 MtCO₂e, or 18%) and industrial processes (mineral products, chemical industry, metal production, production and consumption of halocarbons and SF₆) (174 MtCO₂e, or 8%). The agriculture, waste, solvent, and other product use jointly account for 225 MtCO₂e (10%).

Carbon sinks (forestry and land use) play an important role in Russian carbon balance and are also of high political concern due to perception of the national forest as a source of global ecological gift. In 2011, the net carbon sequestration (in “managed forest”) amounted to 624 MtCO₂e, “compensating” 27% of total national GHG emissions.

In this study, the main focus is on carbon emissions related to the Russian energy sector, covering primarily CO₂ emissions from electricity generation, industries, transport, buildings, and other sources. The share of these sources is approximately two-thirds of total national emissions (Figure 1).

Total GHG emissions in Russia decreased by 31% over 1990-2011, from 3,300 to 2,300 MtCO₂e (Figure 2), caused by dramatic drop of industrial production after the collapse of USSR in 1991. The 1999-2011 period was remarkable for Russia as it demonstrated clear decoupling of economic growth and carbon emissions (only 17% increase of emission for 95% GDP increase). The main drivers of this evolution include economic growth, structural changes in the economy, technological changes (modernization), fuel switch from coal to gas, growth of energy prices, and corresponding energy saving. Less, but still

¹²<http://minenergo.gov.ru/aboutminen/energostrategy/>

¹³http://minenergo.gov.ru/press/min_news/3915.html

¹⁴<http://kremlin.ru/acts/6365>

¹⁵<http://kremlin.ru/acts/19344>

¹⁶<http://government.ru/media/files/41d4d0082f8b65aa993d.pdf>

important factors for carbon emission dynamics include transport and infrastructure development, waste management, agricultural production, forest policy (reforestation, forest management), etc.

Figure 1. Decomposition of GHG and Energy CO₂ Emissions in 2010

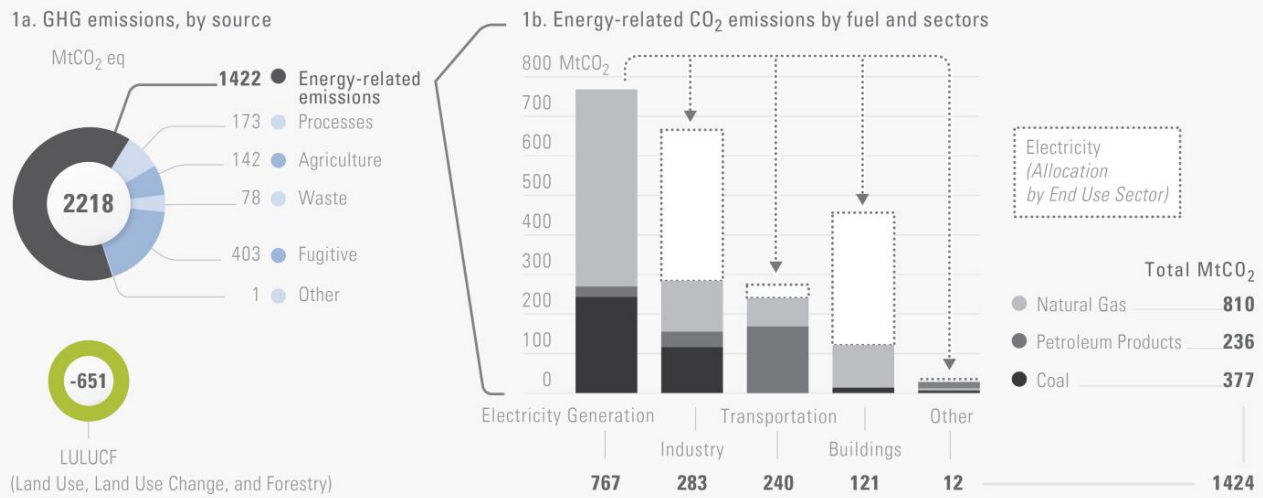
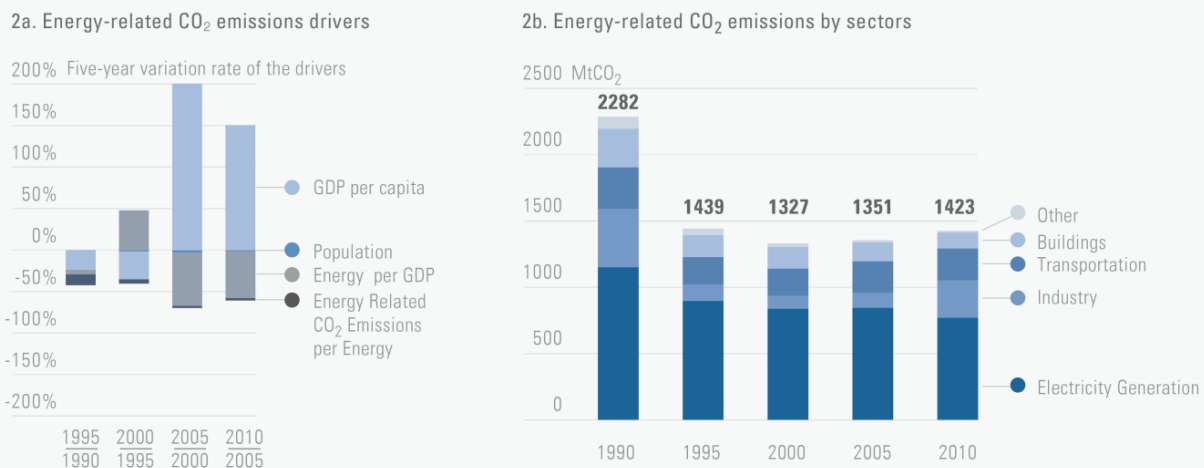


Figure 2. Decomposition of historical energy-related CO₂ Emissions, 1990 to 2010



2. National deep decarbonization pathways

2.1. Illustrative deep decarbonization pathway

2.1.1. High-level characterization

The illustrative scenario discusses the technical feasibility of a low-carbon economic development under assumptions on economic growth (notably, increase of steel and cement production, as well as

increase of mobility) and patterns of development integrating a set of assumptions from official,¹⁷ independent, and experts' visions and assumptions of Russian long-term economic development, technologies development reviews, and projections by the Russian and international organizations, as well as extensive expert consultations.

Then the scenario of economic development is simulated with technological model RU-TIMES with a decarbonization target set up at 1.67 t of CO₂ per capita in 2050. Uncertainties and robustness of conclusions are discussed in section 2c.

Table 1. Selected assumptions and results about the socio-economic and energy sector development for the deep decarbonization scenario in Russia

	2010	2020	2030	2040	2050
Population (millions)	142	137	132	126	120
GDP per capita (constant 2012 US\$)	13,116	19,127	25,726	32,932	40,833

The scenario assumes a population decline from 142 to 120 million people in 2050 and the (almost) tripling of per capita GDP. The simulation of total primary energy supply (TPES) and final energy production are shown in Figure 2. The deep decarbonization results in a decline of TPES by 27% in 2050, with significant changes in the structure of energy production: total coal use drops to 2.8% (half of it with CCS); natural gas contributes 36% of TPES but almost half of it should use CCS; the share of oil should drop to 7.1%; renewables' share including biomass rises to 32.5%; and the share of nuclear can reach 21.8%.

The final energy consumption (from 538 Mtoe in 2010 to 428 Mtoe in 2050) in Russia should also be significantly transformed in the deep decarbonization scenario: coal use to be phased out to 1.6%; the share of gas to reach 23.5% of TPES; liquid fuel to decline to 9.1%; while the share of biomass should reach 11.9% of TPES and electricity and heat 53.9% by 2050.

The scenario pinpoints a decline of energy-related CO₂ emissions from 1,422 Mt in 2010 to 200 Mt in 2050. The share of renewables in energy balance moves up to 10% in 2050 (0% in 2010).

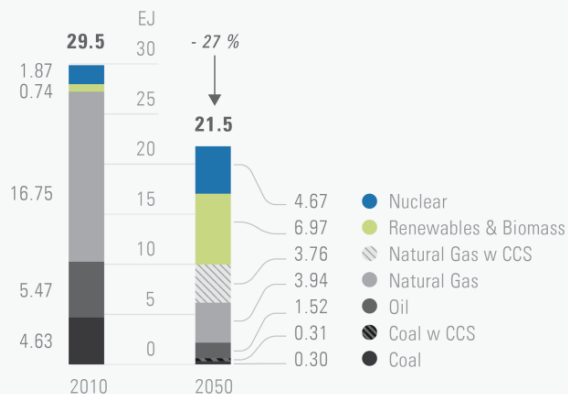
The decomposition of energy-related CO₂ emission drivers and its pillars show that the growth of GDP per capita drives CO₂ emission up and is offset by the following emissions abating drivers:

- The reduction of the use of primary energy per unit of GDP: the energy intensity of GDP must decline from 376 to 141 GJ/\$;
- The decarbonization of energy production: the carbon intensity of electricity generation should decline from 846 to 14 gCO₂/kWh;
- The electrification of the economy: the share of electricity in total final energy consumption should increase from 16% to 34%; and
- A declining population.

¹⁷ Concept of the Long-Term Socio-Economic Development of Russian Federation (2008), Energy Strategy – 2030, industrial and sectoral programs of development (electric power sector, transport, metallurgy and others), IEA Technology Perspectives (2010, 2012, 2014), and others.

Figure 3. Energy Pathways, by source

3a. Primary Energy



3b. Final Energy

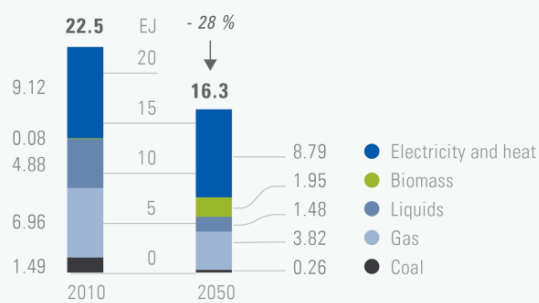
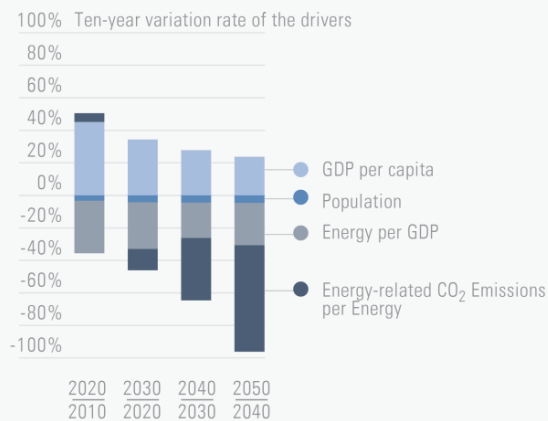


Figure 4. Energy-related CO₂ Emissions Drivers, 2010 to 2050

4a. Energy-related CO₂ emissions drivers



4b. The pillars of decarbonization

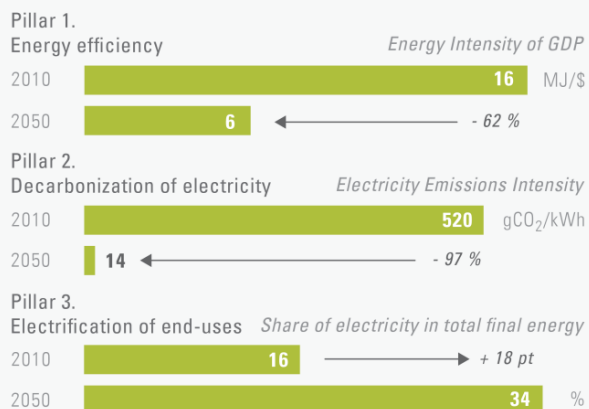
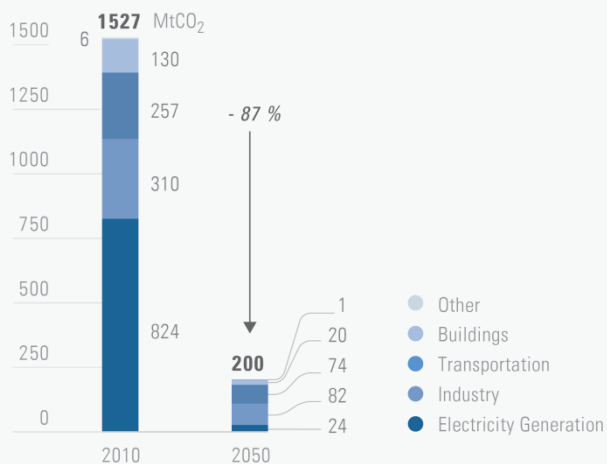


Figure 5. Energy-related CO₂ Emissions Pathway, by Sector, 2010 to 2050



2.1.2. Sectoral characterization

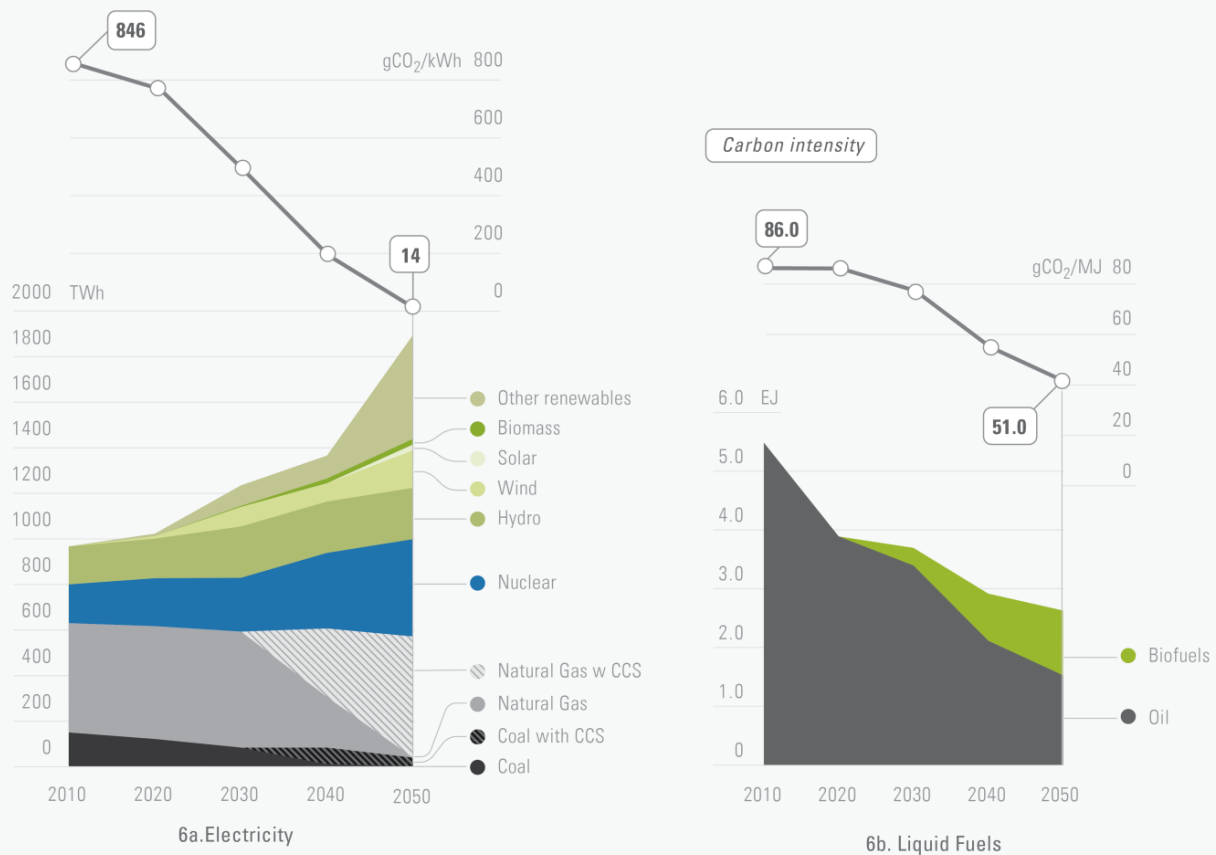
Electric power sector

The electric power sector is key in the decarbonization of the Russian economy. Electricity itself is a convenient, clean energy source that can be produced with zero- or very low-carbon technologies. The Russian electric power sector has 700 power and combined heat and power (CHP) plants (over 5 MW of capacity). The total installed capacity accounts for 223 GW (in 2012), of which zero-emission capacities include 46 GW of hydro and 23 GW of nuclear power plants. The rest is covered by natural gas and coal-fired power plants. The forthcoming retirement, made necessary by the obsolescence of the majority of fossil-based power stations, creates both opportunities and challenges for the industry. The modernization will improve energy efficiency of the sector, which is far below best available technological options. The excessive capacities and slowly-growing demand limit opportunities for investment in the industry.

There are several strategies possible to decarbonize the power industry, including growth of nuclear and hydropower (already planned by the industry) and growth of renewables' share in the energy mix. However, with assumed CCS availability, the significant expansion to meet the low-carbon target will be required only after 2040.

The CCS technologies are assumed to be commercially available, and they will play an important role in the decarbonization strategy in the power sector in Russia beyond 2030. Almost all remaining thermal power plants (coal and natural gas fired) need to be equipped with CCS technology by 2050 to reach the deep decarbonization target (Figure 6).

Figure 6. Energy Supply Pathways, by Resource



Transportation

It is expected that the recent trends of fast-growing mobility demand continues, leading to a 100-150% rise of passenger transportation by 2050 and an increase of light duty vehicles (LDV) and air transport.

The reasons for this growth include growing GDP per capita, expansion of the loan market, and a shift from public transport to private light duty vehicles (LDVs). The low-carbon technological options in the LDV sector include liquefied petroleum gas (LPG) engines in the mid-term and expansion of biofuel use in the long run with updating LDV to the best available technologies. The electric vehicles will likely meet delayed expansion in Russia due to tough (cold) climate conditions, unless the technology improves Plug-in hybrids with internal combustion engines on LPG or biofuel may be more competitive.

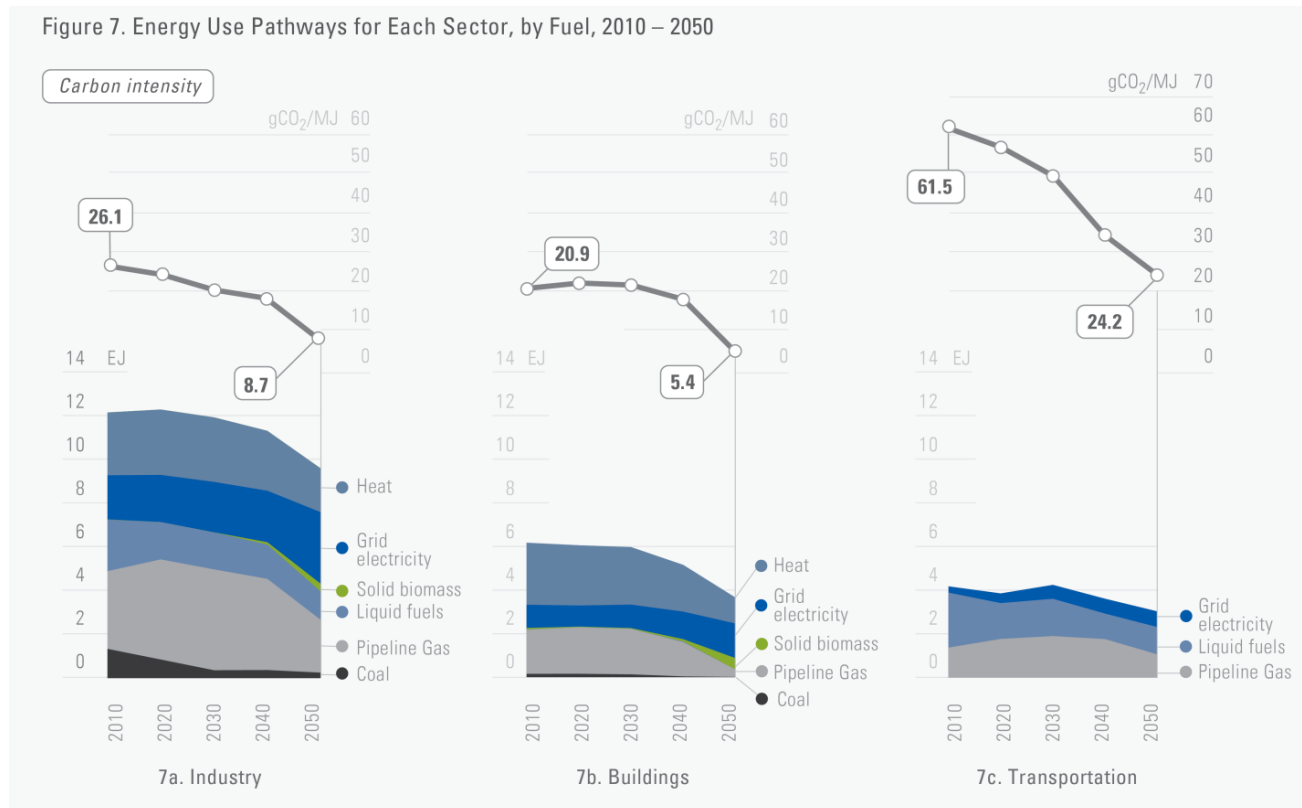
Another challenge is limiting emissions from air transportation, which will notably be permitted by the introduction of biofuels.

The freight transportation (rise from 2,119 bln t*km to 3,608 bln t*km in 2050) can be decarbonized at relatively low costs. The heavy-duty vehicles (HDVs) could use LPG and liquefied natural gas (LNG) in medium-term. In the long-term, biofuels would be the primary option.

The biggest polluter in transport sector will be pipeline transport. There seem to be no alternative to the use of natural gas as fuel to transport natural gas via pipelines. So the amounts of consumed natural gas will be defined by the domestic natural gas consumption and exports via pipelines.

With all the decarbonization measures applied, emissions of the transport sector in 2050 can reach 36.6 MtCO₂e (Figures 7c). In final energy consumption, the share of electricity will move up from 7% in 2010 to 28% in 2050, with fall of oil products from 93% in 2010 to 8%, and increase of biofuels up to 44%.

Figure 7. Energy Use Pathways for Each Sector, by Fuel, 2010 – 2050



Note: Carbon intensity shown in Figure 7 for each sector includes only direct end-use emissions and excludes indirect emissions related to electricity or hydrogen production.

Buildings

The residential buildings in Russia contain huge potential for energy efficiency improvements. The heating system in Russia is historically highly centralized, with around 75% of heat being supplied by district boiler houses and combined heat and power boilers (CHPs). The overall depreciation of the heat supply system is over 50%.

The considered scenario assumes 30% growth of living space area per person, from 23 m² per capita to 30 m² per capita in 2050, as a catch-up with average living space per person for European countries (which is around 35-45 m² per capita). The decline of population over 2010-2050 however limits the expansion of total residential surface.

The deep decarbonization pathway requires tapping the existing reserves in energy efficiency improvement of buildings and overall residential heating systems. The scenario assumes a drop in energy consumption of buildings by 6 times to the level of 60 kWh per m² by 2050 (this is still a

conservative estimate, compared to the best practice estimated around 15 kWh/ m² per year). The fuel mix structure should also be significantly changed with notable increases in biomass, electrification, and wide use of geo-heat pumps for heating.

The commercial and residential buildings have to follow the same strategy of energy efficiency growth, with additional electrification where possible and reduction of fossil energy consumption. Figure 7b shows total energy balance of the residential and commercial sectors, consistent with the deep decarbonization target.

Industry

Industrial output of energy intensive industries (iron and steel, non-ferrous metals, chemicals and petrochemicals, mining, and cement) is assumed to grow up to 26% over the next four decades (steel production rises from 66 Mt to 83 Mt and cement from 49 Mt to 69 Mt), and 10% in other energy intensive industries. Important energy efficiency gains and changes in the energy mix are then necessary to make this significant growth compatible with limitations of associated emissions.

The largest energy consumer in industry is integrated iron and steel (IIS) production. Since 1990, the IIS industry showed significant energy efficiency improvement that resulted in more than 20% reduction in carbon intensity of steel production due to retrofit and replacement of fixed capital. Further improvement, as expected, will lead to 35% additional energy efficiency, mainly due to the adoption of blast-furnace gas recycling technologies, which will increase carbon intensity of the steel production to EU level. However, for deeper reductions, further energy efficiency improvement technologies should be considered, such as direct reduced iron (DRI) on natural gas with potential to reduce CO₂ emissions up to 20-30% (with decarbonized electricity).

Processes of other energy-intensive industries are very diverse, and a moderate decarbonization potential of the remaining industries is considered, mainly by means of electrification of the industries from 14% to 34%, and a 6% energy efficiency growth from 2010 to 2050. The total fuel mix structure of industry and other remaining sectors (agriculture, forestry, fishing) consistent with the deep decarbonization scenario is presented in Figure 7a.

Agriculture, land use and forestry

The land use and forestry sector (LULUCF) is a very important source of carbon emissions and abatement in Russia. Since 1990, the net carbon sequestration in LULUCF increased up to 628 MtCO₂ due to relatively low levels of logging, low shares of over-matured wood, and other factors. However, the carbon net sink in Russian forests is expected to decline, and the net sink will become negative (emissions will exceed sequestration) by the mid-2040s¹⁸ due to an increasing share of over-matured forest, expansion of forest fires and diseases, insufficient adaptation policies and measures, etc.

In order to keep and enhance the carbon sequestration capacity of Russian forests, as a large source of CO₂ absorption from the atmosphere, substantial enhancement and strengthening of climate change policy in the forest sector is required, including international cooperation in scientific, forest monitoring, forest fire and disease control measures, investment, and technological support.

¹⁸http://unfccc.int/files/national_reports/annex_i_natcom/submitted_natcom/application/pdf/6nc_rus_final.pdf

2.2. Assumptions

The major technological conditions for reaching deep decarbonization in Russia include:

- 1) Pursue aggressive end use efficiency across all sectors;
- 2) Electrify where possible, and use gas where not possible to electrify;
- 3) Decarbonize the power sector by increasing the use of renewables, nuclear, hydropower plants, and maximize efficiency of thermal power and CHP plants;
- 4) Methane leakage, especially in extraction, storage, and transportation of natural gas is not covered by the scenario but will require substantial reduction;
- 5) Deep decarbonization of industrial production (*e.g.* metallurgy, cement, chemicals, and other);
- 6) Decarbonization of transport sector via electrification, biofuel use, etc.;
- 7) Energy efficiency improvement of all type of buildings;
- 8) Use of carbon capture and storage (CCS);
- 9) Utilization of huge biomass fuel potential, as well as other renewable energy sources; and
- 10) Large-scale heat production using heat pumps and energy saving in residential and commercial sectors.

2.3. Alternative pathways and pathway robustness

The most critical technological assumption in the analysis is CCS availability, biofuels potential, and scope of application of geothermal heat pumps for district heating. Although CCS has been tested in pilot projects around the world, the technology is not commercial yet, and it is uncertain if it will be available under competitive costs in Russia.

With significant resources of biomass, costs and feasibility of biofuels production depend on many factors, including location, type of bio-resource, process of development, and competitiveness of the technology.

In case one of these technological assumptions cannot be realized, alternative low-carbon strategies should be considered. If CCS is not available, renewables might be used instead. The current scenario is quite conservative for renewable energy in electricity production (about 25% in total generation) versus other countries, where renewable energy may reach more than 80%. Though Russia has relatively lower potential for mainstream solar and wind power, there is more than significant potential of tidal and hydro energy. A higher share of nuclear power is another alternative. Electrification of transport can be an alternative to biofuels. Higher energy efficiency improvements of buildings can reduce demand for heat and geo-heat pumps.

2.4. Additional measures and deeper pathways

Though the discussed scenario already has an ambitious target, additional measures could be envisaged to trigger deeper emission reductions notably through further electrification of industry, transport, final use sectors, and energy efficiency improvement. In particular, under specific conditions to be investigated more precisely, the following measures could be envisaged:

- Maximizing production of renewable electricity, harvesting tidal energy, hydro-power;
- Maximizing energy efficiency of buildings;
- Application of CCS in industry, including cement and iron and steel;

- Combination of biomass energy with CCS;
- Hydrogen-based technologies where possible, including transportation and steel production; and
- Optimizing public transportation, reducing number of trips, switching from private cars to public transport, and from air-transport to trains.

2.5. Challenges, opportunities and enabling conditions

The deep decarbonization of Russian economy will require significant efforts from government, businesses, and citizens. Rearrangement of the national economy in favor of low-carbon production technologies and a much less traditional use of fossil fuels will require dramatic changes in strategic planning, technological innovations, environmental regulation, low-carbon energy production technologies, relevant transport standards and infrastructure, household behavioral changes and, certainly, strong political will.

Evidently, Russia has an enormous potential for deep decarbonization. It has the necessary natural capital and territory, technological and scientific potential, and financial resources. The biggest challenge though is to channel the political will and business efforts towards the deep decarbonization pathway.

In the current context, when the major share of Russia's industrial capital assets are depreciated and require renovation and modernization, it is a great opportunity for starting the new capital investment cycle based on the deep decarbonization platform.

Russia can also play a significant role in exporting clean (carbon free) energy and products to neighboring countries, based on the implementation of large-scale projects on tidal energy generation in the North-West and Far East of Russia (with unique natural conditions), production of the second generation liquid and solid biofuels. The competitiveness of the new types of energy will be unlocked by emission reduction targets around the world.

Obviously, the international "decarbonization regime" would play an extremely important role in Russia's mitigation efforts, both in terms of scale and speed of changes required. Involvement of Russia in international initiatives would be crucial, including technological cooperation, implementation of investment projects (*e.g.* using Russian renewable energy sources, new generation nuclear power projects, etc.), global carbon pricing mechanisms, forest carbon sequestration and adaptation mechanisms (LULUCF, REDD+), scientific research on low-carbon development, etc.

These long-term cooperation frameworks need to be provided in the new climate change agreement with active participation of all major-emitting countries, as well as other international agreements under the UN, WTO, and others.

2.6. Near-term priorities

Near-term priorities for the Russian deep decarbonization pathway should include:

- Establishment of the information basis for emission management (monitoring, verification, and reporting on the source level);

- Development and introduction of the GHG emission regulation system (providing incentives for emission reduction, project-based, cap-and-trade schemes, etc.);
- Strengthening the current decarbonization efforts (gasification programs, energy efficiency, renewable energy use, energy saving, decarbonization of transport, cement, chemical, metal production, etc.);
- Enhancing R&D in and implementation of breakthrough technologies (*e.g.* biofuels, electrification of transport and infrastructure, CCS, new generation nuclear power plants, etc.); and
- Improvement of the adaptation/mitigation policies and measures in forestry and agriculture, supporting carbon sequestration capacities.

These efforts will allow continuing decoupling GDP growth and GHG emission trends and will facilitate finding new solutions to deep decarbonization in Russia. Partly, these measures correspond to the activities approved in the Governmental Action Plan on reduction of GHG emissions (adopted on February 4, 2014) and other decisions. However, the deep decarbonization approach will require significant adjustments in strategic planning of the economic development, technological, and institutional changes aimed at the creation of climate-neutral Russia.

South Africa

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Harald Winkler, *Energy Research Centre, University of Cape Town*

Bruno Merven, *Energy Research Centre, University of Cape Town*

1. Country profile

1.1. The national context for deep decarbonization and sustainable development

The African Climate Change Response White Paper (DEA 2011) states, “South Africa is committed to contributing its fair share to global GHG mitigation efforts in order to keep the temperature increase well below 2°C. With financial, technology, and capacity-building support, this level of effort will enable South Africa’s GHG emissions to peak between 2020 and 2025 in a range with a lower limit of 398 MtCO₂eq and upper limits of 583 MtCO₂eq and 614 MtCO₂eq for 2020 and 2025 respectively, plateau with a lower limit of 398 MtCO₂eq and upper limit of 614 MtCO₂eq for approximately a decade, and decline in absolute terms thereafter to a range with lower limit of 212 MtCO₂eq and upper limit of 428 MtCO₂eq.” This is referred to as the Peak Plateau Decline (PPD) benchmark trajectory.

South Africa has a modern urban economy, with an advanced service sector and a large energy-intensive industrial base, dependent on huge mineral resources. There are high levels of inequality and poverty, given that society is divided along spatial, economic, and social lines established in colonial and then Apartheid eras (South Africa, 2013a):

- The top decile of the population accounts for 58% of income while the bottom half accounts for less than 8% (World Bank 2013), resulting in one of the highest inequality levels of the world as indicated by a Gini coefficient of 0.69.
- 45% of the population lives under the upper-bound poverty level (R706 [66.36 US\$] per month in 2009 prices).

Unemployment is also a major, related concern. The unemployment rate reaches 25.5% according to standard definitions (40% when including discouraged work seekers [Gumede, 2013]); this is the highest rate out of 40 emerging markets tracked by Bloomberg (Bloomberg, 2014).

These issues are acknowledged in key policy documents, namely the National Development Plan (NDP) and the New Growth Path (NGP), and they are highly relevant in economic policies related to GHG emissions mitigation. Social grants were extended to 14.8m people in 2011, an increase from 3.8m in 2001 (Gumede, 2013), but relying on grants is not sustainable and substantial socio-economic development is required to address poverty, inequality, and unemployment.

The population of South Africa was some 52m in 2011, is 60% urbanized, and grew 21% between the 1996-2011 censuses. South Africa will need to make provisions for the projected 8m new urban residents by 2030. Of 10m households, 3m remain without electricity connections.

The average GDP growth of 3.5% over the past decade has not been associated with a significant increase in employment. The NDP envisages an average GDP growth of 5.4% until 2030 (NPC, 2011), and the NGP states that GDP growth between 4-7% is necessary (South Africa, 2011a) to meet development objectives.

The shift in the twentieth century of the South African economy from primarily a rural, agricultural economy to an urban, industrial one was initially based on mining and then transitioned to energy-intensive minerals-based industrialization, with the energy supply primarily based on coal and imported crude oil.

The structure of the economy has evolved from a tertiary sector accounting for 57% of total GDP in 1984 to 70% today. There are important linkages between the tertiary sector and the minerals-based components of the primary and secondary sectors, and the economy relies on the primary and secondary sectors for much foreign direct investment and 60% of foreign exchange export earnings.

South Africa's recoverable coal reserves amount to approximately 49,000 Mt, giving the country the world's sixth-largest coal reserves (SACRM, 2013) and a reserve/production ratio of more than 200 years. Fluri (2009) estimates 548 GW of potential for concentrated solar power (CSP). Hageman (2013) estimates wind potential at 56 GW, 157 TWh p.a. There is a large regional hydro potential, greater than 40 GW.¹⁹

The NDP recognizes that the South African economy is highly energy and (mineral) resource-intensive but states: "a resource-intensive development path is unsustainable (NPC 2011)." This is at odds with parts of the Industrial Policy Action Plan 2013-2016 (South African Department of Trade and Industry, 2013), the Beneficiation Strategy in the NGP and the current Integrated Resource Plan (DOE, 2013), which all envisage strong growth in the resource-intensive sectors and labor absorbing industrialization (South Africa, 2011a).

1.2. GHG emissions: current levels, drivers, and past trends²⁰

GHG emissions in 2010 were around 543 MtCO₂eq, 78% of which were from fossil fuel combustion, amounting to 10 t/cap. This high level is the combined result of an energy and electricity-intensive economy, since 95% of electricity is generated from coal and about 35% of liquid fuels are manufactured from coal (coal to liquids, CTL).

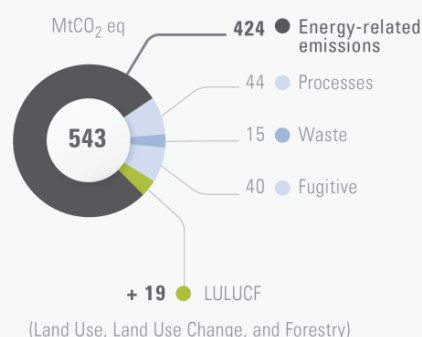
¹⁹ This would require construction of regional transmission lines but projects are already under development and official planning (DOE 2013) includes Grand Inga in the Democratic Republic of Congo some 3000km from SA and other research reports indicate firm resource availability see IRENA 2013.

²⁰ Most energy-related figures in this chapter, including energy GHG emissions, are estimated based on: (i) DOE 2006 statistics (DOE 2009) which are the latest available official statistics covering all energy sub-sectors and related time series from 1992-2006; (ii) Eskom statistics published in the Eskom annual report; and (iii) where public data is not available, estimates are made based on work by the Energy Research Centre (ERC) at the University of Cape Town (UCT) related to the SATIM energy and emissions model. see <http://www.erc.uct.ac.za/Research/esystems-group-satim.htm>

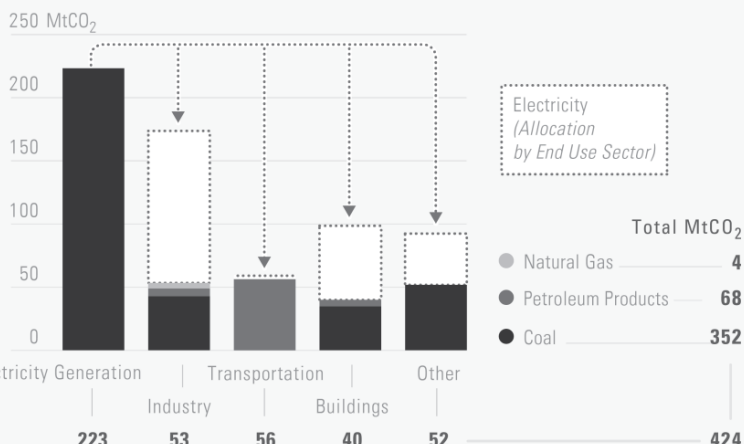
Of 250 Mt coal mined annually, 44% is for electricity generation, 28% exported, 18% for CTL, and 10% used directly. Of the 10% used directly, 65% is used in industry, 23% in households, and 12% in commerce (DOE, 2009).

Figure 1. Decomposition of GHG and Energy CO₂ Emissions in 2010

1a. GHG emissions, by source



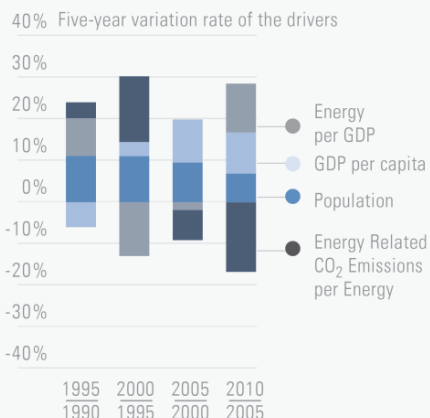
1b. Energy-related CO₂ emissions by fuel and sectors



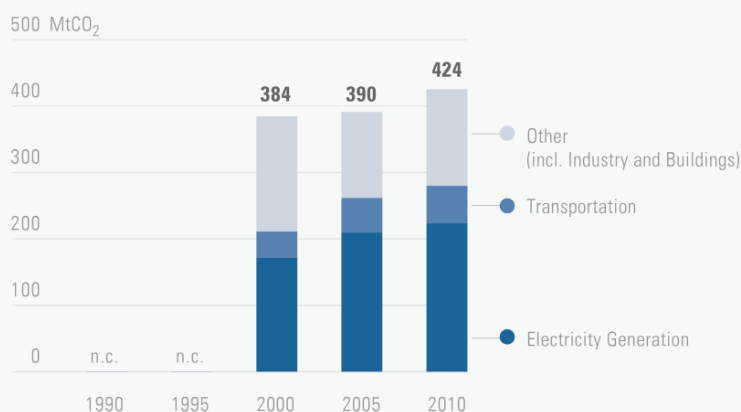
Note: The “other” category includes both energy and process emissions of South Africa’s unique coal to liquids plants.

Figure 2. Decomposition of historical energy-related CO₂ Emissions, 1990 to 2010

2a. Energy-related CO₂ emissions drivers



2b. Energy-related CO₂ emissions by sectors



Note: Sector specific data for 1990 and 1995 were not available for this report.²¹

In 2010, industry, residences, and commercial buildings accounted for 60%, 20%, and 15% of electricity demand respectively. Electricity consumption grew steadily for decades until 2007 when a supply constraint, which is still at work, arose. Electricity prices have more than doubled in real terms and are set to double again by 2015. Two large coal-fired power stations totaling 9.6 GW, equivalent to

²¹ South Africa did develop GHG inventories for the years 1990, 1994 and 2000. However, between them there are wide variations in methodologies and results and the 1990 and 1994 versions do not have sufficiently detailed supporting information to resolve the variations to derive sufficiently meaningful trends for DDDP purposes. The 2010 inventory has been released for comment in June 2014 and is therefore not final.

some 25% of currently installed capacity, are under construction. More than 3 GW of low-carbon electricity generation, mainly utility scale wind, solar photovoltaic (PV), and concentrated solar (CSP), are also being contracted or under construction.

2. National deep decarbonization pathways

2.1. Illustrative deep decarbonization pathway

2.1.1. High-level characterization

The South African Illustrative DDP is based on an economy that prioritizes meeting socio-economic development needs in terms of adequate income levels and income distribution and providing energy services for South African residents, business, and industry. This is done while retaining the GDP structure of the economy and configuring an energy supply and end-use system that is consistent with the PPD. The GDP structure is retained to provide products such as steel and cement crucial for development and to maintain the macro-economic stability provided by investments in and foreign exchange contributions of the minerals and industrial sectors. These assumptions are discussed in section 2.2.

In the illustrative scenario, the economy has average GDP growth of some 4%, which is consistent with the low end of the range of the NDP and NGP. Over 2010-2050, there is an improvement in income distribution, and by 2050 there are no households with “low incomes” (below R19,200 [around 1,800 US\$]). Meaningful employment impacts could not be estimated.

Table 1. Development Indicators and Energy Service Demand Drivers

	2010	2020	2030	2040	2050
Population [Millions]	50	58	67	69	70
GDP per capita [\$ /cap]	5,052	6,355	8,008	11,411	16,339
Electrification rate [%houses connected]	81%	90%	95%	97%	100%
Household income distribution [m residents]					
Low Income (R0 - R19,200)	24	14	9	5	0
Middle Income (R19,201 - R76,800)	15	32	39	34	27
High Income (R76,801 and above)	11	12	19	29	44

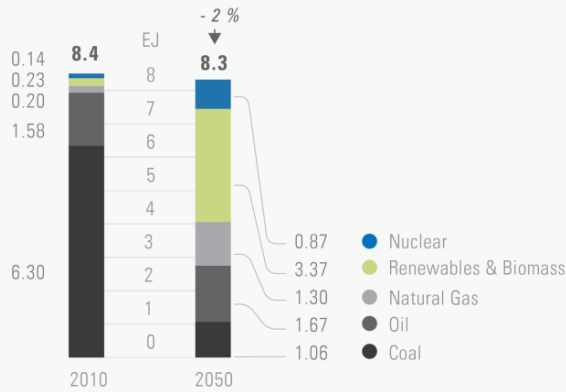
Energy end-use demand per sector for the illustrative economy is used as input to the ERC’s TIMES model of the South African energy system (SATIM)²² using a cumulative energy emissions constraint over 2010-2050 of 14 GtCO₂eq. This is consistent with cumulative emissions of the median of the PPD trajectory, achieving the same cumulative emissions but a higher end level. A technically feasible energy system for the DDP is achieved with a 2050 level of energy emissions of 257 MtCO₂eq. There is a large

²² For details of the SATIM modeling framework and methodology, see <http://www.erc.uct.ac.za/Research/esystems-group-satim.htm>.

increase in end-use energy required for the illustrative economy with a net decrease in primary energy over 2010-2050 and a significant decrease in primary energy per GDP.

Figure 3. Energy Pathways, by source

3a. Primary Energy



3b. Final Energy

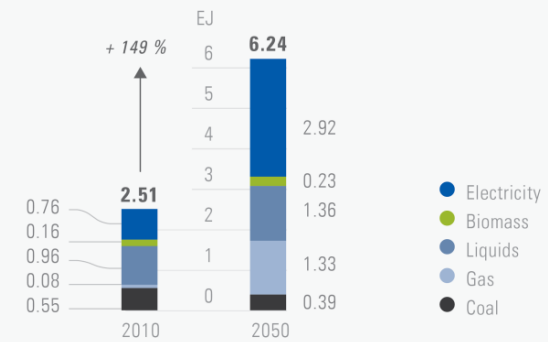
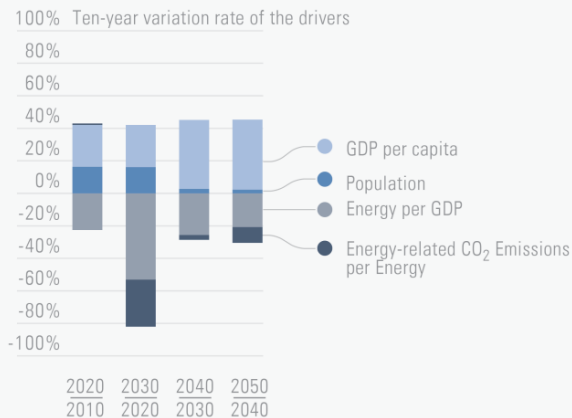
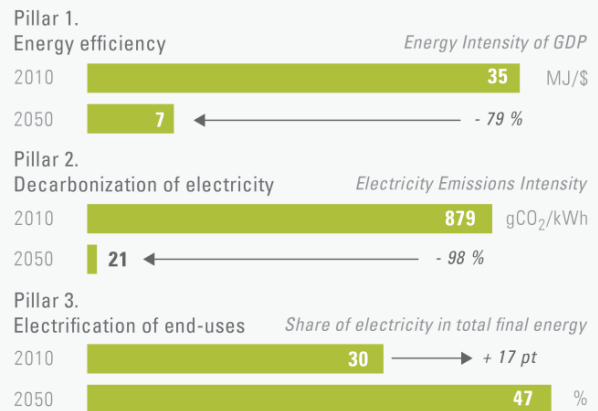


Figure 4. Energy-related CO₂ Emissions Drivers, 2010 to 2050

4a. Energy-related CO₂ emissions drivers

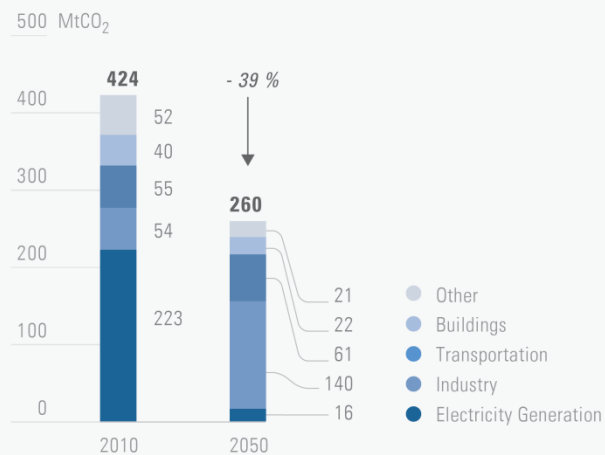


4b. The pillars of decarbonization



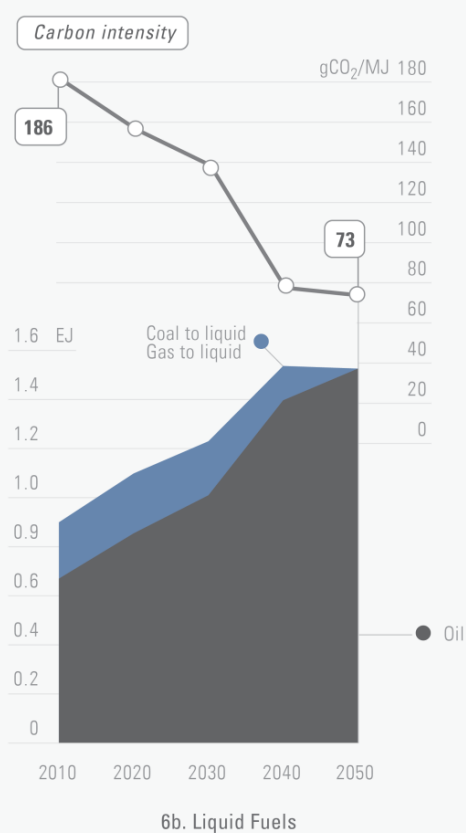
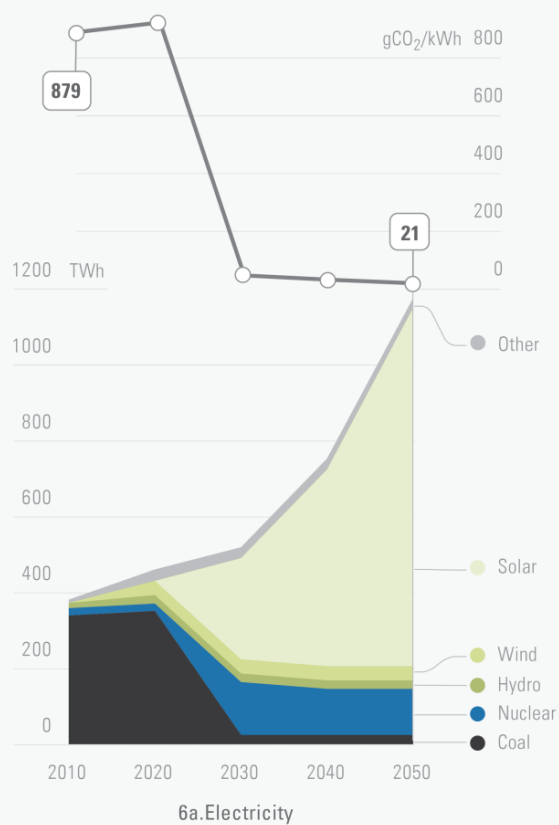
Electricity sector emissions reduce radically, emissions from buildings halve, and emissions from industry increase threefold. Transport emissions remain relatively constant. The “other” sector (in Figure 1), which is largely CTL, is phased out.

Figure 5. Energy-related CO₂ Emissions Pathway, by Sector, 2010 to 2050



2.1.2. Sectoral characterization

Figure 6. Energy Supply Pathways, by Resource



Electricity

Electricity generation increases threefold. Electricity generation emissions decrease from 880g/kWh in 2010 to 20g/kWh in 2050, mainly through the replacement of coal-fired generation with CSP with storage and construction of significant additional CSP, nuclear, and widespread rooftop PV. With South Africa's solar radiation resource, the extensive use of CSP with storage and PV across a wide geographic spread combined with some dispatchable generating assets provides a system with satisfactory loss-of-load probability.

Liquid fuels

Liquid fuels production emissions intensity is radically reduced through phasing out of CTL, and by 2050 all liquid fuels are produced locally from crude oil.

Industry

The industrial sector remains a constant proportional contribution to GDP, and it significantly expands at some 4% p.a. along with the rest of GDP, which leads to a significant increase in energy demand. Concurrent decreases in total emissions attributable to industry (*i.e.* direct and induced emissions) are achieved through fuel switching from coal to gas, improvements in efficiency of end-use technologies, and shifting to electricity for some thermal applications.

Transport

Passenger Transportation

Supply of significant additional passenger transport from 285 bn p-km to 509 bn p-km, a per capita increase from 5,724 km/cap to 7,233 km/cap, meets basic development objectives. Private vehicle transport increases from 2,669 km/cap to 3,861 km/cap and public transport from 3,055 km/cap to 3,327 km/cap. Public transport involves a significant shift from mini-bus taxi (MBT) to Bus-Rapid-Transit (BRT) and rail, which are far safer and more comfortable. The number of private vehicles doubles from 5m to 10m (9 people/vehicle to 6.5 people/vehicle).

Passenger transportation achieves a large increase in supply combined with a small decrease (from 31 Mt-29 Mt CO₂eq, 2010-2050) in emissions through a combination of modal shift and vehicle efficiency improvements. The emissions intensity of private transport improves from 160 to 59 gCO₂/p-km.

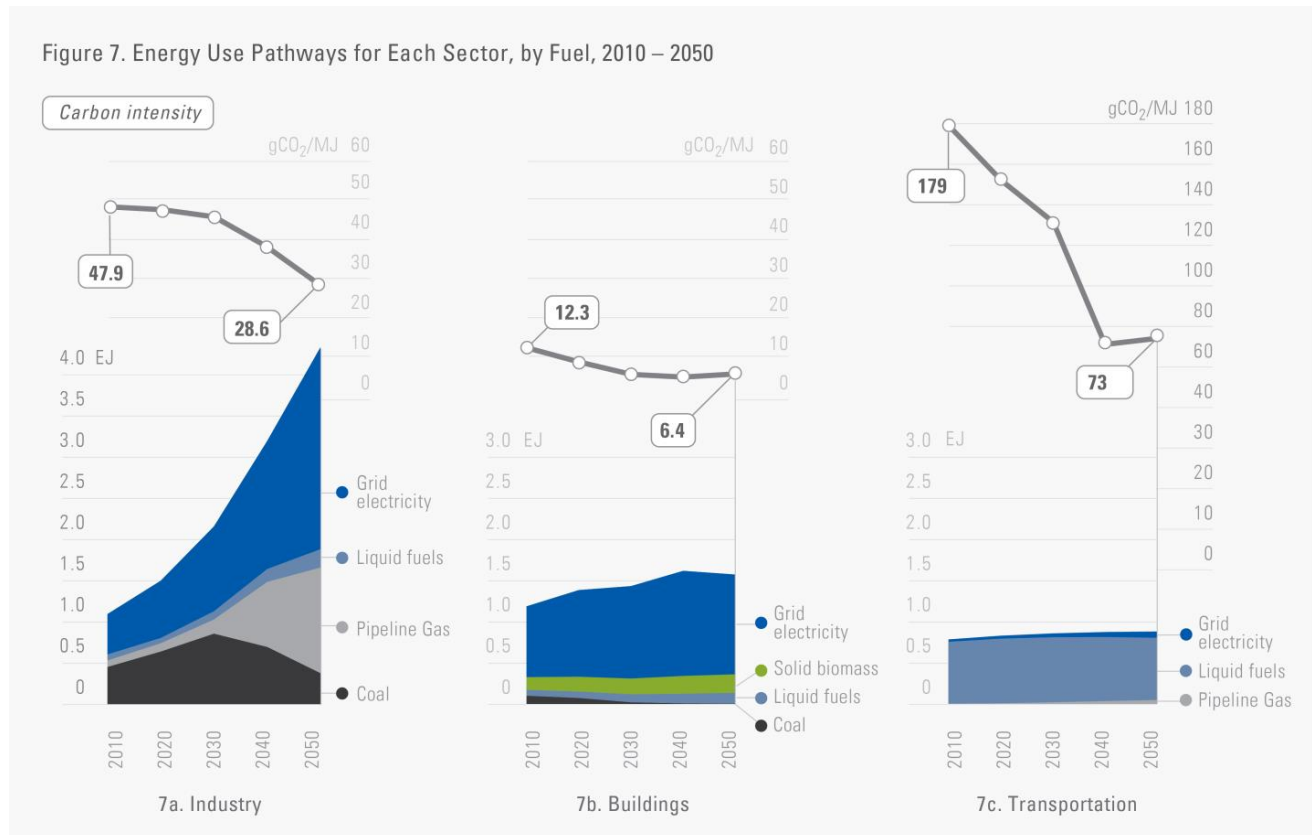
The Illustrative DDP has a low 5% level of electric private vehicles, but by 2040 around 19% of Bus Rapid Transit (BRT) vehicles introduced are electric and 25% compressed natural gas (CNG)-powered, increasing to 50% by 2050.

Jet air transport emissions nearly double over the 2010-2050 period and remain largely un-mitigated as standard fossil fuels are used. There is no shift to high-speed inter-city rail.

Freight Transportation

More than 90% of freight is carried by heavy commercial vehicles (HCV) or rail in 2050 with export of minerals and beneficiated minerals accounting for 20%; thus heavy haulage dominates.

Freight transport demand derives from sectoral GDP growth and related transport requirements and increases from 292 bn t-km to 998 bn t-km (~240%) with an increase of 342 PJ to 492 PJ in energy and 24 Mt to 32 Mt in emissions. The large increase in transport supply combined with the proportionally smaller increase in emissions is achieved mainly through a combination of modal shift and vehicle efficiency improvements: a shift from HCV to rail and improvement in HCV fuel economy from 39.1 to 16.6 l/100km. All rail is electrified. Average freight emissions intensities improve from 83 to 32 tCO₂/t km.



Note: Carbon intensity shown in Figure 7 for each sector includes only direct end-use emissions and excludes indirect emissions related to electricity or hydrogen production.

If biomass is sustainably harvested and paraffin is replaced with biofuels, the liquid fuels and solid biomass components in figure 7b reduce to zero, and the South African building sector contributes a negligible amount to GHG emissions in 2050 because all other energy services are supplied with very low-carbon electricity.

Of some 10m households, 3m remain without electricity connections in 2010, but Tait and Winkler (2012) show that providing adequate electricity for poor households in the medium term will not contribute significantly to emissions associated with coal-fired electricity in comparison with the emissions from other sectors. South African climatic conditions allow for provision of adequate energy services with little energy on average (<1000kW p.a.) required for home space heating and cooling. 60% of water heating (currently largest single household energy component accounting for 50% of mid-income households) can be provided with solar water heaters and with very efficient lighting and electronic technologies that are already commercially available, cooking becomes the largest electricity

energy service at around 5,000 kWh p.a. Thus, with adequate thermal performance, an additional 6m households could require only some 36 TWh p.a., less than 5% of total demand in 2010.

2.2. Assumptions

The central assumption used in formulating the Illustrative DDP for South African is that it is based on known resources and technologies currently deployed commercially although by 2050 industrial end-use technologies are assumed to improve significantly in efficiency beyond current available levels.

Availability and suitability of electricity generation technology and fuel and renewable energy resources

Achieving the required 14 GtCO₂eq cumulative emissions, while maintaining a feasible energy supply to industry as per economic development assumptions requires early retirement of coal-fired electricity generation and deployment of low-carbon technologies to meet additional demand.

The specific configuration in the Illustrative DDP, with 80% CSP, is one of many very different but equivalently feasible configurations that could provide similar performance; South Africa has excellent low-carbon natural energy resources.

Industrial end-use technology: efficiency improvements and lower-carbon alternatives to coal

Generic assumptions were made regarding end-use technology per major sub-sector: steady rates of improvement in end-use technologies were implemented, as were rates for switching from coal to gas technologies, with limits for totals. This conservative approach has been taken in the absence of detailed plant and end-use technology inventories. The rates and limits are considered to be conservative. For example, improvements made in the iron and steel sector, which increases its production from 10 Mt p.a. to 47 Mt p.a. from 2010-2050, achieve an intensity of 0.83 MtCO₂eq/Mt by 2050. This is at the top end of the range of the international benchmark range of 0.47-0.84 tCO₂eq/t.

Switching from coal to gas is an essential component to decarbonize industry. Although South Africa does not currently have significant gas resources or the required capacity for gas importation, transmission, and distribution, it is assumed that it is technically feasible for this to be provided.

Transport vehicle efficiencies

Efficiencies across the range of small-medium passenger vehicles increase by between 50-60% from 2010-2050. Gasoline and diesel vehicles improve from 9.0 to 4.0 and 7.5 to 3.2 l/100km respectively, and diesel MBT improve from 11.3 to 5.5 l/100km. It is assumed that 5% passenger vehicle sales are EV's in 2050.

2.3. Alternative pathways and pathway robustness

The central assumption used in formulating the Illustrative DDP for South African is that it is based on known resources and technologies deployed at commercial scale.

Decarbonization of electricity generation

The electricity decarbonization relies heavily on CSP with storage. There is a more than adequate solar resource. CSP technology is already operating at scale (NREL 2014), and bids have been accepted by the South African government for supply of a Power Purchase Agreement for the Bokpoort 50 MW station with storage which is already under construction. Thus, from a technical point of view CSP should be a robust solution.

However, should CSP not prove to be viable, there are alternative configurations. A combination of wind generation, solar PV, and regional hydro could substitute all or at least most of the CSP and additional nuclear could make up the difference (See IRP 2010 documentation DOE 2013).

Industrial end-use technology: efficiency improvements and lower carbon alternatives to coal

As mentioned previously, assumptions are conservative and should not be a threat to robustness.

Transport: vehicle efficiency improvements

The 2050 vehicle efficiencies are robust. For example, average light vehicle efficiencies assumed in 2050, namely 4 and 3.2 l/100km for gasoline and diesel vehicles, are already available for individual commercial models available today. The 5% sales of EV's by 2050 is a conservative target and hence robust.

2.4. Alternative pathways and pathway robustness

Carbon Capture and Storage (CCS)

CCS has not been included because South Africa has not identified disposal sites despite the considerable efforts that have been devoted to their exploration. A government decision has been taken not to pursue ocean storage; geological storage is still being investigated and could provide additional reduction potentials, notably in the industrial sectors.

Industry

Four subsectors account for 85% of direct (non-electricity induced) emissions, namely iron and steel (28%), "other" (24%), mining and quarrying (19%), and chemical and petrochemical (14%). Cement and glass (6%) and paper and pulp (6%) raise this to 97% of emissions.

Opportunities for significant deeper cuts that have been quantifiable, based on data and knowledge accessible in this phase of the DDPP project, mainly exist through improving emissions intensities in the iron and steel subsector and/or limiting production of the subsector to local requirements, which is viewed as an option in the DDPP approach.²³

The DDP includes an iron and steel sector that increases production from 10-47 Mt from 2010-2050 with emissions of 39 MtCO₂eq in 2050, i.e. 0.83 tCO₂eq/t. This can be compared with an international benchmark range of 0.47-0.84 tCO₂eq/t. Most of these emissions are coal and gas emissions

²³ Insufficient data has been (readily/publically) accessible in this phase on other industrial subsectors to assess cuts deeper than the DDP. Improvements are probably possible in cement and glass and paper and pulp but their relatively small contribution made this too minor to consider in this phase.

associated with providing thermal end-use energy. Substituting the remaining coal with gas technology would achieve 0.73 tCO₂eq/t, i.e. a reduction of 4.7 MtCO₂eq. If intensity were decreased²⁴ from 0.73 t/tCO₂eq/t to 0.47 t/tCO₂eq/t, further emissions reductions of some 12.2 MtCO₂eq could be achieved, reducing emissions to 24 MtCO₂eq.

The iron and steel sector exports about a third of its production. If this remained similar for 2050 production and the sector was limited to providing for local demand, another approximately one-third of 24 MtCO₂eq, i.e. 8 Mt, could be saved.

The majority of South African energy intensive industrial plants were constructed in an era of very low electricity and coal prices and no GHG emissions constraints; it is therefore reasonable that substantial improvements in energy efficiencies and GHG emissions performance, similar to those in the iron and steel subsector, could be achieved, but the lack of readily available or accessible data for other subsectors has not allowed for meaningful estimations in this phase of the DDP project.

Transport

There is a low level of electrification of passenger transport in the Illustrative DDP, and only conventional fossil-based liquid fuels are considered, providing opportunities for significantly deeper cuts involving electric vehicles (EVs) and biofuels. The large contribution of kerosene combustion emissions for jet-transportation also provides a potential deep cut.

If 50% of EVs were introduced by 2050, approximately 80 PJ of gasoline + 35 PJ diesel p.a. would be saved, reducing emissions by 8 MtCO₂eq. If biofuels were introduced for 50% of the remaining light passenger vehicles, 14%, or 4 MtCO₂eq would be saved. If biofuels were substituted for the jet-fuel, then roughly 6 Mt CO₂eq would be saved. These ballpark estimates of fuel and technology substitutions save 18 MtCO₂eq of the 29 MtCO₂eq of passenger emissions in 2050, or some 60% of passenger transport emissions.

Substituting 50% of the diesel used in freight transport with biofuels would save 11 MtCO₂eq.

2.5. Challenges, opportunities, and enabling conditions

CTL

CTL facilities are the core of the largest industrial complex and largest industrial company in South Africa. Phasing out or decarbonisation of CTL thus presents a significant challenge.

The electricity generation system

The early retirement of large coal-fired electricity generation plants departs radically from official plans (DOE, 2013) and requires the construction of considerably more costly CSP plants and a large expansion to the transmission network. It is unlikely that South Africa could cover such major costs without international assistance.

²⁴ These estimations are not based on actual South African iron and steel plant performance metrics but on estimations based on public energy consumption data and aggregate projections 35 years ahead and thus are indicative only.

Industry: Improvements in efficiencies and switching to gas and electricity

Production capacities in 2050 are multiples of 2010 capacities, and so by 2050 most of the plant and equipment will be new and in theory should be able to be at the best end of international benchmarks' ranges. Industries involved in the majority of emissions, which are from large facilities, are typically owned and operated by multinationals who own and operate world-class facilities worldwide. The challenge would thus be to get these multinationals to invest in the best-emissions class facilities in South Africa.

If industry is to grow at a rate consistent with an economy that can support socio-economic development and make an appropriate contribution to achieving the PPD, regulations and incentives will have to be put in place to ensure that consistency with the PPD is maintained and that investment remains attractive when the trade-offs between cost and reducing emissions intensity are considered.

Transport

The challenge will be to develop and mobilize policy, strategic planning, finance, project implementation, and administration to realize the BRT and rail projects and to implement complimentary policies in road traffic management to achieve the modal shifts. This will require significant development of management and administrative capacity and sourcing of finance.

2.6. Near-term priorities

- Avoiding lock-in to large emissions intensive energy system assets with long economic lifetimes is crucial. Emissions from coal-fired electricity generation will take up emissions space required by other sectors and maintain a level of emissions in electricity that will cause induced emissions from other sectors to limit their potential to contribute to socio-economic development in a carbon-constrained world.
- The PPD policy as specified in the Climate Change Response White Paper (CCRWP) needs to be implemented. The CCRWP defines the PPD and elaborates how policies will be implemented to achieve the PPD.
- Fast tracking of the necessary capacity to develop and implement transport strategies and plans to build transport infrastructure and to regulate and incentivize modal shifts is necessary.

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SOUTH KOREA

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1. Country profile

1.1. The national context for deep decarbonization and sustainable development

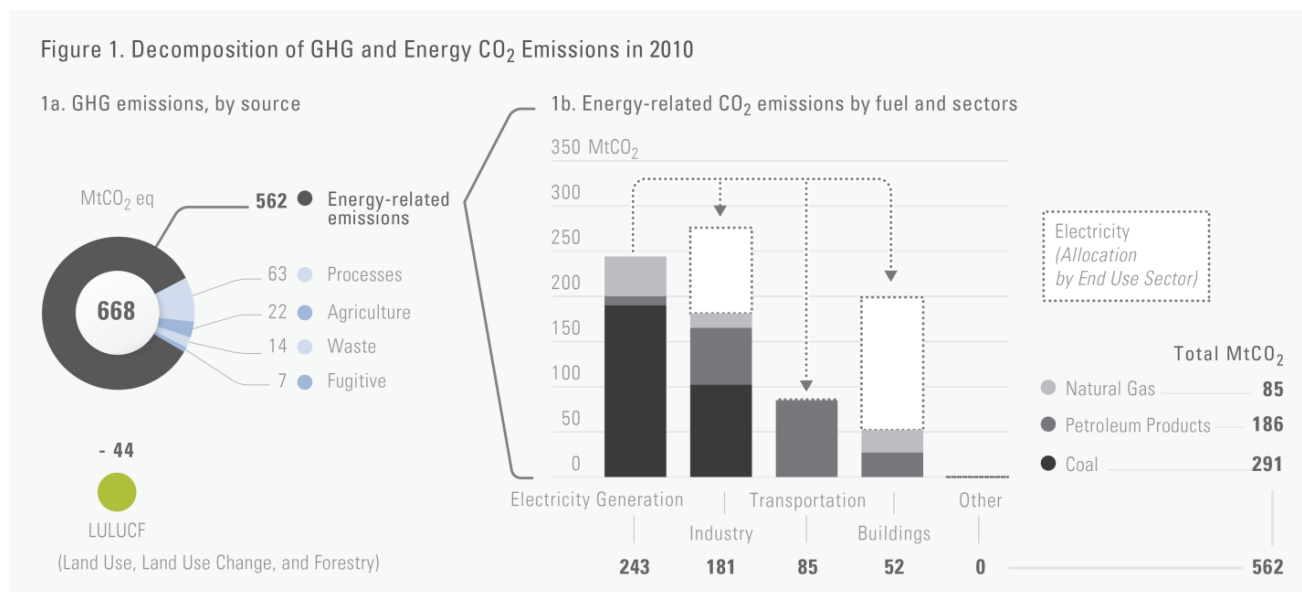
The Republic of Korea ('South Korea' or 'Korea', hereafter) recorded per capita GDP of 20,159 US\$ in 2010. The Korean economy recorded a high growth rate of 6.9% p.a. from the 1960s until the 2000s, following the export-led industrialization strategy. As of 2010, industry was the main sector of the economy (41% of GDP), dominated by manufacturing, which alone represented 30.3%. Electricity, gas, water, and construction accounted for 8.3%, and agriculture, forestry and fishery made up the remaining 2.6%. This fast industrial development has been driven by the strong growth of exports; in 2010, they accounted for 46% of GDP. The development of industry has also encouraged rapid urbanization, with the urbanization rate reaching 83% in 2010.

Manufacturing accounted for 51.6% of Korea's final energy consumption, of which energy-intensive heavy industries constituted the dominant share of 81.0%. Korea's economy is highly dependent on fossil fuels, which represent 85% of total primary energy supply. Given its very low domestic endowment of fossil resources, 96.5% of this fossil fuel demand is met by importation, which poses the crucial question of energy security. On the other hand, renewable energy, including wastes and hydro power, accounted for only 2.8% of total primary energy supply due to the limited endowment of renewable energy resources, such as solar and wind supply. Nuclear energy accounted for 12.2% of total primary energy supply in 2010.

In 2008, under President Lee Myung-bak, the Korean government launched the National Strategy for Green Growth (2009-2050), along with the first 5-Year Plan for Green Growth (2009-2013), proposing to pursue the following three objectives: (1) climate change action and energy independence, (2) the creation of new growth engines with investment in green technologies and industries, and (3) greening of the national territory, transportation, and lifestyles, while promoting a shift to high-value-added services over the period to 2050. The succeeding government of President Park Geun-hye has launched the 2nd 5-Year Plan for Green Growth (2014-2017), proposing to focus on GHG emissions reduction, a sustainable energy system, and adaptation to climate change.

1.2. GHG emissions: current levels, drivers, and past trends

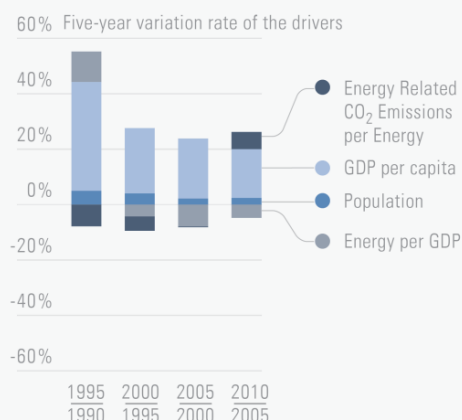
Net GHG emissions including all sources and sinks were 624 MtCO₂-eq in 2010, about 12.63 tons per capita. Emissions from fuel combustion were 562 MtCO₂-eq, which corresponded to 84.1% of total emissions (668 MtCO₂-eq, excluding sinks) and 90.0% of net emissions (Figure 1a). Electricity generation and industry are the two main activities responsible for energy-related carbon emissions (Figure 1b).



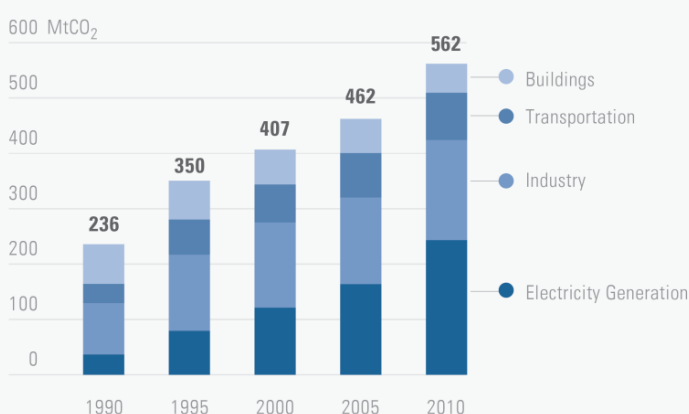
Net GHG emissions rose during the past twenty years by 132% from 269 MtCO₂eq (1990) to 624 (2010), while emissions from fuel combustion increased by 139% from 235 MtCO₂eq to 561 MtCO₂eq. The key driver of the rapid increase of emissions was a rise in energy consumption due to high economic growth dependent on energy-intensive heavy industry that more than offset increases in energy efficiency. Large increases in electricity emissions reflected a massive shift in final energy demand from oil and gas to electricity due to a relatively low price of electricity made possible by increases in nuclear power supply as well as the low electricity price policy of the government. There was also an upturn of carbon intensity during the second half of the 2000s mainly due to an expansion of the coal-using iron and steel industries and coal-power plants (Figure 2).

Figure 2. Decomposition of historical energy-related CO₂ Emissions, 1990 to 2010

2a. Energy-related CO₂ emissions drivers



2b. Energy-related CO₂ emissions by sectors



2. National deep decarbonization pathways

2.1. Illustrative deep decarbonization pathway

2.1.1. High-level characterization

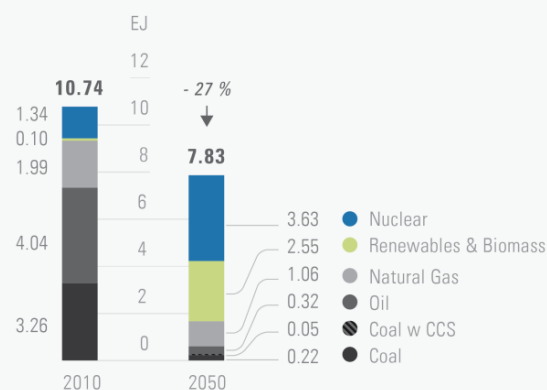
Korea's population is projected to peak in 2030 and to decline thereafter, decreasing from 50 million in 2010 to 48 million in 2050. The economy is projected to grow at the annualized rate of 2.35% on the average over this period. A major uncertainty facing Korea is when, if at all, and how, the inter-Korean unification is likely to occur. The present study ignores this contingency altogether.

With the global benchmark of 1.7 tons of CO₂ emissions per person in 2050, the illustrative pathway seeks a very ambitious decarbonization path for the Korean economy and reaches an 85.4% reduction of CO₂ emissions from fuel combustion. Emissions are projected to fall from 560 MtCO₂ in 2010 to 82 MtCO₂ in 2050.

This is permitted by a drastic decrease of energy consumption (-37.2% in final energy consumption) due to large improvements in energy efficiency. In addition, there are important changes in the fuel mix. In particular, the importance of oil-based fuels, which represent one-half of final consumption in 2010, is significantly reduced, and coal use is almost completely phased-out over the period (Figure 3). In parallel, electricity (and notably of renewable sources) develops with an electrification rate of final uses reaching 60.7% in 2050 (vs. less than 20% in 2010) with significant reductions of the carbon intensity of electricity production, from 531 to 41 gCO₂/kWh (Figure 4). All sectors are concerned and see their emissions decreasing radically over 2010-2050 (Figure 5).

Figure 3. Energy Pathways, by source

3a. Primary Energy



3b. Final Energy

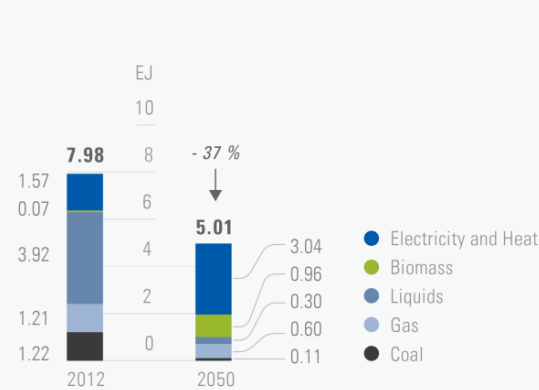
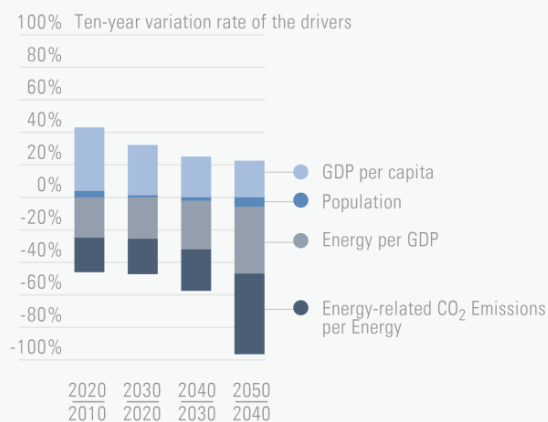


Figure 4. Energy-related CO₂ Emissions Drivers, 2010 to 2050

4a. Energy-related CO₂ emissions drivers



4b. The pillars of decarbonization

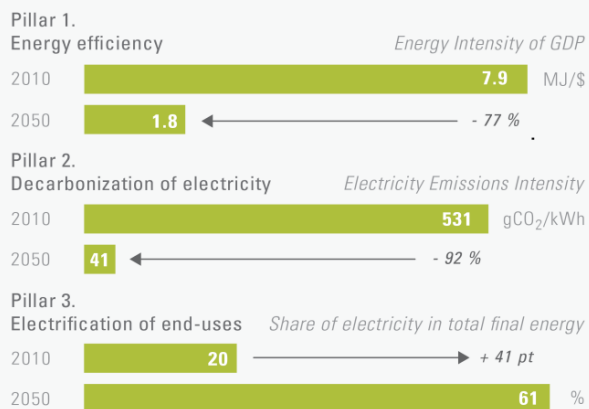
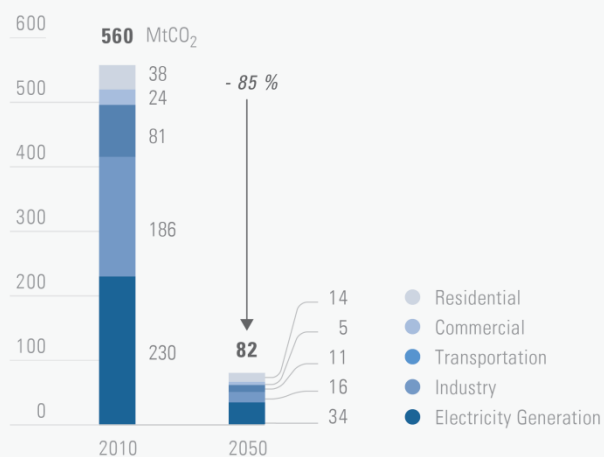


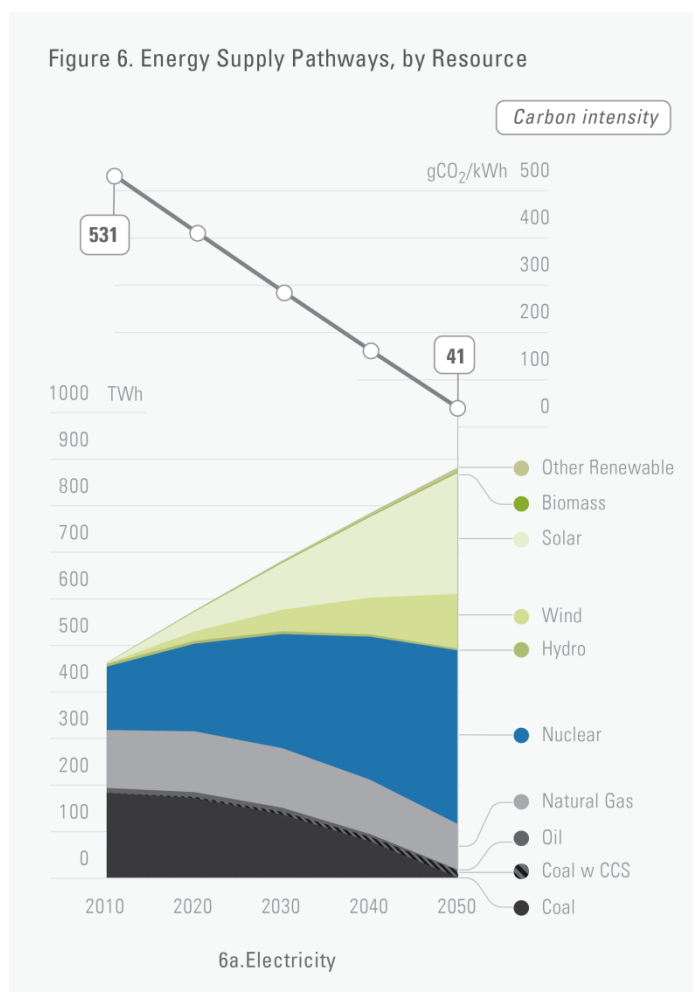
Figure 5. Energy-related CO₂ Emissions Pathway, by Sector, 2010 to 2050



2.1.2. Sectoral characterization

Power

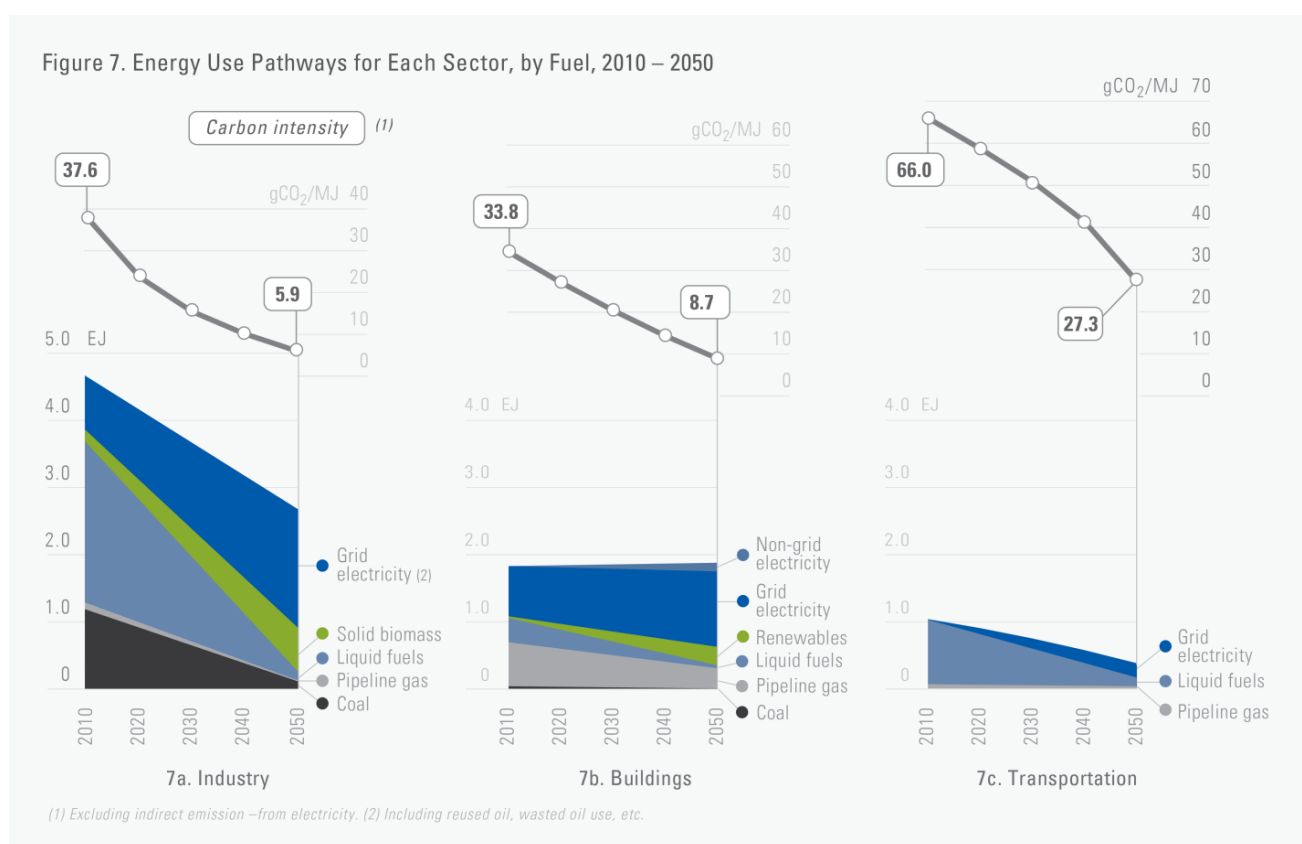
A broad set of low-carbon options for electricity generation (CCS, renewable energy such as wind and solar PV, and nuclear power) are deployed to permit the deep decarbonization of electricity supply as measured by a fall in the carbon intensity of electricity from 531 to 41 gCO₂/kWh. CCS is applied to 4% of coal power generation by 2050, and all coal without CCS and a share of gas are substituted with renewables, specifically wind (14% of electricity production) and solar PV (31% of production), due to the installation of 51 GW of wind and 193 GW of solar PV. Residual fossil fuels are substituted with nuclear energy, requiring the installation of 47 GW of nuclear power. The deployment of renewable energy requires the shift to a large-scale distributed renewable electricity system. As a result, network balancing is likely to be an issue because of the intermittency of renewable energy. Additional tools such as backup facilities and energy storage should be installed to solve this problem.



Industry (manufacturing)

The manufacturing sector was the dominant source of CO₂ emissions in 2010 with 186 MtCO₂. It includes the energy-intensive heavy industries,²⁵ and the share of these industries in GDP is projected to increase from 27.2% in 2010 to 35.3% in 2050. This aggregate figure hides a structural change among industrial sub-sectors, as the share of fabricated metal industries increases while that of other heavy industries (such as cement, petrochemical, and iron and steel) decreases).²⁶

Manufacturing is almost decarbonized by 2050 to 16.4 MtcCO₂ of emissions, excluding indirect emission through electricity.²⁷ This occurs through a combination of significant deviations from the current trajectory, notably through efficiency improvements resulting in 1) three-fold and six-fold decreases of energy intensity (with respect to the 2010 level) in light and heavy industries, respectively, 2) substitution for 20% of fossil fuels in distributed CHP in heavy industries, 3) 30% deployment of CHP to fuel light industries, and 4) an increase to 28% and 72% of the shares of electricity in light and heavy industries, respectively.



Note: Carbon intensity shown in Figure 7 for each sector includes only direct end-use emissions and excludes indirect emissions related to electricity or hydrogen production.

Buildings: Residential and Commercial

In the **residential buildings sector**, a 62% reduction of emissions is experienced, from 37.5 MtCO₂ in 2010 to 14.5 MtCO₂ in 2050. The floor space decreases from 24 m²/person to 21 m²/person. This is permitted by a

²⁵ Heavy industries include iron & steel, petrochemical, cement, non-metallic and fabricated metal industries. The last one here includes machinery, electronic & electric and shipbuilding sectors.

²⁶ The share of these 3 industries in GDP is projected to decrease from 8.0% in 2010 to 4.3% in 2050.

²⁷ Carbon intensity shown in Figure 7a also excludes indirect emission through electricity consumption.

combination of the following four broad groups of measures (listed in order of the ease of deployment): 1) the diffusion of LED lighting (which substitute for all exiting lighting by 2050), 2) higher efficiency of heating and cooling obtained with new technologies, 3) substituting fossil fuels in distributed Combined Heat and Power (CHP) (which substitute 17% of fossil fuels in distributed CHP in 2010 mainly with wastes and complementarily with biomass), and 4) substituting fossil fuels with renewable energy (solar-thermal and geo-thermal energy substitute 35% of the remaining fossil fuels in 2010).

The **commercial buildings sector** includes buildings in business, public, and agricultural sectors. In this sector, despite the continuous increase of floor space per capita (from 14 m²/person in 2010 to 31 m²/person in 2050), CO₂ emissions are reduced by 78% from 24.5 MtCO₂ in 2010 to 5.4 MtCO₂ in 2050. This is notably permitted by efficiency improvements in heating and cooling, waste heat and biomass in distributed CHP (substituting 11% of fossil fuels in distributed CHP in 2010 primarily with waste heat and complementarily with biomass), and the diffusion of renewable energy (substituting 35% of residual fuels in 2010 with solar-thermal and geo-thermal energy).

Transportation

The passenger kilometers per person increases from 13,400 pkm/person in 2010 to 26,300 pkm/person in 2050. The transportation sector, however, experiences a drastic 87% reduction of CO₂ emissions from 81.4 MtCO₂ in 2010 to 11.2 MtCO₂ in 2050. This is permitted by a major efficiency improvement in fossil fuel vehicles (cars, trucks, and buses), biofuel deployment (biodiesel representing 20% of the diesel used in 2050), deep electrification of the car fleet (up to 80% of the stock), and the modal shift in both passenger transportation, with 70% of passenger cars in 2010 substituted with public transport such as urban buses and trains, and freight transportation, with 78% of road freight in 2010 substituted with rail freight. Such a revolutionary modal shift²⁸ would require a reorganization of the national transportation system as elaborated in section 2.5.

2.2. Assumptions

In the illustrative pathway discussed above, the technical options have been introduced based on a consideration of the presumed relative costs or ease of implementing the options, as determined through discussions with leading experts from both research institutes and the related business firms with expertise in the individual technology options

This has privileged particular efficiency improvements, waste energy use and fuel change, or new energy resources (e.g., renewable), while other solutions face greater technical or public opinion difficulties as detailed more precisely below:

- LED in lighting: the LED's energy saving rate is 72%.²⁹
- Higher efficiency in heating and cooling in residential and commercial sectors: energy savings due to improved insulation are 58.4%.³⁰
- Advancements in the efficiency of fossil fuel cars: the efficiency improvements of cars (excluding buses) and buses should be 158.5% and 45.9% respectively by 2050.³¹

²⁸ Being studied by the Korea Transport Institute.

²⁹ Average saving rate compared to incandescent & fluorescent lighting (Source: Technology DB provided by Korea Institute of Energy Research)

³⁰ Korean technology DB, Korea Energy Management Corporation (KEMCO)

- Biodiesel deployment in transport: biodiesel is to be blended into diesel for 20% of the diesel used in 2050. The existing diesel vehicles can accommodate this option.³²
- Solar PV facilities' specification is about 0.163 GW/km.² The total area allotted to transport roads in Korea is about 3,000 km², and 193GW can be supplied from 40% of this area.
- Introduce CCS: The CCS capture efficiency will be 90%. The storage potential in Korea is estimated to not exceed 15MtCO₂.³³ Accordingly, introduction of CCS for more than 5% will be prohibited by the storage space constraint.

2.3. Alternative pathways and pathway robustness

The illustrative pathway scenario for the power sector depends on renewable energies, mostly for emission reduction.

An alternative scenario depends mainly on CCS:

- (1) Introduce CCS for 76% of coal power generation by 2050.
- (2) Substitute 20% of gas with renewable energies, such as wind and solar PV. 51 GW of wind and 69 GW of solar PV should be installed.
- (3) Substitute all residual coal without CCS with nuclear energy. 44 GW of nuclear power should be installed.

In this scenario, CO₂ emission reductions from CCS add up to 300 MtCO₂ or 92.8% of total reduction in the power sector. However, this amounts to twenty times the domestic storage potential. This scenario assumes the availability of foreign storage spaces, an assumption that must be examined and confirmed.

Korea could consider another pathway that depends mainly on nuclear power:

- (1) Introduce CCS for 5% of coal generation by 2050.
- (2) Substitute fossil fuels with renewable energy by installing 29 GW of wind power and 14 GW of solar PV.
- (3) Substitute all coal without CCS and gas with nuclear energy. 84 GW of nuclear power should be installed.

In this scenario, CO₂ emissions reductions from nuclear adds up to 296 MtCO₂ or 91.1% of total reductions in the power sector. This scenario assumes that the problem of public acceptance associated with nuclear energy, which is currently very serious in Korea, will be addressed as discussed in the next section.

2.4. Additional measures and deeper pathways

Korea has one of the highest energy intensities in the OECD largely because of its industrial sector, which is dominated by energy-intensive heavy industries. Korea's green growth strategy proposes to

³¹ *Ibid.*

³² A more extensive deployment of this option in Korea is expected to be difficult because of the insufficient resource potential for biodiesel.

³³ According to assessment by relevant Korean experts.

promote a shift of the economic structure toward high value-added services. The present analysis has not allowed for such policy-induced structural changes of the economy.

High levels of emissions are associated with some production processes, notably, those of the steel industry. POSCO, the leading steel producer, is responsible for about 10% of Korea's GHG emission. They have developed and begun to deploy a new technology called FINEX, which reduces emissions by 40%.³⁴ New and replacement installations of plants over time will allow for the increased deployment of FINEX, leading to even greater reductions in CO₂ emissions by 2050.

There is significant unexplored potential for energy savings and efficiency improvements in all sectors from a reform of the electricity pricing system. Currently, Korea's power system operates on an antiquated pricing system, which distinguishes several customer groups (residential, industrial, commercial, agricultural, educational, and public) and charges different prices set by the government according to economic, industrial, and social considerations. The prices are occasionally adjusted, with a major systemic impact on the energy system. The current system is biased toward underpricing below the cost of generation and encourages the wasteful consumption of electricity, not only by underpricing per se but by more critically by preventing demand response and cost-based optimization of electricity consumption by customers. More broadly, it discourages investment in energy efficiency and renewable energy.

Shifting to a market-based pricing system would dramatically transform the energy system by broadening the choice space and deployment potential for various options. Exploration of these possibilities requires rather extensive study.

Further along this line of analysis, over the long-term to 2050, there is an explosive potential for deep decarbonization from the disruptive convergence of renewable energy, energy storage, advanced materials (such as graphene and carbon nanotubes), and Internet of Things, involving transformation toward a distributed power generation system.³⁵

The Asian Super Grid proposed by the Softbank Group of Japan should be seriously explored.³⁶ The core idea is to harness Mongol's enormous endowment of wind and solar energy resources. When fully deployed, these resources are projected to supply 70% of the global power demand, including demand from Japan, Korea, China, and others, and even replace all current nuclear power plants.³⁷ The Asian Super Grid would connect national transmission lines through the existing internet cables and link all major Asian cities from the renewable energy power stations in the Gobi Desert to Beijing, Seoul, Tokyo, Shanghai, Hong Kong, Bangkok, even to Delhi and Mumbai, and eventually to the European Desertec Super Grid.

³⁴ While direct emission is reduced by 40%, it indirectly increases emission by 30% by using more electricity under the current carbon intensity of electricity.

³⁵ 'The 21st Century Energy System: Transformation of Energy System through Convergence', A power point presentation by Namsung Ahn, Korea Institute Energy Technology Evaluation and Planning (KETEP), June 10, 2014.

³⁶ Proposed by Masayoshi Sohn, Chairman of the Softbank Group on September 13, 2012, as he launched the Japan Renewable Energy Foundation, as a solution to replace the nuclear power system in Japan as well as in the rest of Asia.

2.5. Challenges, opportunities, and enabling conditions

Under the Illustrative Deep Decarbonization scenario presented in this study, CO₂ emissions from fuel combustion in 2050 are reduced by about 85% relative to 2010. Key challenges for this scenario are summarized as follows:

- Considering Korea's low energy efficiency relative to value-added in energy-intensive industries (such as steel, petrochemicals, and cement³⁸), improvement of the efficiency in these industries would depend largely on process innovation and dematerialization of production; a modernization of the electricity pricing system would also be necessary to provide the correct price incentives for energy efficiency improvements.
- Substituting 80% of fossil fuel cars with electric vehicles by 2050 requires cutting the cost of batteries (which essentially depends on international technology actions) and building a nationwide charging infrastructure;
- Decarbonizing the power sector requires the shift to a large-scale distributed renewable electricity system as well as installation of backup facilities (gas-fired combined-cycle, etc.), large energy storages (pumping power, batteries, etc.) and the deployment of a smart grid to solve the intermittency problem of renewable energy;
- The large modal shift in both passenger and freight transportation to public and rail transportation projected in this study would require a revolutionary reorganization of the national transportation system. Key to reorganization should be an extensive national high-speed rail network with urban and regional rapid mass transportation systems built around high-speed-rail stations, supplemented with new conveyor-belt type rail freight services,³⁹ and double-deck freight trains serving main freight transportation routes. The current system of explicit and implicit subsidies for freight trucking and urban parking should be withdrawn;
- Continued deployment of nuclear power requires a fundamental solution to the widespread concern over its safety and especially over disposal of the spent fuel. Deployment of the SMART⁴⁰ model, which allows passive cooling, would considerably allay the maintenance safety concern by preventing a Fukushima-type meltdown of the reactor. Development and deployment of the pyro-processing technology for transmutation of high-level waste to mid-level waste would fundamentally allay the concern over the spent-fuel disposal problem by recycling the fuel. But it would take one to two decades of international R&D cooperation to develop the necessary technology;
- Shift to a distributed power generation system will be necessary in order to overcome the Not-in-My-Back-Yard (NIMBY) problem obstructing the installation of various facilities including the transmission lines.

³⁷ According to the Japan Renewable Energy Foundation, wind power generation in the Gobi Desert will amount to 8,100TWh and solar power generation in Gobi to 4,800TWh annually.

³⁸ Korea is among the countries which boast the highest energy efficiency in these industries when the efficiency is measured against output.

³⁹ This technology is being developed by the Korea Transport Institute.

⁴⁰ SMART stands for 'System-integrated Modular Advanced Reactor'. SMART was developed by Korea in 2012, is one tenth (100MW) the size of the existing model (1000MW) and would fit distributed power system.

2.6. Near-term priorities

To be realistic, nuclear power and fossil-fuel power generation with CCS each offer the largest scope for decarbonization of the energy system to 2050. But the problem of disposal of the spent fuel from nuclear power presents one of the most serious obstacles to deploying nuclear power. The pyro-processing technology, if and when it becomes available, will essentially solve this problem. Accordingly, Korea should urgently enter a joint international research program on the technology with the United States, in which Korea has a binding agreement on disposal of its spent fuel. In the case of CCS, the seemingly limited availability of storage space in Korea's coastal seas is the main obstacle. Korea should urgently explore the possibility of entering agreements with suppliers of coal and natural gas, such as Australia, which could allow Korea to lease storage spaces.

Improving the energy efficiency, in buildings, transport, and industry offers the largest scope for decarbonization in the near-term. This requires, among other things, increases in energy prices, including that of electricity, carbon pricing of energy in general, and market-based pricing of electricity. Correct pricing is necessary and urgent, accompanied by strengthening of the appropriate energy efficiency and emission standards. The same set of measures would also facilitate development and deployment of renewable energy.

In Korea, in particular, there seems to be a serious limit to deployment of solar panels because of the large space requirement. An alternative should be the installation of BIPV on the walls of buildings. Accordingly, development and deployment of BIPV should be a high priority. As to wind power, the objections from local residents or national park authorities to installation of the wind turbines is a serious obstacle to its deployment on land. The promising alternative is the ocean wind turbine. The development and deployment of this technology is a high priority.

Another high-priority plan is the replacement of the current centralized electricity generation system with a distributed electricity generation system, including extensive deployment of the smart grid. This calls for a systemic reorganization of the national power system, a major reform to be carried over a decade or longer.

The most urgent priority, however, is to develop and build a national consensus on the long-term target for deep decarbonization of the Korean economy. This would in turn require widespread understanding of the objective conditions for Korea's positioning on how to apportion the collective responsibility for global decarbonization among the leading emitters today, of the range of the plausible technological pathways as well as their implications for the requisite energy system transformation. Furthermore, such consensus-building should be informed by understanding of what the pathways would entail in terms of benefits and costs to the economy and society.

The present deep decarbonization study conducted as part of an international collaborative project involving 15 main emitters provides an ideal science-based platform on which to build such understanding and the needed consensus. And Korea's green growth strategy provides an ideal organizing framework for studies and debates toward those understanding. Within the framework of the green growth strategy, Korea should seriously explore the long-term decarbonization potential to build a national consensus on the best pathway as well as the requisite action agenda for green growth

during next few years. Such exploration should be based on a concrete roadmap for development and deployment of the necessary technologies.

United Kingdom

Steve Pye, UCL Energy Institute

Gabriel Anandarajah, UCL Energy Institute

1. Country profile

1.1. The national context for deep decarbonization and sustainable development

Part of the G20 group of nations, the UK is an advanced economy with trade focused in services, and a declining manufacturing base over recent decades. Once a large producer of oil and gas, declining reserves have increased import dependency in recent years. A large energy infrastructure exists due to the historical reliance on gas for heating and high level of electrification. The changing economy and energy system have led to three key energy policy issues emerging over the last 10 years: energy security, affordability, and system decarbonization.

The case for deep decarbonization of the UK energy system was first made in a landmark report by the Royal Commission on Environmental Pollution in 2000,⁴¹ which proposed a voluntary 60% reduction in CO₂ emissions by 2050, recognizing the serious challenge of climate change. Over the decade that followed, the Government undertook a number of strategic analyses, notably in 2003 and 2007,⁴² which further assessed the techno-economic implications of deep decarbonization. These strategies, and supporting modelling,⁴³ laid the foundation, in 2008, for the UK to be the first G20 economy to legislate a long-term emission reduction target. Under the Climate Change Act 2008,⁴⁴ a GHG reduction target of 80% is to be achieved by 2050 (relative to 1990 levels), with a set of 5-year carbon budgets independently proposed and monitored by the Committee on Climate Change (CCC).

The Illustrative Deep Decarbonization Pathway scenario described in this chapter reflects both government-led and independent analysis undertaken over the past 5 years, assessing a range of transition pathways. Its core focus is on timely emission reductions to ensure that the longer-term target objective is not undermined, and on delivery of these reductions in the most cost-effective way. The scenario also assumes domestic action only, with no explicit use of international offsets.

⁴¹ RCEP (2000). Energy - The Changing Climate. 22nd report of the Royal Commission on Environmental Pollution. London. TSO.

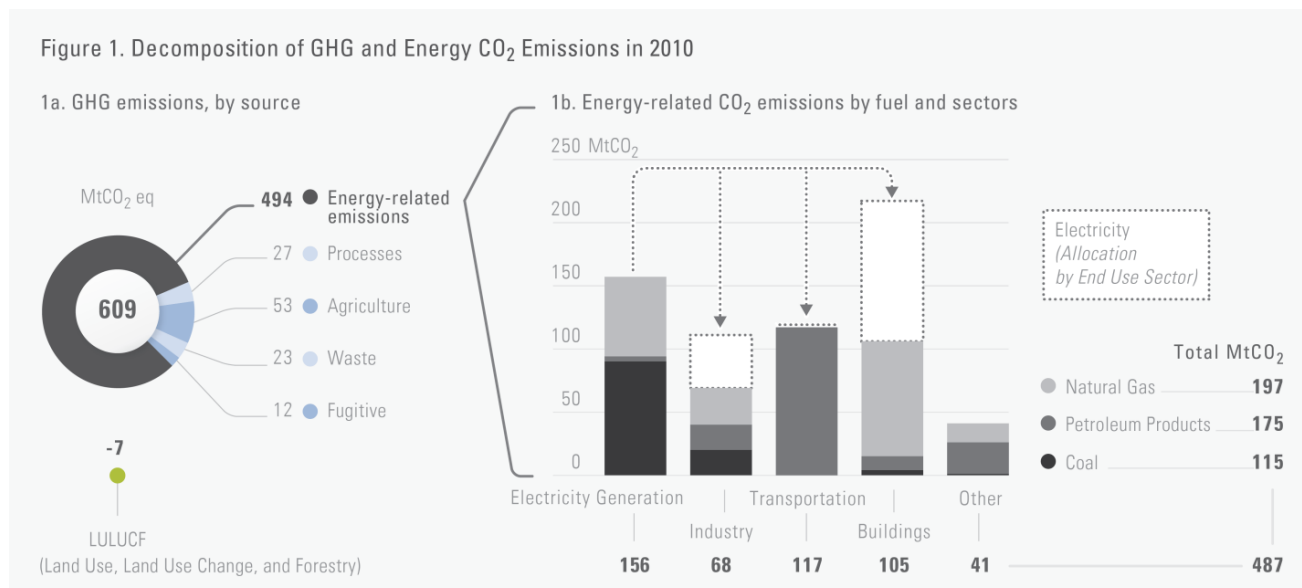
⁴² DTI (2003). Our energy future – creating a low carbon economy. Energy White Paper. Department for Trade and Industry. London; DTI (2007). Energy White Paper: Meeting the Energy Challenge. Department of Trade and Industry. London

⁴³ Strachan, N., Kannan, R., & Pye, S. (2007). Final report on DTI-DEFRA scenarios and sensitivities using the UK MARKAL and MARKAL-macro energy system models. Policy Studies Institute / UK Energy Research Centre. http://www.ukerc.ac.uk/support/tiki-download_file.php?fileId=205

⁴⁴ Climate Change Act, 2008. Climate Change Act. Available at: http://www.opsi.gov.uk/acts/acts2008/ukpga_20080027_en_1S

1.2. GHG emissions: current levels, drivers, and past trends

The level of UK GHG emissions in 2010 was 602 MtCO₂e (excluding international aviation and shipping), 82% of which were CO₂ emissions related to fuel combustion. The three sectors that constitute the largest sources of emissions include power generation, transport, and buildings, accounting for 77% of total CO₂ emissions. In per capita terms, GHG emissions are 9.6 tCO₂e/capita, and 7.9 tCO₂/capita for CO₂ emissions only.

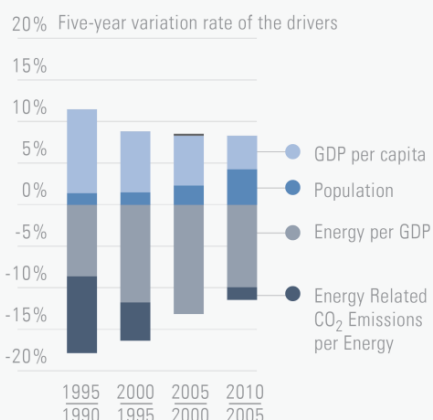


Source: UK Greenhouse Gas Inventory, 1990 to 2012. Annual Report for Submission under the Framework Convention on Climate Change. April 2014. <https://www.gov.uk/government/publications/uk-greenhouse-gas-inventory>

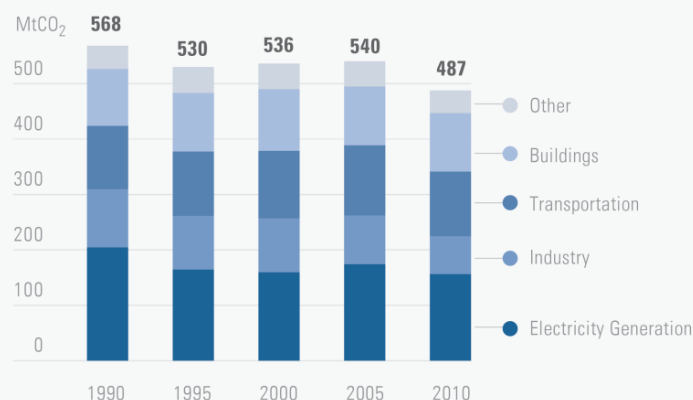
Since 1990, GHG emissions have been falling, and in 2010 were 22% below 1990 levels. Over half of this reduction (56%) can be attributed to CO₂ emissions, with the remainder from non-CO₂ emissions. A key driver of the reduction in CO₂ emissions has been the large-scale take-up of gas for power generation (the so-called 'dash for gas'), reducing the UK's historical reliance on coal (Figure 2). The other key driver has been economic restructuring, with large reductions in emissions from industrial energy use (including in iron and steel sector) over the period and a general shift to a lower energy-intensive economy. Efficiency gains in end-use sectors (buildings, transport) have led to either no growth or small decreases in emissions, relative to 1990, despite rising incomes and population growth. For non-CO₂ gases, the main reductions have been in CH₄ emissions in the agriculture sector, and N₂O emissions in specific industrial processes.

Figure 2. Decomposition of historical energy-related CO₂ Emissions, 1990 to 2010

2a. Energy-related CO₂ emissions drivers



2b. Energy-related CO₂ emissions by sectors



Source: Strachan, N., Kannan, R., & Pye, S. (2007). Final report on DTI-DEFRA scenarios and sensitivities using the UK MARKAL and MARKAL-macro energy system models. Policy Studies Institute / UK Energy Research Centre.

2. National deep decarbonization pathways

2.1. Illustrative deep decarbonization pathway

2.1.1. High-level characterization

Current government forecasts suggest that the UK economy will continue to grow at around 2.5% over the long term (between 2022 and 2050) and 2.2% in the near term⁴⁵ and that population will increase to 70.8 million by 2030 and 76.6 million by 2050,⁴⁶ from the current population in 2012 of 63.7 million. These underlying drivers make emission reductions challenging.

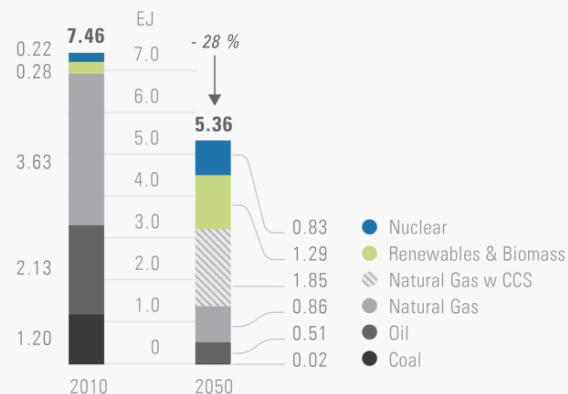
This illustrative UK decarbonization pathway has a strong focus on early decarbonization of the power sector by 2030, with low-carbon electricity becoming an enabling route for emission reductions in end-use sectors over the 2030-2050 period, replacing gas use in buildings and use of liquids fuels in transport (see Figure 3). In combination with fuel switching through electrification, robust efficiency and technology retrofit by 2030 in the transport and buildings sectors are also envisaged, with more radical technological and infrastructure change through to 2050, as the energy system further decarbonizes.

⁴⁵ OBR (2013). Fiscal sustainability report. http://cdn.budgetresponsibility.independent.gov.uk/2013-FSR_OBR_web.pdf

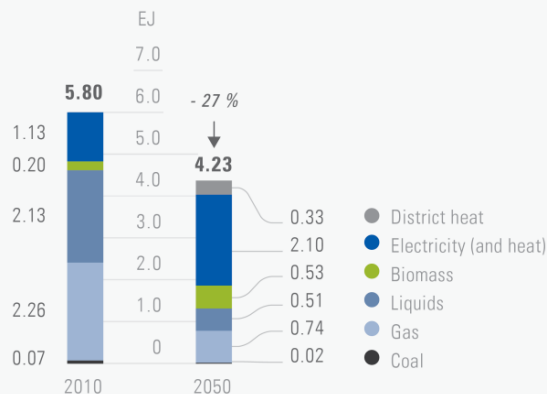
⁴⁶ ONS population projections, <http://www.ons.gov.uk/ons/rel/npp/national-population-projections/2010-based-projections/index.html>

Figure 3. Energy Pathways, by source

3a. Primary Energy



3b. Final Energy

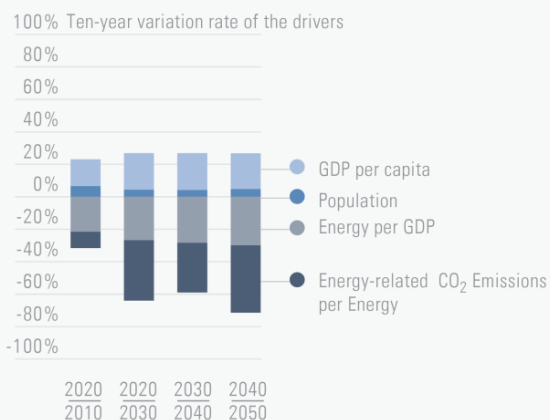


The role of biomass is also critical in the decarbonization of the energy system, with a supply of over 230 TWh by 2050, from current levels of around 40 TWh. Use is focused in power generation and district heating, but also in industry and buildings. Biofuel use in the transport sector does not increase by 2050 in absolute terms due to the large-scale reduction in use of oil products, which fall from 46 to 11 Mtoe by 2050. Gas, while only playing a small role in end-use sectors (as shown above), remains important for power generation in CCS plants, and by 2050, the sector uses over 30% more than current levels. Overall, gas use decreases by 23% due to its reduced role in heating buildings and industrial production.

Changes result in energy-related CO₂ reductions being 40% below 2010 levels by 2030 and 68% lower by 2050 (relative to 1990 levels, this is a 57% and 86% reduction respectively). This equates to a reduction in per capita CO₂ levels from 7.9 tonnes in 2010 to 3.6 tonnes in 2030 and to 1.1 tonne in 2050.

Figure 4. Energy-related CO₂ Emissions Drivers, 2010 to 2050

4a. Energy-related CO₂ emissions drivers



4b. The pillars of decarbonization

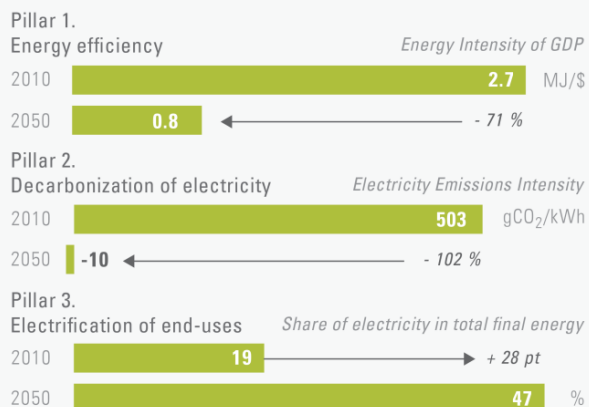


Figure 4 highlights the key drivers of emissions and the impact of pillars of decarbonization. The switch to lower-carbon fuels is a key pillar, with carbon intensity of final energy consumption (FEC) falling 78%

by 2050. This reflects increasing electrification of end-use energy services, a shift away from gas use in buildings (-69%), and increasing uptake of bioenergy. Abatement action in power generation plays a critical role in the decarbonization of energy supply; by 2050, the carbon intensity of generation is less than zero. Energy efficiency gains are illustrated by a 21% reduction in FEC and a 71% reduction in energy intensity of GDP. This reflects significant uptake of increasingly efficient technologies, particularly in the transport and building sectors, by 2050. As shown in Figure 4, all of these drivers are decreasing at a rate much greater than growing emission drivers, including population and GDP per capita (Table 1).

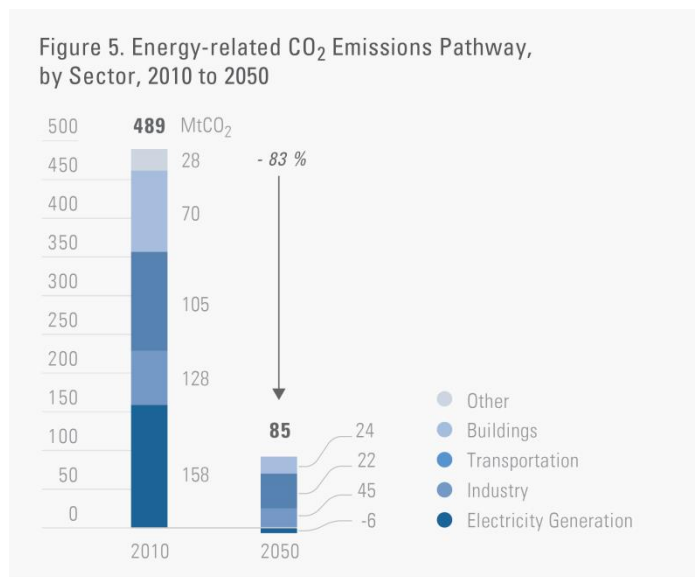
Table 1. Aggregate indicators under UK illustrative scenario

Scenario indicators	Unit	2010	2050
Population	Millions	63	77
GDP/capita	US \$/capita	35600	75800

Finally, structural and behavioral change play important roles in reducing FEC. In addition to efficiency gains, the reduction in energy intensity of industrial consumption also reflects structural changes in the economy, with growth in high value, less energy-intensive sectors, and a reduction in energy-intensive industries, in part due to global competitiveness impacts. Price-induced behavioral change further reduces energy service demand in passenger transport and building by 7.5% and 10% in 2050, saving an additional 4% of CO₂ emissions.

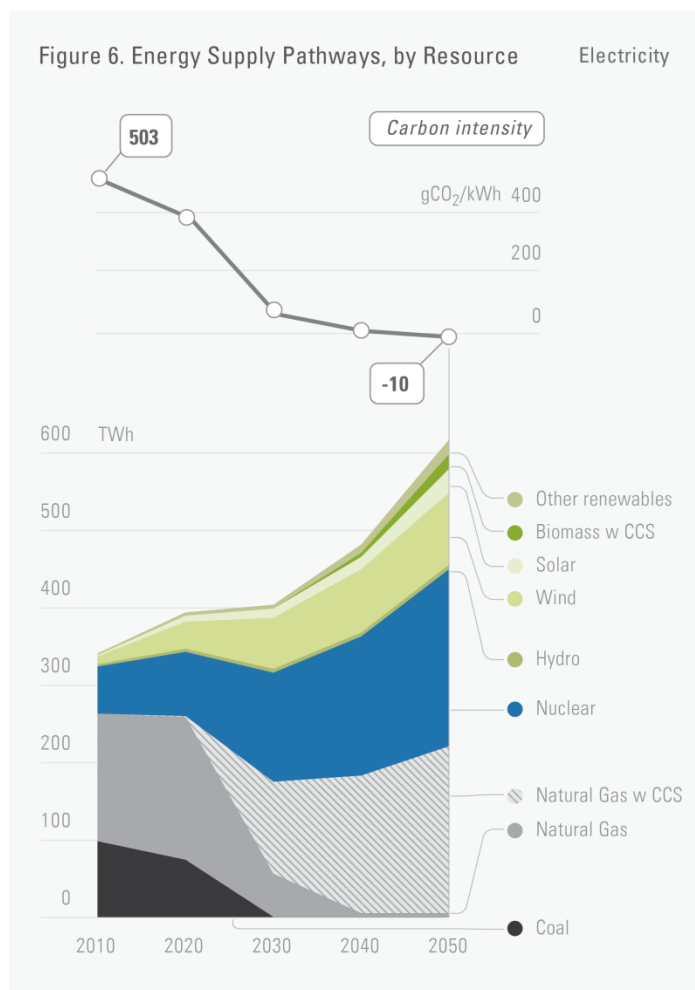
2.1.2. Sectoral characterization

The change in energy-related CO₂ emission levels highlight the efforts required across all sectors (Figure 5). The power generation sector sees dramatic reductions in both absolute and relative terms. Buildings and transport sectors also see large absolute reductions although retain similar shares of overall emissions. Overall, energy-related CO₂ emissions decrease by 83%. Lower reductions in non-CO₂ emissions of 57% mean that their share of total emissions in 2050 nearly doubles, to around 35%.



Power generation

This scenario is characterized by early decarbonization of the power sector and a large expansion in capacity to enable electrification of end use sectors. To achieve this, investment in 30-40 GW of low-carbon capacity in the 2020s is required, reducing carbon intensity of generation from a current level of 500 gCO₂/kWh to well below 100 gCO₂/kWh by 2030. By 2050, a large expansion in nuclear and gas with CCS and wind is envisaged (Figure 6), all well within the estimated UK wind and CO₂ storage resource potential. The overall capacity of the system is expected to increase to more than 140 GW, from the 2010 level of 88 GW. The intensity of carbon generation falls to below zero, due to the generation of electricity from biomass with CCS, which saves an estimated 19 MtCO₂. With over 50 GW of intermittent capacity on the system in 2050, there is a continued role for open cycle gas turbine (OCGT) plant as backup and other grid-based and end-use sector storage technologies.

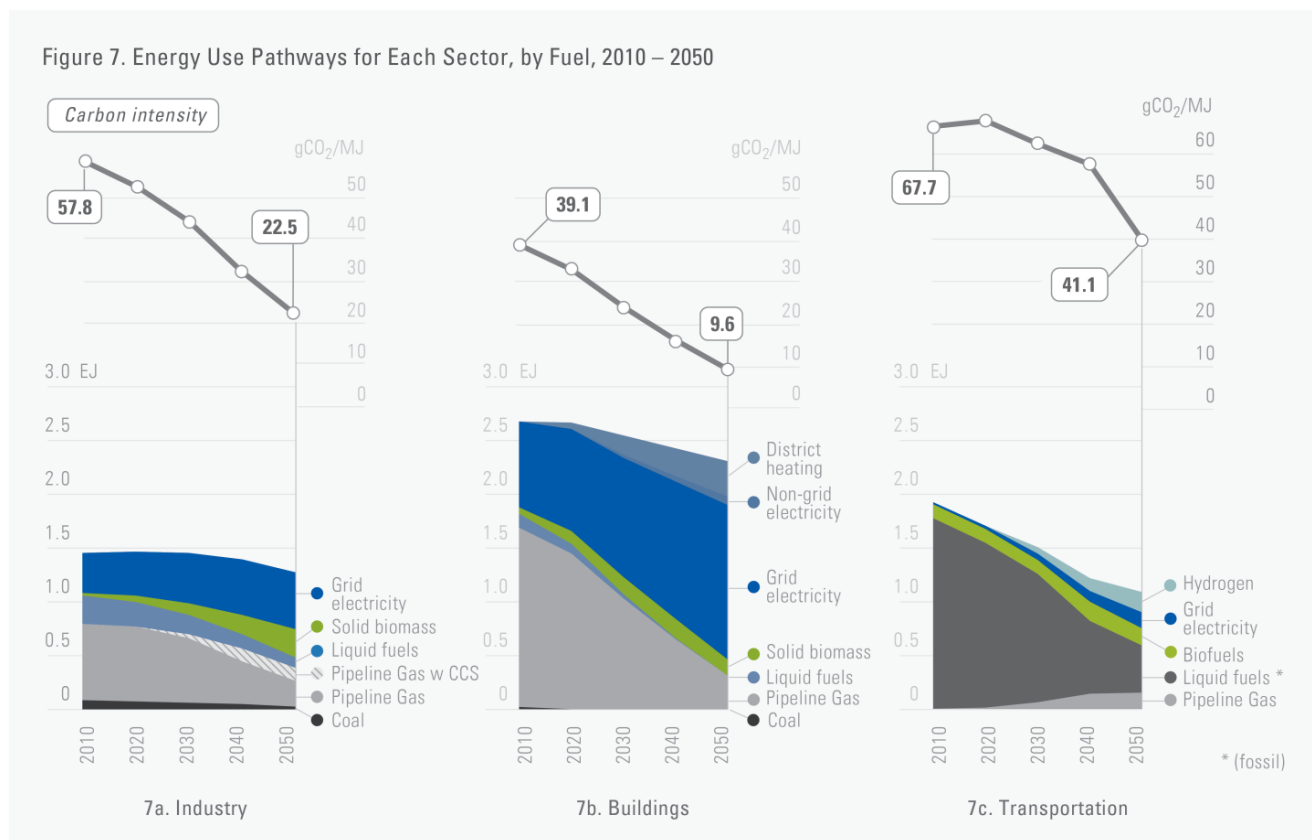


End use sectors

Strong growth in passenger and freight transport demands to 2050 make deep emission reductions especially challenging. Passenger demand is driven by population growth, and an 8% increase in per capita demand for passenger travel along with a 45% increase in freight transport demand reflect a growing economy and increasing per capita consumption. As a result, the transport sector accounts for around 50% of energy-related emissions in 2050 (Figure 5). In the car vehicle stock, action to reduce emissions is first through a strong transition to hybrid vehicles in the 2020s and then to plug-in

hybrid/battery electric vehicles (EVs) in 2030s and beyond. By 2050, 65% of car passenger travel is met by EVs. Limited penetration of a hydrogen network in specific regions sees hydrogen provide only 20% of demand. Overall, efficiency of road passenger travel increases significantly, with a 40% reduction in FEC despite growing demand. Transport road freight sees a move towards hydrogen and dual gas fueled vehicles. Diesel still accounts for 30% of road freight demand but with a higher share of biodiesel than observed for lighter duty vehicles.

Energy demand in residential buildings is based on projected growth in dwellings of 34% between 2010 and 2050, rising from 26.6 to 35.5 million. While constituting a much smaller share of total energy use, commercial sector floor space is also projected to grow from 0.55 to 0.86 billion m². The key mitigation actions in this sector include retrofitting of the existing build stock using a range of different energy efficiency measures (near- to mid-term) and decarbonization of heat through electrification (heat pumps/resistive electric heaters) and district heating (mid- to longer-term). District heating is primarily supplied via waste heat recovery, biomass, and gas. The scenario suggests a pathway that radically reduces the role of gas for heating in buildings, with supply reducing from 44 to 7 BCM by 2050.



Note: Carbon intensity shown in Figure 7 for each sector includes only direct end-use emissions and excludes indirect emissions related to electricity or hydrogen production.

Industrial sector emissions fall in part due to a reduction in energy intensity of production, which decreases from 62 to 35 toes/£m. This is both due to efficiency gains and ongoing industrial restructuring, with a move to higher value production sectors (for example, in chemicals) and shrinking energy intensive production capacity (including iron and steel and non-ferrous metals). The decrease in

the carbon intensity of FEC (Table 2) reflects fuel switching to electricity and biomass, accounting for about 70% of total FEC in 2050, and industrial CCS on industrial plants which continue to use gas.

2.2. Assumptions

The decarbonization pathway described relies on a large-scale shift to low-carbon power generation, based on a portfolio of options including nuclear, CCS, and renewables, particularly wind. Nuclear capacity is 32 GW in 2050, implying a build rate of 1 GW/year from 2020, the date when the first 3rd generation plant is planned to have been built. Higher annual build rates for gas CCS capacity of 1.5 GW will be needed, which will be challenging given the technological and CCS infrastructure novelty. Once demonstrated, the UK is well placed to benefit from this emerging technology, with significant storage capacity for captured CO₂, particularly in the North Sea. The technical capacity of the UK (including continental shelf) is estimated to be in the region of 70 billion tonnes, sufficient to store a 100 years' worth of current emissions from the energy sector.⁴⁷ Wind generation also plays a strong role in this scenario, providing almost 100 TWh in 2050, based on capacity levels of 35 GW, which is well within the practical resource potential available of over 400 TWh for UK.⁴⁸ Implied build rates of under 1 GW are similar to those being currently observed in the UK.

The building sector offers strong potential for retrofit to reduce energy use through fabric upgrade. In 2030, the CCC estimate annual savings of 7 MtCO₂ (sector emissions are approx. 40 MtCO₂).⁴⁹ Key measures include solid and cavity wall insulation, loft insulation, improved controls, and behavioral measures. However, there is also an important heat replacement effect due to more efficient appliances, which increases heating requirement (and reduces savings). Rapid switching to heat pumps and establishment of large numbers of district heating schemes see the gas distribution grid redundant by 2050. In household terms, this equates to 20 million homes switching to these systems from gas by 2050, or an average of 500,000 per year over the period.

The electrification of passenger road transport is assumed to take place at scale in the 2030s. This assumes EVs will be cost-competitive, the required manufacturing capacity is in place to meet demand, and a level of charging infrastructure is in place that provides confidence for uptake. This scenario assumes around 25 million EVs are on the road by 2050. Penetration in the market place during 2020s of 20-25% of new cars sales (on average) could establish a fleet of 5 million EVs by 2030. Post-2030, stronger growth would be required, with EVs accounting for 50-60% of new car sales.

Biomass plays an increasingly important role in the energy system transition. The bioenergy levels used in the UK scenario are in the center of the range of resource potential considered in recent UK analysis, taking account of share of global resources.⁵⁰ Modelling for the study suggested optimal use in power

⁴⁷ DECC (2012). CCS Roadmap: Supporting deployment of Carbon Capture and Storage in the UK. Department of Energy & Climate Change. April 2012. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/48317/4899-the-ccs-roadmap.pdf

⁴⁸ CCC (2011). The Renewable Energy Review. Committee on Climate Change, May 2011. <http://www.theccc.org.uk/>

⁴⁹ CCC (2013). Fourth Carbon Budget Review – part 2: The cost-effective path to the 2050 target. Committee on Climate Change. December 2013. <http://www.theccc.org.uk/>

⁵⁰ CCC (2011b). Bioenergy review. Committee on Climate Change. December 2011. <http://www.theccc.org.uk/>

generation with CCS, if this option was available. This is reflected in the UK scenario described in this chapter, alongside a strong role in the buildings (including district heating provision) and industry.

2.3. Alternative pathways and pathway robustness

The pathway described for the UK is challenging and requires a substantial diffusion of a wide range of mitigation options. However, it is important to highlight that many other decarbonization pathways are technically feasible and could be delivered under the right conditions. A recent UK synthesis study draws out commonality across modelling studies, but also highlights the different options that could achieve deep emission reductions, particularly in the power sector.⁵¹ Uncertainty analysis published by the CCC highlights differences in deployment of renewable technologies. Even when both nuclear and CCS are available, shares of renewable generation ranged from 30% to 94%, with most solutions in the range of 40% to 70%.⁵² This highlights the uncertainties even where all options are available and that the illustrative pathway presented here is one of many plausible futures.

Further analysis is being undertaken in the UK to explore other uncertainties in energy system decarbonization, and what that means for different pathways.⁵³ What is evident from such analyses is that reductions, particularly in the power sector, can be achieved by a range of different technologies. However, the non-availability of key technologies such as nuclear and/or CCS increases costs substantially, and tends to both increase the role of renewables and reduce the role of electrification in the energy system.

In the transport sector, under an alternate pathway, hydrogen-fuelled vehicles can play an important role as a dominant vehicle technology especially for passenger cars. This depends on the cost assumptions of the relative fuel production systems, the technology and infrastructure costs, and the system-wide role for electrification. For road freight, there is less flexibility, due to the limited role for electrification. Switching to natural gas and hydrogen-based vehicles is therefore critical. There could also be a stronger role for biofuels across the transport system, the penetration of which has been limited in this scenario.

Electrification of heating in buildings has been a strong feature of most modelling analyses undertaken in the UK, as gas use rapidly decreases out to 2050. Alternatives to electricity-based heating (through heat pumps) include increasing use of bioenergy, solar thermal, and district heating, which is a key element of this scenario. In summary, a significant role for electricity is required in the UK for decarbonization, although the extent of its role can be balanced against other options.

Further systematic assessment of robustness of different pathways is needed, to better understand what are the key technologies and associated uncertainties that impact deep decarbonization. From a UK perspective, key issues around pathway robustness include ensuring security of electricity supply given higher peak demand and a more intermittent supply, maintaining bioenergy supply, and delivering

⁵¹ Ekins, P., Keppo I., Skea J., Strachan N., Usher W., Anandarajah G. (2013). The UK Energy System in 2050: Comparing Low-Carbon, Resilient Scenarios. (UKERC Report UKERC/RR/ESY/2013/001). UK Energy Research Centre: London, UK. <http://www.ukerc.ac.uk/>

⁵² See endnote 11.

⁵³ Trutnevyte, E., & Strachan, N. (2013). Nearly perfect and poles apart: investment strategies into the UK power system until 2050. International Energy Workshop 2013.

demand-side reduction. Recent analysis assessing the impacts of key uncertainties on delivery of decarbonization pathways analysis points to critical assumptions concerning the availability of biomass (due to its use for delivering negative emissions in 2050), and the price of gas and cost of nuclear in determining the generation mix.⁵⁴ The prospective role played by demand reduction and other behavioral change measures is also highly uncertain but critical in the mix of demand and supply-side responses needed for meeting stringent targets.⁵⁵

2.4. Additional measures and deeper pathways

Additional reductions beyond those considered in the illustrative pathway significantly increase abatement costs and stretch credibility of technology deployment rates. Modelling studies have considered more stringent decarbonization levels,⁵⁶ using scenarios to explore CO₂ reductions of 90-95% below 1990 levels (95% is equivalent to ~0.4 tCO₂/capita). These scenarios are by nature exploratory but do provide some interesting insights. In the power sector, CCS becomes a less relevant technology, due to the residual emissions, resulting in larger nuclear and renewable capacities. The exception is biomass CCS (in one analysis), which provides important negative emission credits. In the transport sector, the share of biofuels increases while all hydrogen production is fully decarbonized. In a number of scenarios, it is only the increased role of price-induced demand response that allows the model to meet the stringent reduction levels.

The feasibility of this level of reduction is questionable, both from a techno-economic and political perspective. Most of these analyses suggest marginal costs of abatement of over \$US 1,200/tCO₂ or higher by 2050. The question is whether this level of mitigation could be incentivized and whether political will could be sustained. However, it is also worth noting that most modelling studies do not account for radical social change resulting in changing behavior. For example, there are a range of measures in the transport sector that could lead to radical demand reductions *e.g.* modal shift, including a move to non-motorized transport, changes in patterns of living/work aided by urban planning, and increased uptake of telecommunications as an alternative.⁵⁷

2.5. Challenges, opportunities, and enabling conditions

Transforming the energy system requires strong and maintained policy interventions in technology development, leveraging capital investment, removal of market barriers, and enabling behavioral change. In the power sector, a key challenge is the scale of investment required in low-carbon technologies. For strong decarbonization of the sector by 2030, estimates of total cumulative

⁵⁴ Pye, S., Sabio, N. & Strachan, N. (2014). An integrated systematic analysis of uncertainties in UK transition pathways. UKERC Working Paper. London, UK: UK Energy Research Centre (UKERC).

⁵⁵ Pye, S., Usher, W. & Strachan, N. (2014). The uncertain but critical role of demand reduction in meeting long-term energy decarbonisation targets, Energy Policy (Accepted).

⁵⁶ i) AEA (2011). Pathways to 2050 – Key Results. A Report to the Department of Energy and Climate Change. May 2011. AEA, London. ii) AEA (2008). MARKAL-MED model runs of long term carbon reduction targets in the UK, Phase 1. Authored by Pye, S., N. Hill, T. Palmer, and N. Ozkan. On behalf of the Committee on Climate Change. November 2008. iii) Usher, W. and Strachan, N. (2010). Examining Decarbonisation Pathways in the 2020s on the Way to Meeting the 2050 Emissions Target. On behalf of the Committee on Climate Change. November 2010.

⁵⁷ For example, see Anable, J., Brand, C., Tran, M., & Eyre, N. (2012). Modelling transport energy demand: A socio-technical approach. Energy Policy, 41, 125-138.

investment range from £200bn to over £300bn. Based on recent analysis, this means an average investment requirement of £6.1bn/year (3.4 GW per year of new capacity) to 2020, increasing to £12.3bn (5.7 GW) to 2030 due to the increased construction of capital-intensive low-carbon plant, and greater levels of plant retirement.⁵⁸ Mitigating investment risks is critical; the Electricity Market Reforms (EMR) introduced by the UK Government seeks to incentivize large-scale investment in less mature low-carbon generation.⁵⁹

Notable uncertainties remain about the viability of CCS, since it has not yet been sufficiently demonstrated at scale. A strong focus now on CCS by the UK and other countries could see its wide-scale deployment in the late 2020s. Strong capacity in the offshore industry means the UK would be in a good position to benefit from this technology (as is the case for offshore wind). Demonstrating cost-effective deployment of the first new nuclear reactor in the UK in 20 years (at Hinkley Point C) will be critical to increase acceptability on cost grounds, as well as broader public acceptability. An increased role for renewables, particularly wind, could lead to increased technical operational challenges due to the higher share of intermittency. However, analysis suggests that high shares need not materially impact the security of supply given a range of options to address intermittency, such as demand response, storage, and interconnection.⁶⁰ Finally an additional challenge is high infrastructure costs. For wind, other renewables, and CO₂ storage, much of the resource is offshore and often located in remote areas, such as Northern Scotland.

Decarbonization of heat in buildings will require a radical shift away from piped natural gas (and potential decommissioning of the gas distribution system) to electrification via heat pumps and/or introduction of district heating systems. Large-scale uptake of heat pumps will require householder incentives for switching and a supply chain capacity to be in place. There may also need to be significant reinforcement of the electricity distribution system, especially with smart metering and two-way flows of electricity. District heating systems will require a financing mechanism, perhaps via local authorities, and could run up against public acceptability issues.

Electrification of road passenger cars (especially for the 70% of travel demand that is made up of trips of less than 50 miles) is a key mitigation option. A major challenge concerns large-scale uptake which will be dependent on some level of charging infrastructure, and the necessary incentives to get around the higher costs associated with the battery technology.⁶¹ In a recent study, three key uncertainties were highlighted to large-scale uptake, as envisaged under this scenario: 1) long-term certainty across different incentives, 2) lack of an integrated payment mechanism for EV charging, and 3) more robust methodologies for the estimation of the environmental performance, costs, and range limitations to

⁵⁸ Blyth, W., McCarthy, R. & Gross, R. (2014). Financing the power sector: is the money available? UKERC Working Paper. UK Energy Research Centre. London, UK.

⁵⁹ DECC (2013). Electricity Market Reform Delivery Plan. Department of Energy and Climate Change. December 2013.

https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/268221/181213_2013_EMR_Delivery_Plan_FINAL.pdf

⁶⁰ Poyry (2010). Options for low-carbon power sector flexibility to 2050. Report to Committee on Climate Change. October 2010. <http://www.theccc.org.uk/>

⁶¹ Element Energy (2013). Pathways to high penetration of electric vehicles. December 2013. http://www.theccc.org.uk/wp-content/uploads/2013/12/CCC-EV-pathways_FINAL-REPORT_17-12-13-Final.pdf

ensure confidence.⁶² Points 1) and 3) are also relevant for other low-emission vehicles, such as hydrogen.

For the industry sector, limited modelling on economic structural change, the role of CCS, and potential for fuel switching make the uncertainties considerable. Capturing the impact of global decarbonization on UK industry is also challenging. In terms of burden on different industrial groups and regions, government action will be needed to mitigate such distributional impacts.

2.6. Near-term priorities

Whilst challenging, and with large inherent uncertainties, a transition to a low-carbon economy is an opportunity for significant investment in R&D and infrastructure. This could have major benefits for economic growth due to the emergence of new industries and investment, whilst replacing and developing new energy infrastructure. A move towards lower-carbon technology and resource base could also strengthen energy security.

It is clear that the Government has a strong role to play in creating the right investment environment for the transition. Key actions, many of which have or are in the process of being developed, include:

- Maintaining the political will to enact the independently set 5-yearly carbon budgets with a corresponding set of implementation policies that are backed across government.
- Through electricity market reforms, incentivizing investment in low-carbon generation that is capital intensive, less mature, possibly more intermittent, and requires significant payback periods.
- Focusing R&D on technologies that the UK can develop economic benefits from, including offshore renewables but also in automotive industries and other energy technology manufacturers.

⁶² Morton, C., Anable, J. & Brand, C. (2014) Perceived Uncertainty in the Demand for Electric Vehicles: A qualitative assessment. UKERC Working Paper. London, UK: UK Energy Research Centre (UKERC).

United States

Energy and Environmental Economics, Inc.

1. Country profile

1.1. The national context for deep decarbonization and sustainable development

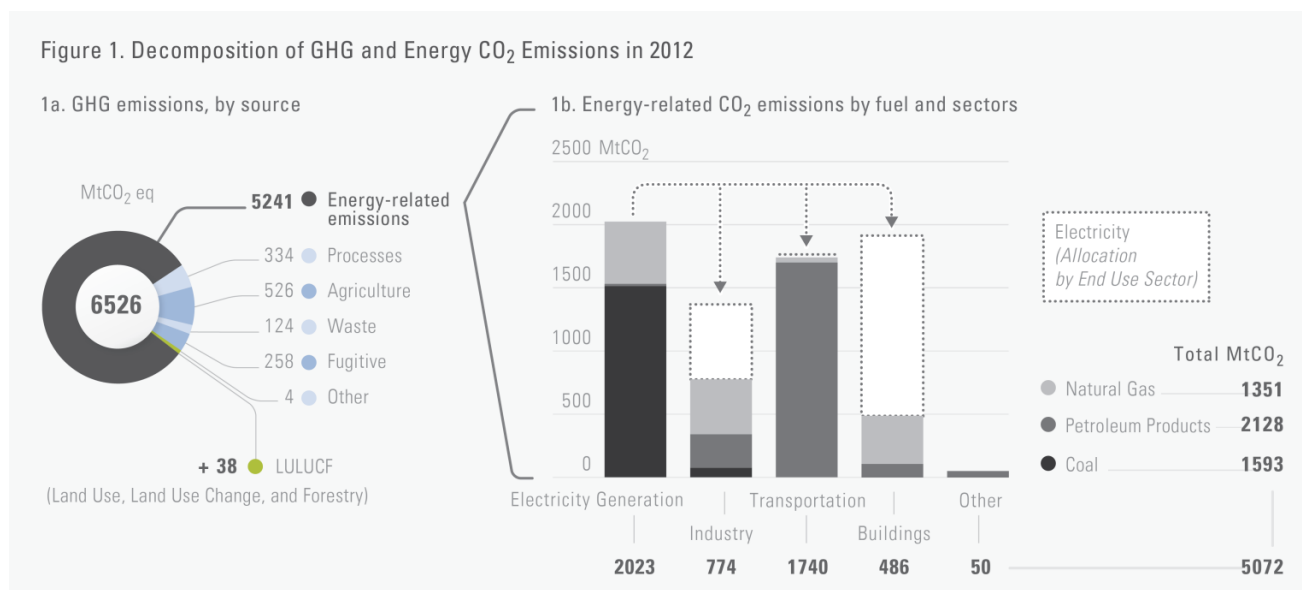
The United States is the world's second largest emitter of greenhouse gases (GHGs), and one of the highest per capita consumers and producers of energy and fossil fuels. Deep decarbonization will require a profound transformation of the way energy is produced, delivered, and used, in a transition that is sustained over multiple generations. This analysis provides insight into what very low-carbon energy systems in the U.S. could look like and describes key steps and alternative routes to reaching a level of energy-related CO₂ emissions that is consistent with an increase in global mean temperature below 2°C. In 2010, U.S. energy-related emissions were approximately 18 metric tons of CO₂ per person. For the U.S. to do its share in reaching the 2°C target, by 2050 this per capita emissions level will need to decrease by an order of magnitude. Developing a long-term strategic vision of how the U.S. can reach this goal is essential for informing near-term policy and investment decisions and for conveying to domestic and international audiences how the U.S. can provide climate leadership while maintaining economic growth and improving standards of living.

The U.S. currently does not have comprehensive federal climate legislation or a binding national GHG emissions target. Nonetheless, the U.S. has taken important steps in low-carbon policy and technology deployment at the federal, state, and local government levels. Significant recent federal government executive branch actions include setting vehicle fuel economy standards, which will nearly double for passenger cars and light trucks by the 2025 model year relative to 2010, and establishing appliance energy efficiency standards for more than 50 product categories, leading to dramatic reductions in unit energy consumption for technologies such as refrigeration and lighting. In June 2014, the Obama Administration announced plans to apply the federal Clean Air Act to CO₂ emitted by power plants, setting a target of a 30% reduction below 2005 levels by 2030, which, if implemented successfully, will hasten the transition from uncontrolled coal generation to natural gas or coal with CCS.

In the U.S., states have primary jurisdiction over many key elements of the energy system, including electric and natural gas utilities, building codes, and transportation planning. This has enabled many states to develop climate and clean energy policies in the absence of federal legislation. Twenty states have adopted GHG emission targets, 29 states have renewable portfolio standards (RPS) for electricity generation, and 39 states have building energy codes. Nine Northeastern states have joined the Regional Greenhouse Gas Initiative, the first market-based program in the U.S. for reducing power sector emissions. California, with a legally binding statewide GHG target for 2020, a deep decarbonization goal for 2050, ambitious sectoral policies, and a carbon market, is a national test case for demonstrating the cost and feasibility of a low-carbon transition.

1.2. GHG emissions: current levels, drivers, and past trends

U.S. GHG emissions are dominated by CO₂ from fossil fuel combustion. In 2012, energy-related emissions of all kinds (including fugitive emissions from fuels) accounted for 5,499 MtCO₂e, nearly 85% of total gross GHG emissions of 6,526 MtCO₂e (Figure 1A). Of these, 5,072 Mt (78%) were fossil fuel combustion CO₂, which is shown disaggregated by fuel source and end-use sector in Figure 1B.



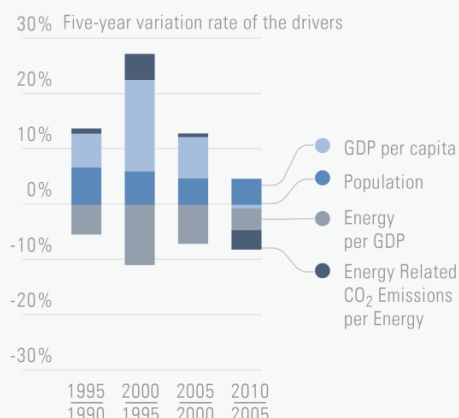
Source: U.S. Environmental Protection Agency (EPA), Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2012, April 15, 2014. Excludes impact of LULUCF net sink, which would reduce net emissions by 979 MT CO₂e in 2012. <http://www.epa.gov/climatechange/Downloads/ghgemissions/US-GHG-Inventory-2014-Main-Text.pdf>

Electricity generation constituted 2,023 Mt (40%) of CO₂ emissions from fossil fuel combustion in 2012. With electricity emissions allocated to end-use sectors, the building sector (both residential and commercial) is the largest emissions source (38%), followed by transportation (34%) and industry (27%). Transportation-sector CO₂ emissions are almost entirely from direct fossil fuel combustion, while industrial-sector CO₂ emissions are divided between direct fuel combustion and electricity consumption, and building-sector emissions are primarily from electricity consumption (Figure 1B).

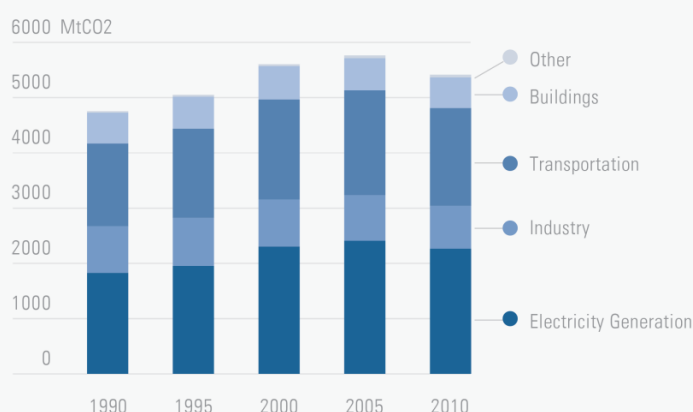
U.S. fossil fuel combustion CO₂ emissions rose from 1990 through 2005, mainly due to population and GDP growth. This growth was partly offset by improvements in energy efficiency, measured as a reduction in the energy intensity of GDP (Figure 2A). Emissions declined from 2005 to 2010, largely due to the economic slowdown after 2008. The electricity and transportation sectors accounted for the bulk of growth in CO₂ emissions from fossil fuel combustion between 1990 and 2010 (Figure 2B). The continued decline in emissions since 2010 is due to a combination of factors, including coal displacement in power generation by inexpensive natural gas.

Figure 2. Decomposition of historical energy-related CO₂ Emissions, 1990 to 2010

2a. Energy-related CO₂ emissions drivers



2b. Energy-related CO₂ emissions by sectors



Source: Based on EPA, 2014 and data from the U.S. Energy Information Administration (EIA), <http://www.eia.doe.gov>.

Note: Buildings, transportation, and industry emission are direct /emissions only, and electricity use, which is categorized separate. National deep decarbonization pathways

2. Illustrative deep decarbonization pathway

2.1.1. High-level characterization

This study's most important finding is that it is technically feasible for the U.S. to reduce CO₂ emissions from fossil fuel combustion to less than 750 MtCO₂ in 2050, which is 85% below 1990 levels and an order of magnitude decrease in per capita emissions compared to 2010. This finding is demonstrated by preliminary modeling results for four different scenarios: a main case, plus three alternative scenarios that more heavily emphasize renewable, CCS, or nuclear power generation. All four scenarios assume continued growth in key macroeconomic indicators and energy service demand drivers, consistent with the U.S. Energy Information Administration (EIA) *Annual Energy Outlook 2013* reference case (Table 1).

Table 1. Selected Economic Indicators and Energy Service Demand Drivers

Indicator	Unit	2010	2050*	AAGR 2010-2050
Population	Million person	310	441	0.9%
GDP	\$Billion (\$2005)	13,063	34,695	2.5%
GDP per capita	\$/person	42,130	78,723	1.6%
Industry value added	\$Billion (\$2005)	2,337	4,925	1.9%
Residential floor area	Million square meter	17,691	28,102	1.2%
Commercial floor area	Million square meter	7,539	11,167	1.0%
Passenger transport	Billion kilometers traveled	7,834	11,121	0.9%
Freight transport	Billion ton-kilometers	7,004	10,361	1.0%

*2050 values based on AEO 2013 Reference Case (2010-2040) extrapolated to 2050 using linear 2020-2040 growth rates

Scenario design objectives

The scenarios in this study were developed to explore how deep decarbonization in the U.S. can be achieved through a technological transformation of its infrastructure over time, subject to a variety of

economic, technical, and resource constraints. Key constraints (design objectives) considered in this analysis are described in Table 2.

Table 2. Scenario Objectives and Analysis Approach

Scenario Objectives	Analysis Approach
Avoid or limit early retirement of existing infrastructure	Use granular annual stock rollover model with infrastructure inertia, allow equipment to cover full investment cost
Avoid or limit need for new infrastructure	Minimize the use of measures that require the creation of major new types of infrastructure (e.g. CO ₂ pipeline)
Emphasize technologies that are already commercialized	Minimize use of non-commercialized technologies and use conservative technology performance assumptions.
Maintain electric reliability	Use hourly dispatch model to ensure adequate capacity and flexibility for all generation mixes
Make decarbonization measures realistic and specific	Require granular subsector decarbonization strategies to isolate difficult cases (e.g. freight, industry) when evaluating feasibility
Avoid environmentally unsustainable measures	Adhere to non-GHG sustainability limits for biomass use, hydroelectricity
Maintain industrial competitiveness	Adopt measures that keep compliance costs as low as possible while achieving the necessary reductions
Achieve emission reductions domestically	Don't assume international offsets will be available
Exclude forest carbon sink	Focus on reducing energy system CO ₂ , as this is the pivotal transition task and carbon sink behavior is poorly understood
Adapt to regional conditions and preferences	Make decarbonization strategies consistent with regional infrastructure, economics, resources, and policy preferences

Modeling approach

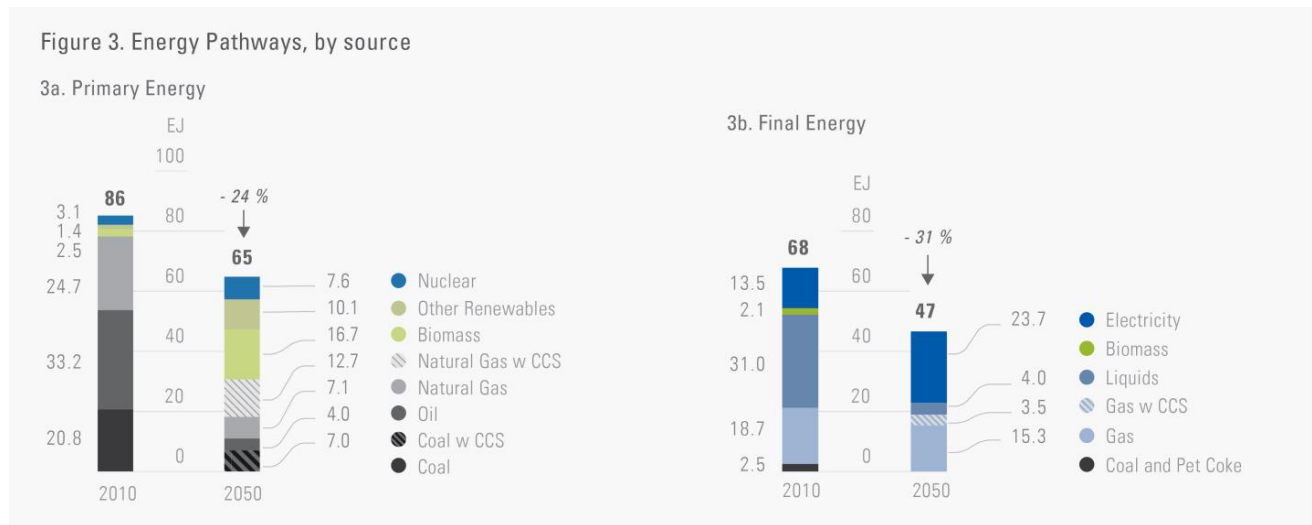
The scenarios were developed using Pathways, a granular bottom-up energy balance model, with 80 energy demand subsectors and 20 energy supply pathways, modeled separately in each of the nine U.S. census regions. Pathways incorporates a stock rollover model, which makes stock additions and retirements in annual time steps, and an hourly electricity dispatch model. The analysis also used the global integrated assessment model GCAM to develop resource assumptions for domestic biomass use in the U.S. The scenario results shown here are preliminary.

Illustrative scenario

The transition to a low-carbon energy system involves three principal strategies: (1) highly efficient end use of energy in buildings, transportation, and industry; (2) decarbonization of electricity and other fuels; and (3) fuel switching of end uses from high-carbon to low-carbon supplies. All three of these strategies must be applied to achieve deep decarbonization, as demonstrated in an illustrative deep decarbonization scenario ("main case"). Table 3 describes the measures by which these strategies were implemented, and Table 4 shows the quantitative results. Despite a near doubling of GDP between 2010 and 2050, U.S. total final energy consumption declines from 68 to 47 EJ. The result is a 74%

reduction in economic energy intensity (MJ/\$). Average annual rates of technical energy efficiency improvement are 1.7% in residential buildings, 1.3% in commercial buildings, 2.2% in passenger transportation (in part from switching to electric drivetrains), and 0.7% in freight transportation.

For the main case, primary energy supply⁶³ decreases by 24% from 2010 to 2050 (Figure 3A). Petroleum falls from the largest share of primary energy in 2010 (39%) to 6% in 2050, while biomass increases to 26%. Collectively, fossil fuels (oil, coal, and natural gas, with and without CCS) decrease from 92% of primary energy supply in 2010 to 47% of primary energy in 2050. Final energy decreases by 31% over the same time period (Figure 3B). The liquid fuels share of final energy falls from 46% to 9%, while electricity's share of final energy rises from 20% to 51%, and gaseous fuels grow from 28% to 41%.



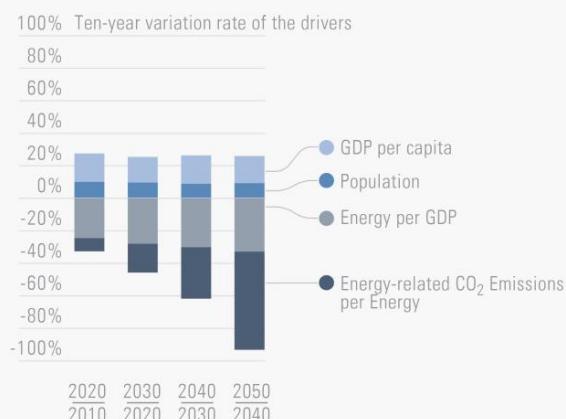
Note: Oil primary energy excludes petrochemical feedstocks. Liquids final energy excludes petrochemical feedstock.

Key drivers of changes in CO₂ emissions between 2010 and 2050 are shown in Figure 4A. A growing U.S. population (+42% cumulative change between 2010 and 2050) and rising GDP per capita (+87%) are more than offset by reductions in the final energy intensity of GDP (-74%) and the CO₂ intensity of final energy (-80%), resulting in an 86% reduction in CO₂ emissions relative to 2010 levels. The three largest contributing factors to CO₂ reductions (Figure 4B) are: (1) improvements in end-use energy efficiency; (2) a near-total decarbonization of electricity generation; and (3) extensive electrification of end-uses. Two additional measures contribute to reductions but are not shown in Figure 4B: (1) fuel switching to partially decarbonized pipeline gas and (2) the use of CCS for some large-scale industrial gas users.

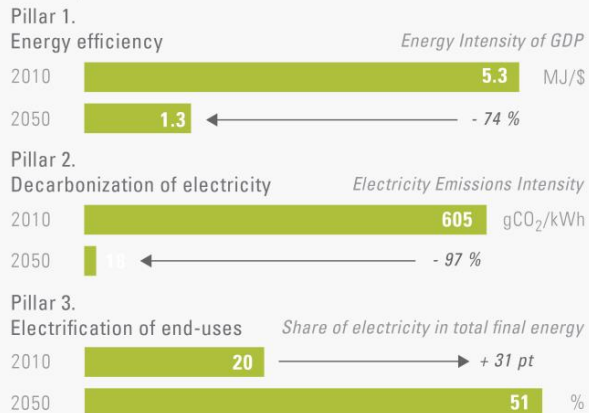
⁶³ Primary energy is calculated based on the “captured energy” method, in which electricity generation from nuclear and renewable sources (excluding biomass) is converted to primary energy at its equivalent energy value with no assumed conversion losses, *i.e.* 1 kWh generated = 3.6 MJ.

Figure 4. Energy-related CO₂ Emissions Drivers, 2010 to 2050

4a. Energy-related CO₂ emissions drivers



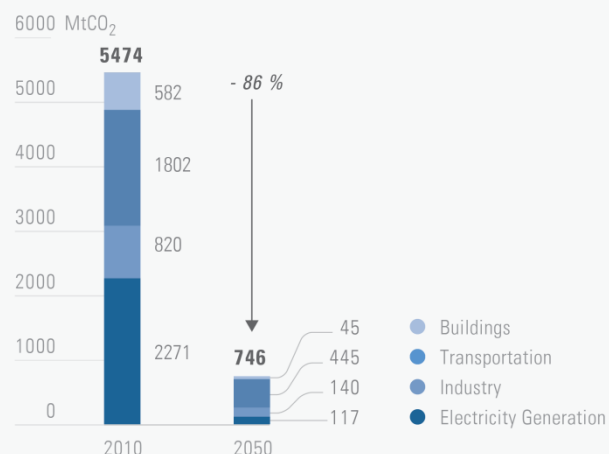
4b. The pillars of decarbonization



Note: Final energy intensity of GDP is shown as a proxy for end-use energy efficiency, though structural factors also drive reductions

By sector, electricity generation's share of CO₂ emissions falls from 40% in 2010 to 16% in 2050 (Figure 5). The remaining electricity emissions are primarily from residual emissions not captured by CCS for natural gas- and coal-fired generation. Transportation's one-third share of emissions rises to 60% of total final emissions by 2050 (excluding electrified transport), as the remaining fossil fuels in the economy are applied to largely to long-distance transport end-uses (including aviation and military use) that are difficult to electrify or convert to pipeline gas. Industrial direct emissions rise from 15% to 19% of total emissions by 2050, while the residential and commercial sectors are nearly completely electrified, leaving negligible amounts of remaining direct emissions.

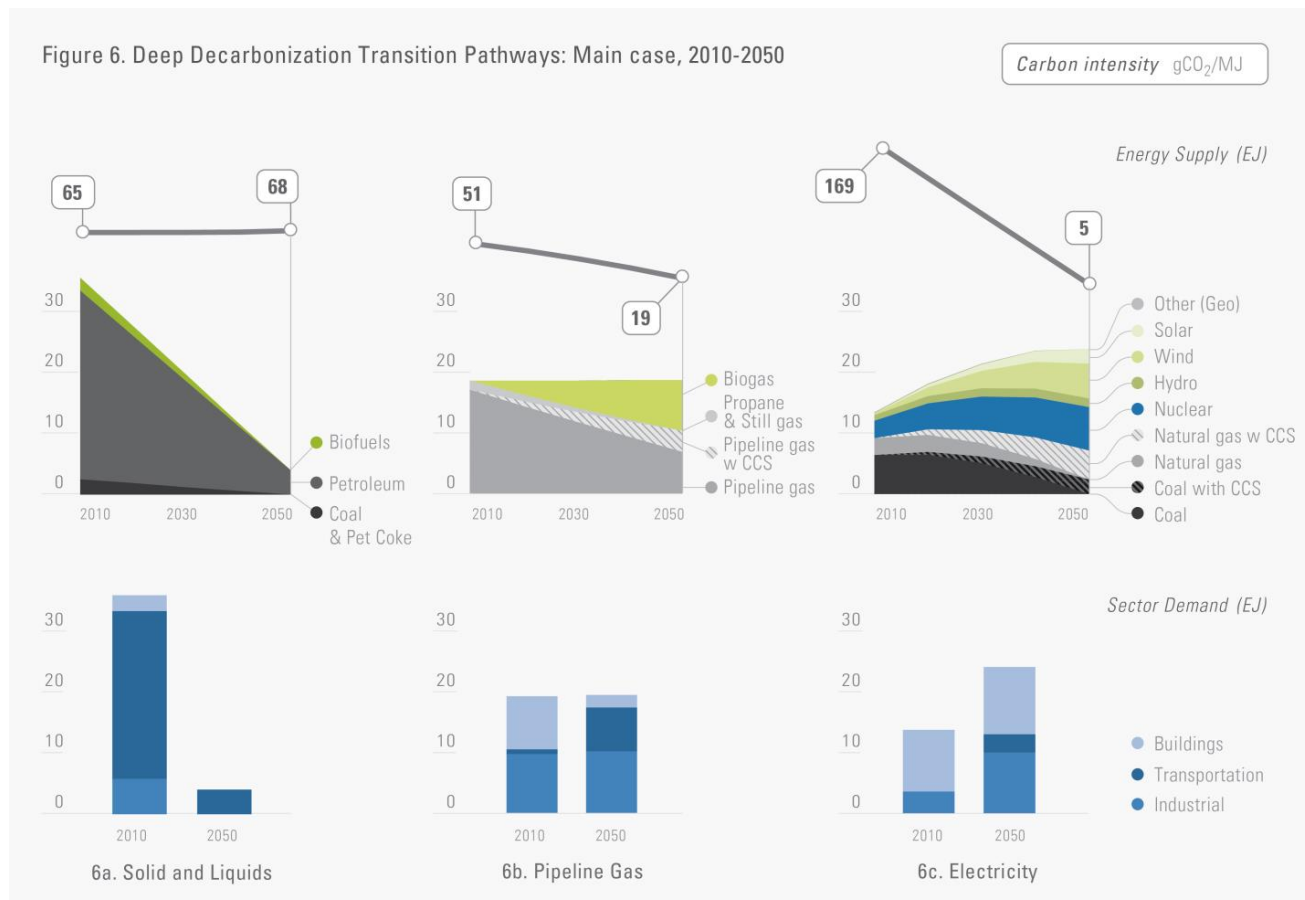
Figure 5. Energy-related CO₂ Emissions Pathway, by Sector, 2010 to 2050



Note: 2010 totals based on modeled data. These emissions are 1% larger than EPA inventory totals due to minor change in emissions accounting approach for certain sources.

2.1.2. Sectoral characterization

Decarbonization and fuel switching in the main case are described in Tables 3 and 4 and illustrated in Figure 6, which shows the evolution of final energy supply and demand by sector and fuel type over time. Electricity becomes the dominant component (51%) of final energy supply, more than doubling its 2010 share, due to extensive electrification of end uses across all sectors. Final electricity consumption increases from 14 EJ to 24 EJ (from 3,750 TWh to over 6,500 TWh). Most of this increase results from electrification of industry and transportation (light duty vehicles), while buildings show little net change in total electric consumption as reductions in consumption through electric energy efficiency offset growth from the electrification of new loads.



Note: The upper row of this chart shows the change in CO_2 emissions intensity of delivered energy by fuel type for 2010 through 2050 ($\text{g CO}_2/\text{MJ}$ is equivalent to $\text{Mt CO}_2/\text{EJ}$). The middle row shows the composition of delivered energy as it changes over this time period. The bottom row shows energy demand by major end use sector and delivered energy type for 2010 and 2050. “Buildings” combines the residential and commercial sectors. “Liquid” and “gas” here are defined by the primary form in which the fuels are transported. For example, liquefied natural gas used in freight vehicles is transported over gas pipelines, so is included as gas here.

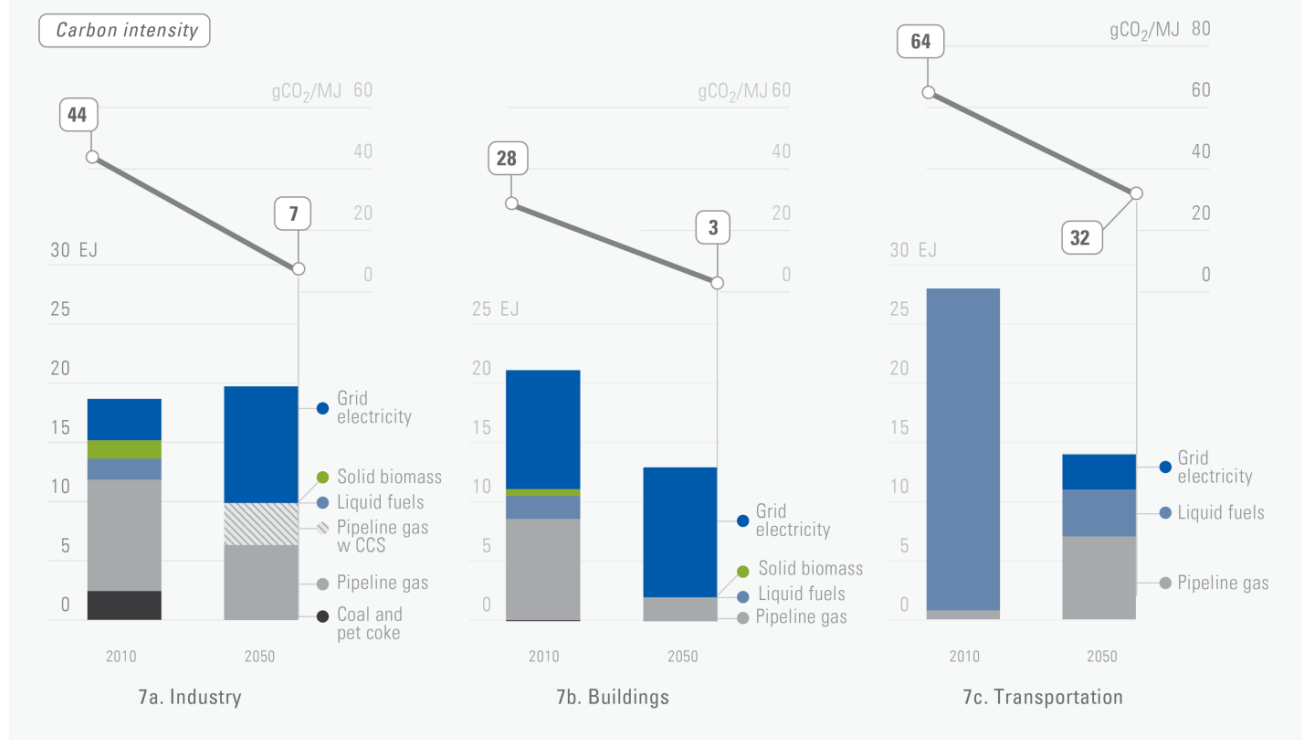
To meet demand, net electricity generation grows by nearly 75% relative to 2010, as shown in the middle right panel of Figure 6. At the same time, a gradual shift in the mix of generation sources results in nearly complete decarbonization of electricity by 2050, with a CO_2 intensity of 18 gCO_2 per kWh (5 gCO_2 per GJ), a 95% reduction from its 2010 value. The 2050 generation mix is a blend of 40% renewables (hydro, solar, wind, biomass, and geothermal), 30% nuclear, and 30% fossil fuel (coal,

natural gas) with CCS. No fossil fuel generation without CO₂ removal remains in the system by 2050. With 34% of generation from intermittent renewables, the combination of 20% gas-fired CCS generation and 6% hydropower, as well as the use of flexible loads such as “smart” vehicle charging, provide adequate balancing resources for reliability on all time scales.

Despite high levels of electrification across sectors, certain end uses remain technically challenging to electrify, especially in industry and long-distance transportation (commercial and freight trucks, freight rail, shipping), where battery electric energy densities appear insufficient for the foreseeable future. Where technically feasible, these end uses are switched from existing fossil fuel supplies (coal, diesel, gasoline, and fuel oil) to “pipeline gas” as the preferred combustion fuel, including compressed (CNG) and liquefied (LNG) forms. Pipeline gas refers to fuel carried in existing natural gas pipelines, which is partially decarbonized over time using gasified biomass. Biomass constitutes 55% of the pipeline gas supply by 2050, resulting in an emission intensity 60% lower than pure natural gas and more than 66% lower than most petroleum-based fuels. Almost all available biomass in this scenario is converted to gas, rather than liquid or solid fuels, requiring 16.7 EJ of biomass primary energy, slightly less than the 17 EJ maximum limit for sustainable biomass energy use assumed in this study.

This scenario assumes that industry employs CCS on-site for approximately one third (36%) of the sector’s use of pipeline gas, the residual combustion fuel. The annual CO₂ storage requirement for generation and industrial CCS combined is approximately 1,200 MtCO₂ in 2050. Solid fuels with uncontrolled CO₂ emissions are eliminated in this scenario, and liquid fuels are dramatically reduced, with petroleum product consumption falling by almost 90% from 2010 to 2050. Residual petroleum use is in the transportation sector, where it continues to be used in some light duty and transit vehicles, civilian aviation, and military vehicles and aircraft. See Figure 7A-C for more detail on decarbonization of each end-use sector.

Figure 7. Energy Use Pathways for Each Sector, by Fuel, 2010 – 2050



Note: Carbon intensity shown in Figure 7 for each sector includes only direct end-use emissions and excludes indirect emissions related to electricity or hydrogen production.

2.2. Assumptions

A qualitative description of strategies and assumptions employed across sectors, fuel types, and scenarios is shown in Table 3, organized by the three strategic areas of energy efficiency, energy supply decarbonization, and fuel switching. Energy efficiency options are similar across demand sectors in all scenarios, with variations based on the form of delivered energy and the associated end-use technologies (*e.g.* electric or internal combustion engine-based drivetrains for vehicles). Energy supply decarbonization strategies vary widely across scenarios based on the type of primary energy used in electricity generation and the amount and allocation of biomass resources (*e.g.* solid, liquid, and gaseous fuels). Electricity balancing requirements also differ widely depending on generation mix. Fuel switching strategies are closely linked to the supply decarbonization pathways chosen.

Table 3. Technical Options and Assumptions in Deep Decarbonization Scenarios

Area	Technical Options and Assumptions*
Energy Efficiency Strategies	
Residential and commercial energy efficiency	- Highly efficient building shell required for all new buildings - New buildings require electric heat pump HVAC and water heating - Existing buildings retrofitted to electric HVAC and water heating - Universal LED lighting in new and existing buildings
Industrial energy efficiency	- Improved process design and material efficiency - Improved motor efficiency - Improved capture and re-use of waste heat - Industry specific measures, such as direct reduction in iron and steel

Transportation energy efficiency	- Improved internal combustion engine efficiency - Electric drive trains for both battery and fuel cell vehicles (LDVs) - Materials improvement and weight reduction in both LDVs and freight
Energy Supply Decarbonization Strategies	
Electricity supply decarbonization	- Different low-carbon generation mixes with carbon intensity < 20 gCO₂/kWh - Main case mix 40% renewable and hydro, 30% CCS, 30% nuclear - High renewable scenario 75% renewable and hydro, 20% nuclear, 5% natural gas - High CCS scenario 50% fossil CCS, 35% renewable and hydro, 15% nuclear - High nuclear scenario 60% nuclear, 35% renewable and hydro, 5% natural gas
Electricity balancing	- Flexible demand assumed for EV charging, certain industrial and building loads - Hourly/daily storage and regulation from pumped hydro, battery, and compressed air energy storage - High CCS scenario balanced with 30% thermal generation plus 6% hydro - High nuclear scenario balanced with 5% natural gas generation, 6% hydro - High renewable case balanced with 5% natural gas generation, 6% hydro, power-to-gas seasonal storage (hydrogen, SNG), and curtailment
Pipeline gas supply decarbonization	- Synthetic natural gas from gasified biomass provides about one-half of pipeline gas in all scenarios except high CCS, which is 100% natural gas - Hydrogen and SNG produced with wind/solar over-generation provides smaller but important (~10-15%) additional source of pipeline gas in high renewables case
Liquid fuels decarbonization	- Liquid biofuels and hydrogen become large share of transportation fuel in high CCS and high nuclear cases, displacing petroleum - No liquid biofuels or hydrogen in central and high renewables cases; emphasis on fuel switching from petroleum to decarbonized pipeline gas CNG and LNG
Fuel Switching Strategies	
Petroleum	- In central and high renewables cases, petroleum displaced in light duty vehicles by electrification, with 75% of drive cycle in battery electric mode, and in heavy duty vehicles by pipeline gas CNG and LNG - In high CCS and high nuclear case, petroleum displaced by combination of biofuels, battery electric, and hydrogen fuel cell vehicles - Industrial sector petroleum uses electrified where possible, with the remainder switched to pipeline gas
Coal	- No coal without CCS used in power generation or industry by 2050 - Industrial sector coal uses electrified where possible, with the remainder switched to pipeline gas
Natural gas	- Low carbon energy sources replace most natural gas for power generation; about 5% non-CCS gas retained for balancing in some scenarios - Switch from gas to electricity in most residential and commercial energy use, including space and water heating and cooking
<i>*Assumptions are common across all scenarios unless otherwise indicated.</i>	

2.3. Alternative pathways and pathway robustness

Three additional scenarios—high renewable, high CCS, and high nuclear—were developed to demonstrate that multiple strategies and pathways are possible for achieving deep decarbonization in the U.S. They also illustrate some of the differences between low-carbon pathways that policymakers, regulators, businesses, and civic groups must assess on the basis of cost, risk, public acceptance, and other criteria. All scenarios result in the elimination of coal without CCS, a nearly 90% reduction in petroleum use, and natural gas use that ranges from current levels to about 70% below current levels. All involve a large expansion of electricity generation and electrification of end uses and expanded use of biomass up to the limits of sustainability (Table 4).

At the same time, the scenarios are not “drop-in” substitutes. Two key choices—(1) the low-carbon sources of energy used to generate electricity and (2) the amount of biomass allocated to energy supply—tend to constrain options for electricity balancing, forms of delivered energy, and demand-side technologies, resulting in substantially different energy systems with self-consistent packages of technologies. For example, some scenarios depend on decarbonized pipeline gas and some do not; some require CO₂ pipeline and storage infrastructure and some do not; some require continental scale hydrogen production and distribution infrastructure and some do not. The transition pathways for the alternative scenarios are shown in Figures 8A-8C.

High renewables scenario

This scenario is similar to the main case in demand-side measures in the residential, commercial, and transportation sectors. It differs significantly in the power sector and industry, because CCS is assumed to not be available. The power sector is decarbonized using primarily solar and wind generation, while maintaining the current share of nuclear power in the U.S. generation mix. Balancing on different time scales is accomplished with a combination of flexible loads, battery and pumped hydro storage, a diverse renewable resource mix, and hydro and natural gas generation. Seasonal balancing is accomplished by overbuilding wind and solar capacity and using periodic over-generation to produce hydrogen and synthetic natural gas (SNG). Hydrogen is produced up to technical limits on the amount that can be transported in natural gas pipelines, and SNG is produced from hydrogen thereafter. These produced gases, in addition to providing system balancing, are inserted into the natural gas pipeline system along with SNG from biomass. In the absence of CCS, this partly decarbonized pipeline gas provides a combustion fuel for industry and transportation.

High CCS scenario

This scenario is similar to the main case in demand side measures in the residential, commercial, and industrial sectors, but differs significantly in power and transportation. The details of this scenario are highly sensitive to assumptions about CCS capture rates and biomass conversion rates to liquid biofuels. For 90% CO₂ capture rates, the upper limit on fossil fuel with CCS as a share of generation mix is about 50% before carbon intensities become too high to achieve decarbonization goals through electrification. Since CCS is used on-site in industry, pipeline gas consists entirely of natural gas, and biomass is devoted entirely to liquid biofuels. In transportation, residual fuel requirements beyond electrification are met with a combination of biofuels and hydrogen produced from steam-reformed natural gas with CCS.

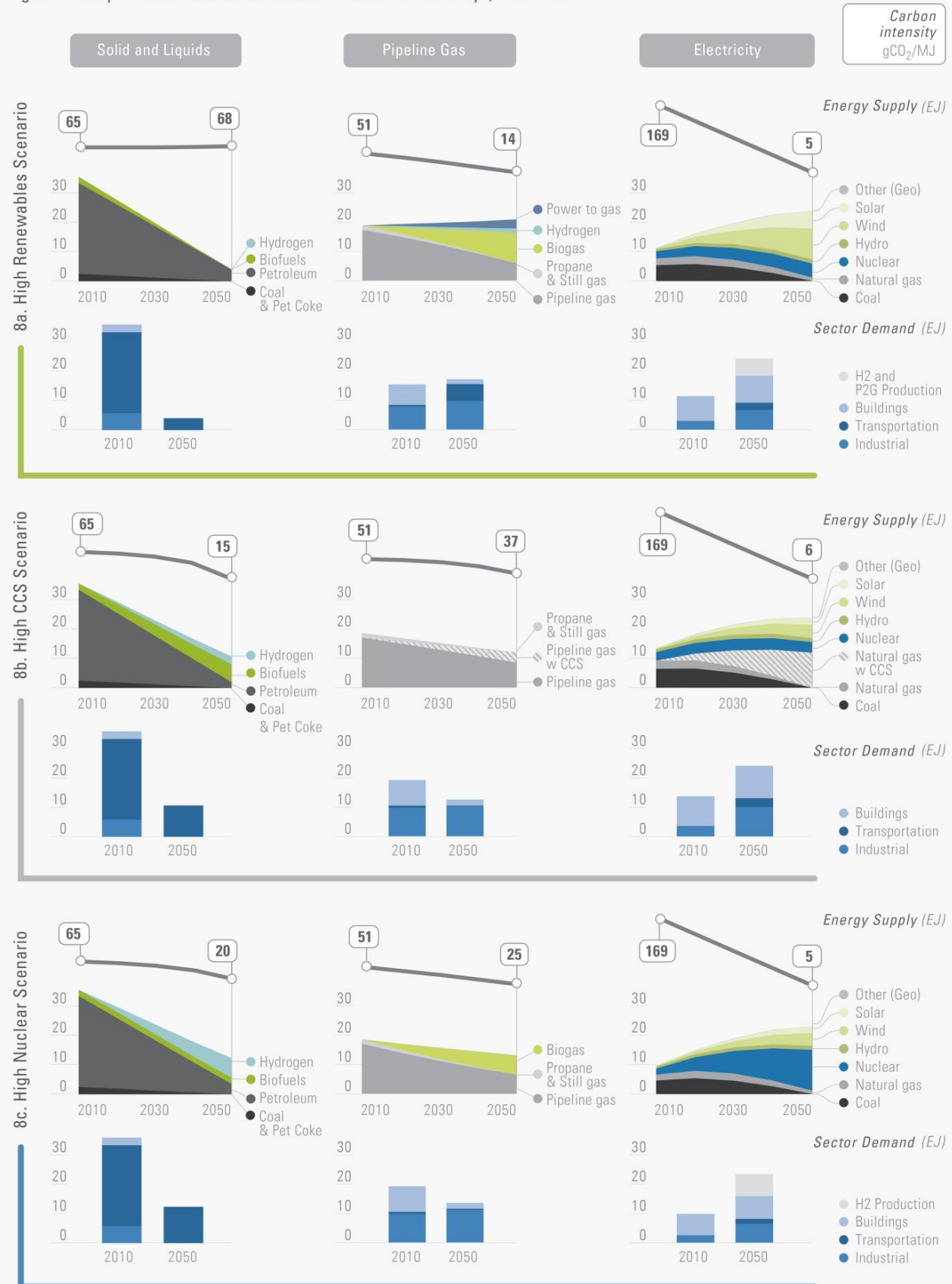
High nuclear scenario

This scenario is similar to the main case in demand-side measures in the residential and commercial sectors. It is very different in other ways, being built around production of hydrogen from nuclear generation, which is used in fuel cells that become the main prime mover in both light and heavy duty transportation. Biomass is used both for pipeline gas, which is used primarily in industry, and for liquid transportation fuels.

Table 4. Key Metrics by Scenario

Indicator	Units	2010	Main	2050 Scenario		
				RNE	CCS	Nuclear
Final energy consumption, by sector						
Total all sectors	EJ	67.8	46.6	46.6	46.5	47.3
Residential	EJ	12.0	6.5	6.5	6.5	6.5
Commercial	EJ	9.0	6.4	6.4	6.4	6.2
Transportation	EJ	28.1	14.0	14.0	13.9	14.9
Industry	EJ	18.6	19.7	19.7	19.7	19.7
CO ₂ emissions, by sector (incl. electric)						
Total all sectors	Mt CO ₂	5,474	746	710	748	723
Residential	Mt CO ₂	1,228	39	35	54	39
Commercial	Mt CO ₂	1,034	60	48	108	61
Transportation	Mt CO ₂	1,805	459	405	195	310
Industry	Mt CO ₂	1,407	188	222	392	313
Electricity share of final energy, by sector						
Total all sectors	%	20%	51%	47%	51%	46%
Residential	%	43%	94%	94%	94%	94%
Commercial	%	53%	76%	76%	76%	76%
Transportation	%	0%	47%	47%	48%	32%
Industry	%	19%	50%	40%	50%	45%
Electric generation						
Total net generation	TWh	4,036	7,008	8,478	7,016	9,548
Delivered electricity (final energy)	TWh	3,753	6,587	7,969	6,595	8,975
Electricity CO ₂ emissions	Mt CO ₂	2,271	117	138	134	155
Renewable energy - non-hydro	%	3%	34%	69%	29%	29%
Renewable energy - hydro	%	7%	6%	6%	6%	6%
Nuclear	%	21%	30%	20%	15%	60%
CCS gas	%	0%	20%	0%	50%	0%
CCS coal	%	0%	10%	0%	0%	0%
Gas	%	21%	0%	5%	0%	5%
Coal	%	48%	0%	0%	0%	0%
Pipeline gas composition						
Final energy	EJ	17	19	21	12	13
Natural gas	%	100%	45%	28%	100%	50%
Electric-SNG	%	0	0%	15%	0%	0%
Electric-H ₂	%	0	0%	7%	0%	0%
Bio-SNG	%	0	55%	50%	0%	50%
Intensity metrics						
Per capita energy use	GJ/person	219	106	106	105	107
Per capita emissions	t CO ₂ /person	17.7	1.7	1.7	1.7	1.6
Economic energy intensity	MJ/\$	5.19	1.34	1.34	1.34	1.36
Carbon intensity of final energy	g CO ₂ /MJ	76.8	15.9	15.7	15.9	15.4
Economic emission intensity	g CO ₂ /\$	419	21	21	21	21
Delivered electric emission intensity	g CO ₂ /kWh	605	18	17	20	21
Pipeline gas emission intensity	g CO ₂ /MJ	50	23	14	50	25

Figure 8. Deep Decarbonization Alternative Transition Pathways, 2010-2050



2.4. Additional measures and deeper pathways

Deeper decarbonization could be achieved by the successful development of technologies and measures that were not employed in the scenarios described in this study. These excluded measures are highlighted in Table 5. They include CCS with capture rates in excess of 90%, advanced liquid biofuels, product and industrial redesign for energy and material efficiency, and significant changes in energy service demand.

Table 5. Technology Assumptions by Scenario

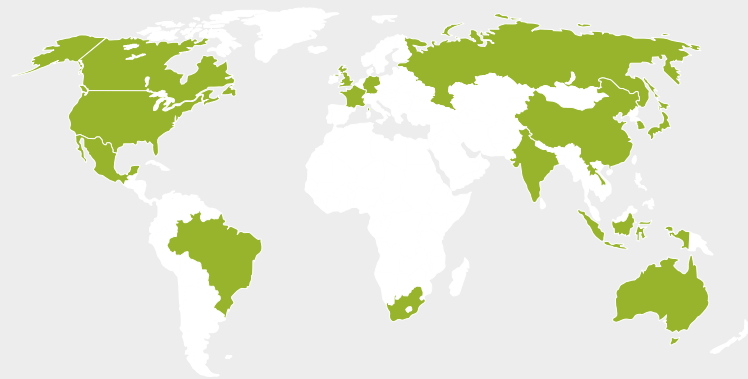
Technology	Included in 2050 Scenario?			
	Central	RNE	CCS	Nuclear
CCS for generation, 90% capture	Y	N	Y	N
CCS for generation, >90% capture	N	N	N	N
Nuclear Gen III	Y	Y	Y	Y
Nuclear Gen IV	N	N	N	N
Solar PV, solar CSP, onshore wind, shallow offshore wind	Y	Y	Y	Y
Deep offshore wind, advanced geothermal	N	N	N	N
CCS for industry, 90% capture	Y	N	Y	N
CCS for industry, >95% capture	N	N	N	N
H ₂ from electricity generation	N	Y	N	Y
H ₂ from natural gas reforming with CCS	N	N	Y	N
Continental scale H ₂ production and distribution system	N	N	N	Y
Power-to-gas - SNG from electricity generation	N	Y	N	N
Biomass conversion to SNG by AD or gasification and shift	Y	Y	N	Y
Fischer-Tropsch liquid biofuels, 35% conversion efficiency	N	N	Y	Y
Advanced cellulosic ethanol	N	N	N	N
Advanced biodiesel	N	N	N	N
Advanced bio-jet fuel	N	N	N	N
Biomass generation w CCS	N	N	N	N
Fuel cell LDVs	N	N	N	Y
Battery electric LDVs	Y	Y	Y	Y
CNG passenger and light truck	Y	Y	N	N
LNG freight	Y	Y	Y	N
Fuel cell freight	N	N	N	Y
Heat pump HVAC	Y	Y	Y	Y
LED lighting	Y	Y	Y	Y
Heat pump electric water heat	Y	Y	Y	Y
Maximum efficiency shell for new buildings	Y	Y	Y	Y
Maximum efficiency shell for retrofits	N	N	N	N
Industrial and product redesign	N	N	N	N
Structural change in economy	N	N	N	N
Reduced demand for energy services	N	N	N	N

2.5. Challenges, opportunities and enabling conditions

Challenges and enabling conditions for deep decarbonization in the U.S. lie primarily in the realms of cost, policy, public support, and resource limitations. Two key potential resource limitations requiring further study and sensitivity analysis are biomass availability and CO₂ storage capacity. Cost reductions for many low-carbon measures are often a function of market transformation and high volume production, but continued R&D is also important in many areas. Two areas of study seem particularly germane to current challenges in low-carbon technologies: (1) electrochemistry and nanotechnology, to develop the chemistries, catalysts, and physical matrices fundamental to improvements in batteries, fuel cells, chemical processes, and CO₂ capture; (2) biotechnology and genomics, which are fundamental to advances in cellulosic and algal biofuels, biomass SNG production, and biological hydrogen production. Public support must be unwavering to impel policymakers to implement transformational changes in energy systems over the course of decades. Public acceptance is also a key variable, especially with regard to siting of low-carbon infrastructure. A high nuclear scenario, for example, seems very unlikely without aggressive efforts to restore public acceptance of the technology.

2.6. Near-term priorities

Although the results here are preliminary, some near-term priorities for investment, policy, and regulatory decision-making in the U.S. are already clear. For instance, significant improvements in end-use energy efficiency—in buildings, appliances, equipment, and vehicles—are critical to deep decarbonization in the U.S. Many types of energy efficiency measures are already cost-effective but face barriers to rapid uptake due to well-known market failures. In these areas, continued improvement of codes and standards at both the federal and state level are a proven remedy. Additionally, it is clear that low-carbon electricity is the linchpin of deep decarbonization, and here too existing state and federal regulatory mechanisms, from renewable portfolio to emission performance standards, can help hasten the transition. Given the long lifetimes of generation assets, meeting a 2°C target by 2050 without stranding assets requires not building new coal generation without CCS. Meanwhile, there is an urgent need for additional R&D to develop low-carbon fuel solutions for industry and freight transport.



COUNTRY RESEARCH TEAMS. **Australia.** Climate Works Australia; Crawford School of Public Policy, Australian National University (ANU); Commonwealth Scientific and Industrial Research Organization (CSIRO); Centre of Policy Studies, Victoria University. **Brazil.** COPPE, Federal University, Rio de Janeiro. **Canada.** Carbon Management Canada; Navius Research; Simon Fraser University; Sharp. **China.** Institute of Energy, Environment, Economy, Tsinghua University; National Center for Climate Change Strategy and International Cooperation (NCSC). **France.** Université Grenoble Alpes, CNRS, EDDEN, PACTE; Centre International de Recherche sur l'Environnement et le Développement (CIRED), CNRS. **Germany.** Dialogik. **India.** The Energy and Resource Institute (TERI). **Indonesia.** Center for Research on Energy Policy-Bandung Institute of Technology, CRE-ITB; Centre for Climate Risk and Opportunity Management-Bogor Agriculture University (CCROM-IPB). **Japan.** National Institute for Environmental Studies (NIES); Mizuho Information and Research Institute (MIRI). **Mexico.** Instituto Nacional de Ecología y Cambio Climático (INECC). **Russia.** Russian Presidential Academy of National Economy and Public Administration (RANEPA); High School of Economics, Moscow. **South Africa.** The Energy Research Centre (ERC) University of Cape Town (UCT). **South Korea.** School of Public Policy and Management, Korea Development Institute (KDI); Korea Energy Economics Institute (KEEI); Korea Institute of Energy Research (KIER); Korea Environment Institute (KEI). **United Kingdom.** University College London (UCL) Energy Institute. **United States of America.** Energy + Environmental Economics (E3).

DDPP PARTNER ORGANIZATIONS. German Development Institute (GDI); International Energy Agency (IEA); International Institute for Applied Systems Analysis (IIASA); World Business Council on Sustainable Development (WBCSD).