Canada Chapter

pathways to

deep decarbonization

2014 report

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SciencesPo.

SUSTAINABLE DEVELOPMENT SOLUTIONS NETWORK
A GLOBAL INITIATIVE FOR THE UNITED NATIONS

Published by Sustainable Development Solutions Network (SDSN)
and Institute for Sustainable Development and International Relations (IDDRI),
september 2014

The full report is available at deepdecarbonization.org.

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Preface

The Deep Decarbonization Pathways Project (DDPP) is a collaborative initiative, convened under the auspices of the Sustainable Development Solutions Network (SDSN) and the Institute for Sustainable Development and International Relations (IDDRI), 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 Partners composed of leading researchers and research institutions from countries representing 70% of global GHG emissions and different stages of development. Each Country Research Partner has developed pathway analysis for deep decarbonization, taking into account national socio-economic conditions, development aspirations, infrastructure stocks, resource endowments, and other relevant factors. The pathways developed by Country Research Partners formed the basis of the DDPP 2014 report: Pathways to Deep Decarbonization, which was developed for the UN Secretary-General Ban Ki-moon in support of the Climate Leaders' Summit at the United Nations on September 23, 2014. The report can be viewed at deepdecarbonization.org along with all of the country-specific chapters.

This chapter provides a detailed look at a single Country Research Partner's pathway analysis. The focus of this analysis has been to identify technically feasible pathways that are consistent with the objective of limiting the rise in global temperatures below 2°C. In a second—later—stage the Country Research Partner will refine the analysis of the technical potential, and also take a broader perspective 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. This comprehensive analysis will form the basis of a report that will be completed in the first half of 2015 and submitted to the French Government, host of the 21st Conference of the Parties (COP-21) of the United Nations Framework Convention on Climate Change (UNFCCC).

We hope that the analysis outlined in this report chapter, and the ongoing analytical work conducted by the Country Research Team, will support national discussions on how to achieve deep decarbonization. Above all, we hope that the findings will be helpful to the Parties of the UNFCCC as they craft a strong agreement on climate change mitigation at the COP-21 in Paris in December 2015.

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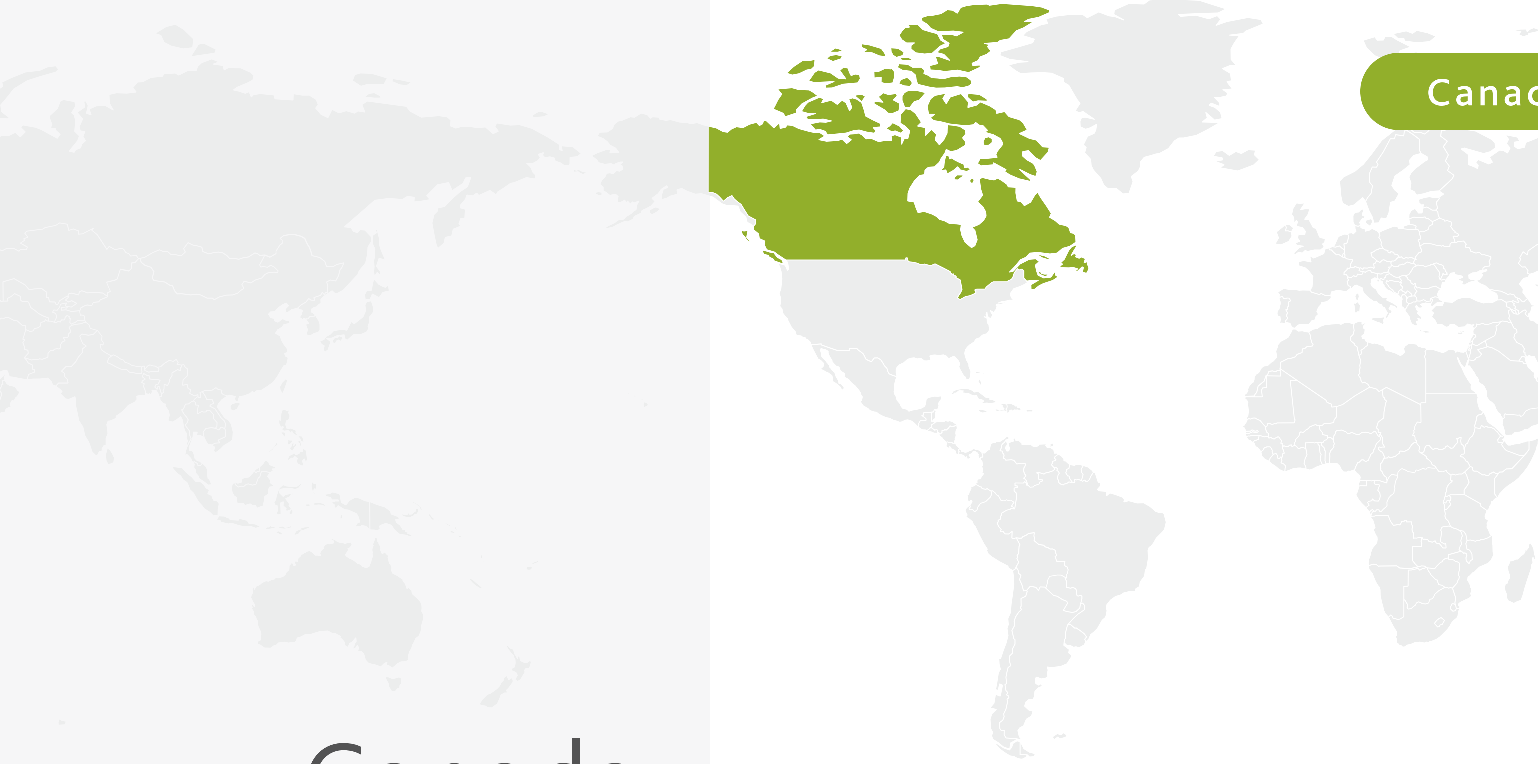

Canada

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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 CO_2 emissions from energy- and industrial process-related activities. Emissions would need to be transformed from 20.6[1] tonnes of carbon dioxide equivalent per capita (tCO_2e/cap) in 2010 to less than 2 tCO_2e/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.

1 Excludes LULUCF emissions

- Second, Canada's natural resource development aspirations are consistent with a global 2ºC 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 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.

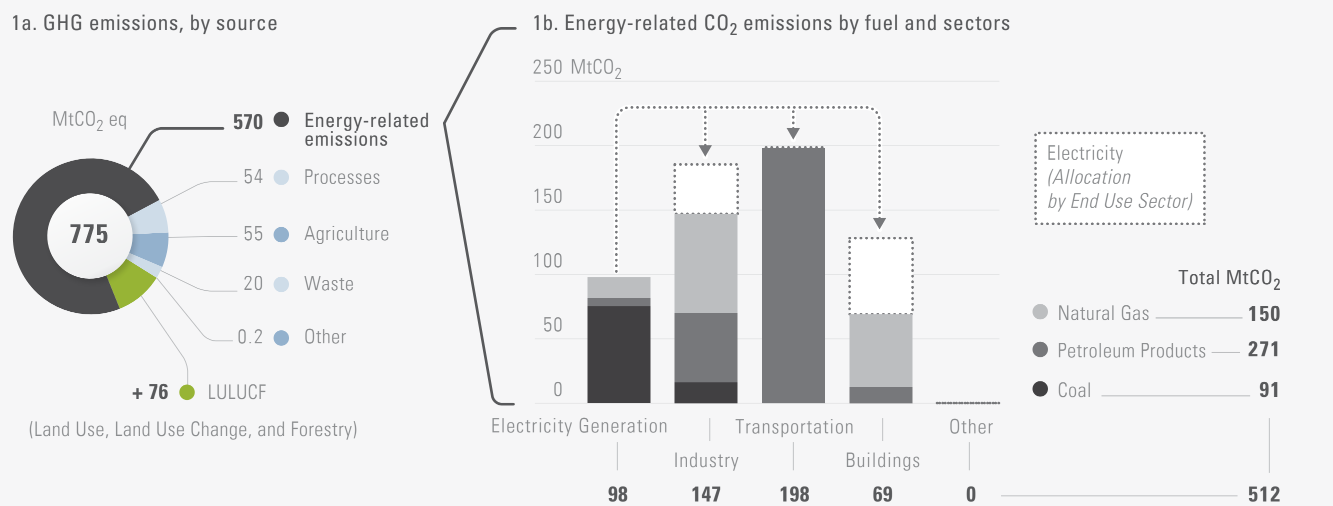
1.2 GHG emissions: current levels, drivers, and past trends

In 2010, total Canadian GHG emissions (including LULUCF) were 775.2 $MtCO_2e$, equivalent to 22.8 tCO_2e 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.

Between 1990 and 2010, energy-related emissions rose by 101 Mt CO_2e, 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.

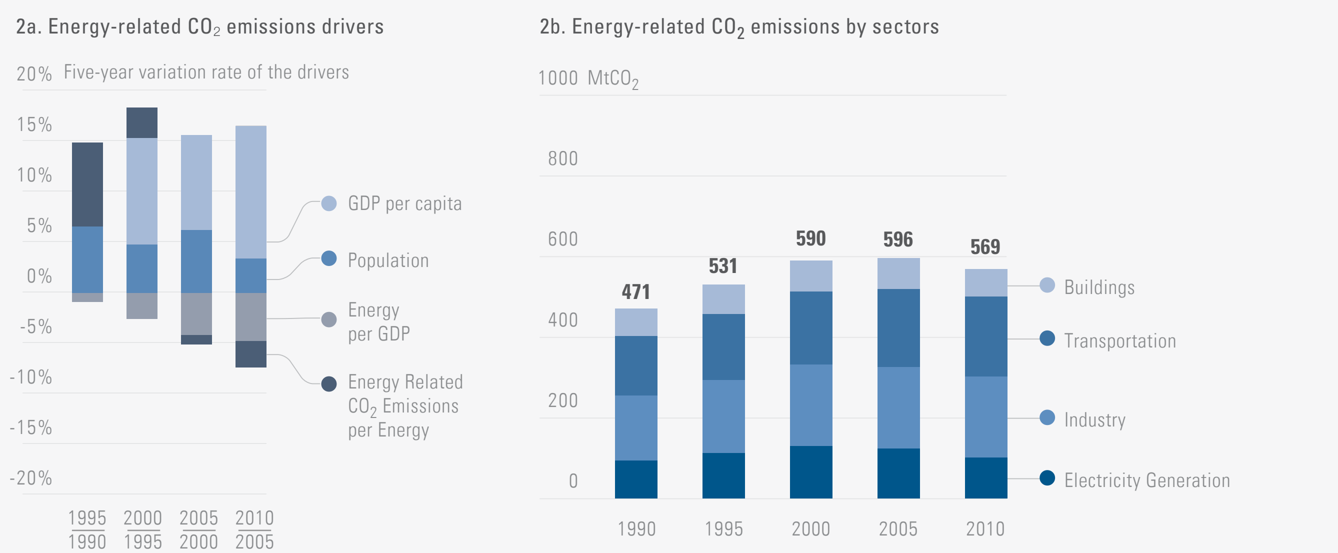
While the overall carbon intensity of energy use did not change significantly between 1990 and 2010, Canadian electricity production has started shifting toward lower and zero emission sources. The Canadian federal government recently imposed regulations effectively requiring all new and retrofitted 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.

Figure 1. Decomposition of GHG and Energy CO_2 Emissions in 2010



Note: Combustion CO_2 emissions does not include upstream fugitive emissions (58 Mt in 2010).

Figure 2. Decomposition of historical energy-related CO_2 Emissions, 1990 to 2010



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 $MtCO_2e$) from 2010 levels by 2050, while maintaining strong economic growth (see Table 1).[2] Over this period, GDP rises from $1.26 trillion to $3.81 trillion (real $2010 USD), a tripling of Canada's economy.

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.

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

2 Net LULUCF emissions are omitted in the DDPP process.

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.

Figure 3. Energy Pathways, by source

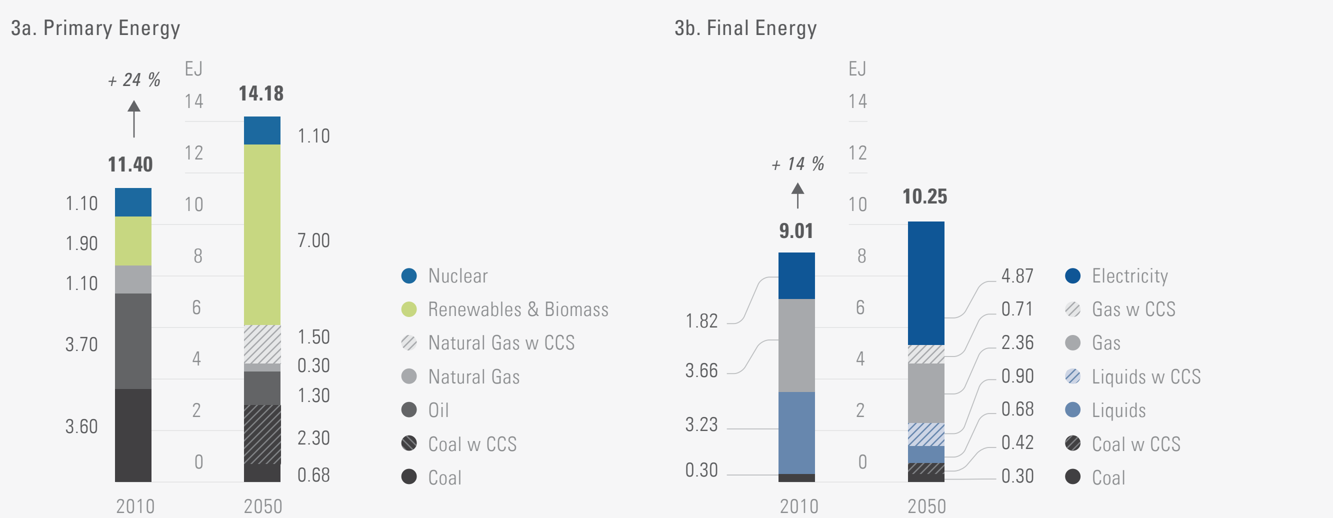
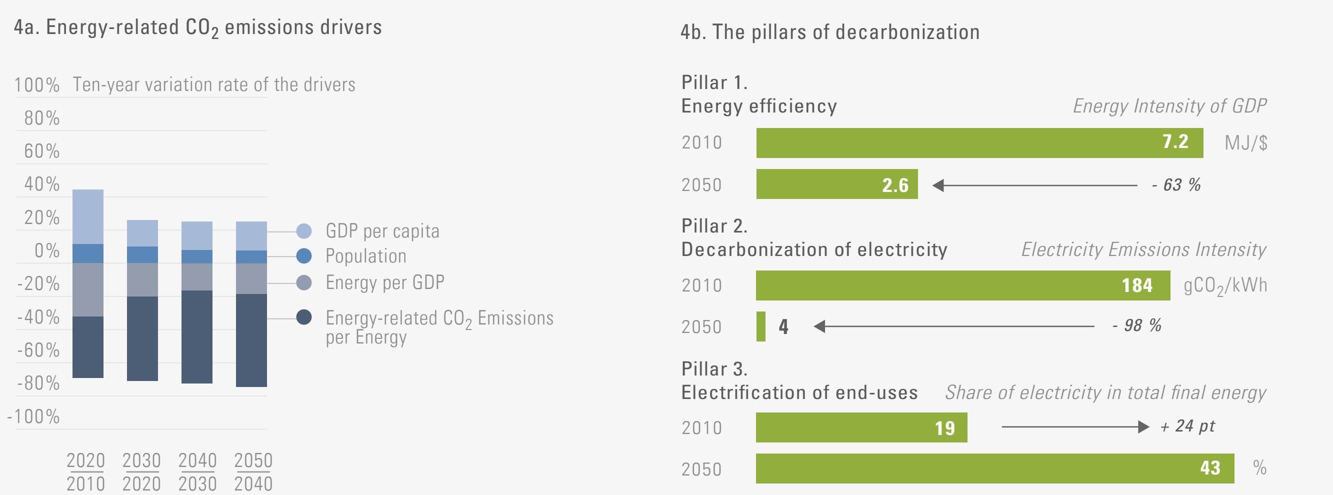


Figure 4. Energy-related CO_2 Emissions Drivers, 2010 to 2050



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.

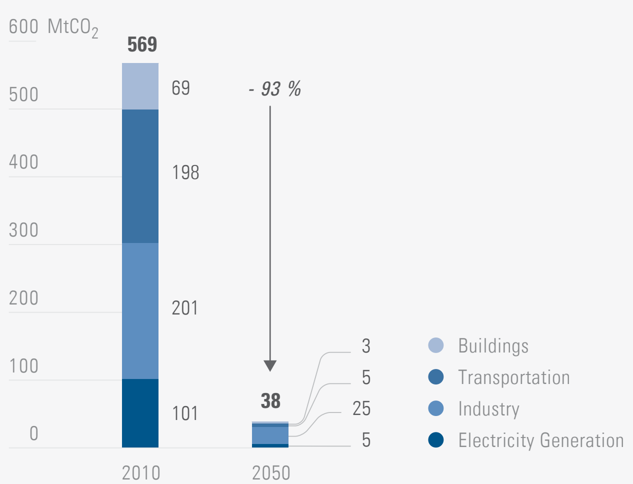
Key Scenario Characteristics

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.

Figure 5. Energy-related CO_2 Emissions Pathway, by Sector, 2010 to 2050



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 $MtCO_2$. 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.

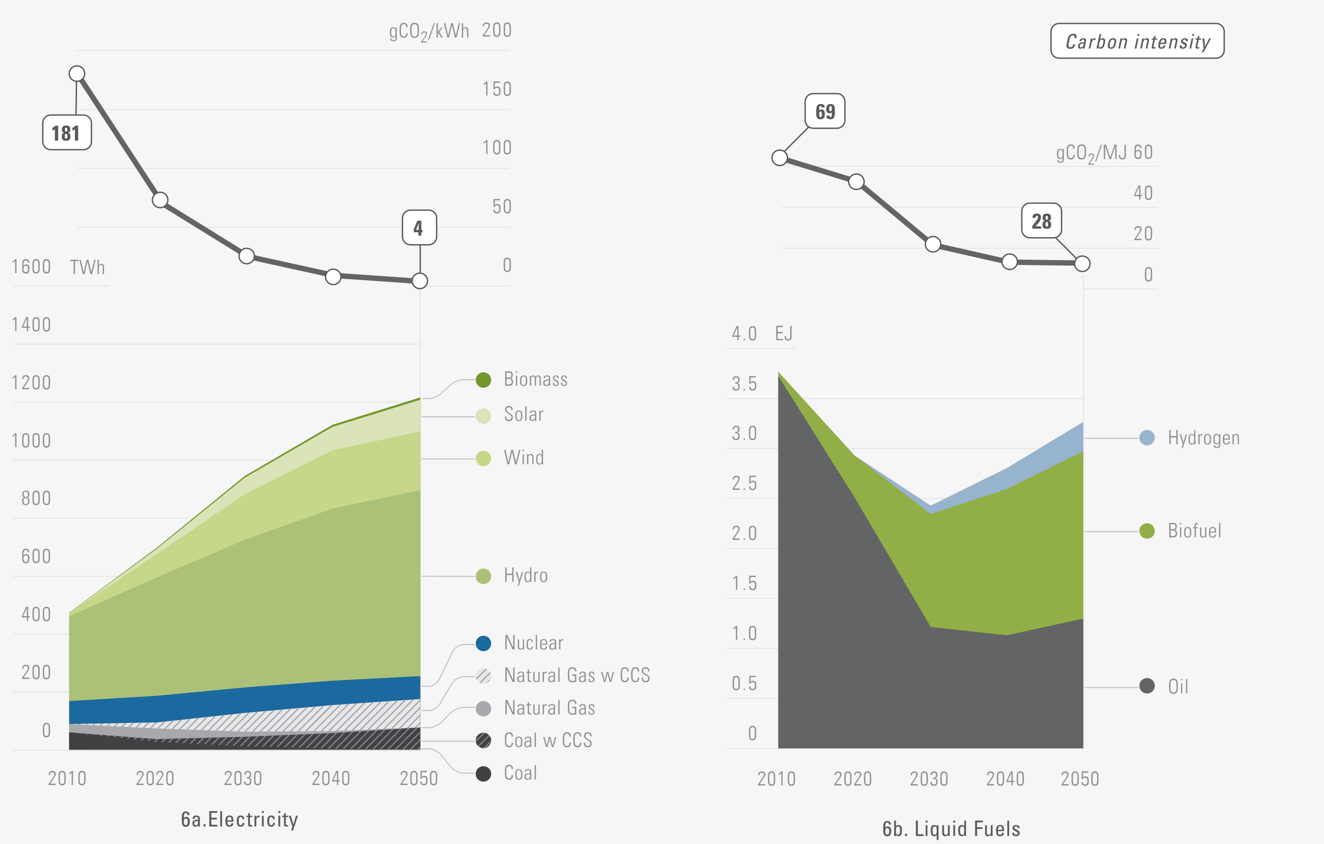
Oil and natural gas consumption decline, while biofuels become the core liquid fuel, and hydrogen enters the energy mix (Figure 6b). Sufficient access to the feedstocks for cellulosic ethanol and biodiesel was assumed; however, the electricity gen-

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.

Figure 6. Energy Supply Pathways, by Resource



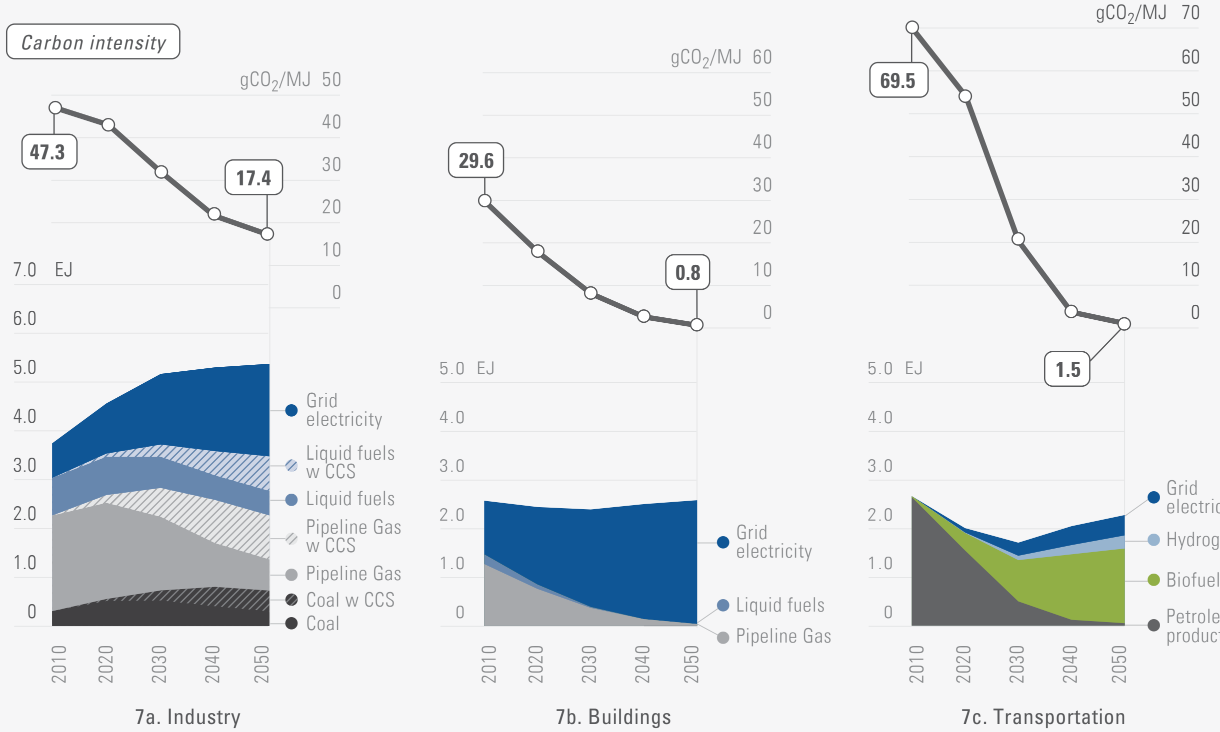
eration mix does not include net sequestration of biomass, given insufficient information regarding the availability of sufficient sustainable feedstock. Due to these fuel supply shifts, by 2050 the electricity, transportation, and building sectors have almost completely decarbonized, and the Canadian emissions profile is dominated by a subset of industrial emissions that are very difficult and expensive to reduce (Table 2). The following sections highlight the key changes that drive emission reductions in each of these sectors.

Transportation

Overall transportation sector emissions fall by 97% between 2010 and 2050, from 198 to 5 $MtCO_2$. 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). 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.

Figure 7. 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.

Buildings

Overall building sector emissions fall by 96% between 2010 and 2050, from 69 to 3 $MtCO_2$. 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 $MtCO_2e$. 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-CO_2 GHG emissions, and the Canadian decarbonization pathway includes an 83% reduction in these emissions between 2010 and 2050 (from 55 to 9.5 $MtCO_2e$). 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 CO_2 waste stream) or a technology of equivalent GHG intensity will be used to achieve approximately 99% CO_2 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.[3]

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 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.[4] 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

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

4 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

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.

Enabling Conditions

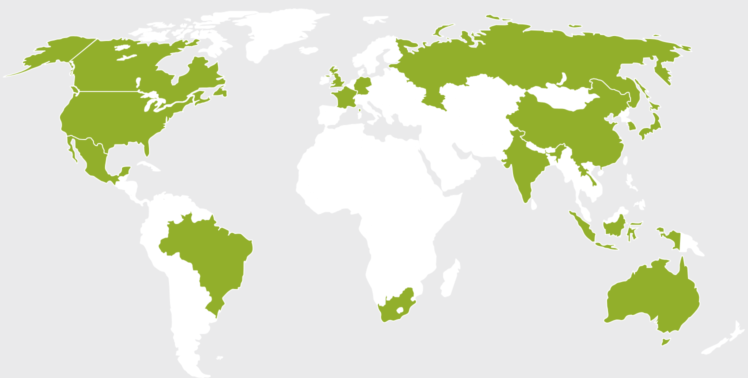
International cooperation is required to support research, development, and deployment of critical decarbonization technologies, as well as to implement a global equimarginal abatement effort through GHG reduction sales and purchases. Technical constraints make the marginal cost of emissions abatement 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 CO_2 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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DDPP PARTNERS ORGANIZATIONS. German Development Institute (GDI); International Energy Agency (IEA); International Institute for Applied Systems Analysis (IIASA); World Business Council on Sustainable Development (WBCSD).