Technology and Policy Options for a Low-Emission Energy System in Canada

The Expert Panel on Energy Use and Climate Change

Council of Canadian Academies
Conseil des académies canadiennes

Science Advice in the Public Interest

TECHNOLOGY AND POLICY OPTIONS FOR A LOW-EMISSION ENERGY SYSTEM IN CANADA

The Expert Panel on Energy Use and Climate Change

THE COUNCIL OF CANADIAN ACADEMIES
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Library and Archives Canada Cataloguing in Publication

Technology and policy options for a low-emission energy system in Canada/Expert Panel on Energy Use and Climate Change.

Includes bibliographical references.

ISBN 978-1-926522-15-9 (paperback)

1. Energy policy–Canada. 2. Power resources–Canada. 3. Greenhouse gas mitigation–Government policy–Canada. 4. Energy development–Government policy–Canada. 5. Sustainable development–Canada. I. Council of Canadian Academies, issuing body II. Council of Canadian Academies. Expert Panel on Energy Use and Climate Change

HD9502.C32T73 201 333.790971 C2015-905748-5

This report should be cited as: Council of Canadian Academies, 2015. *Technology and Policy Options for a Low-Emission Energy System in Canada.* Ottawa (ON): The Expert Panel on Energy Use and Climate Change, Council of Canadian Academies.

Printed in Ottawa, Canada

Council of Canadian Academies
Conseil des académies canadiennes

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Expert Panel on Energy Use and Climate Change

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Message from the Co-Chairs

The available evidence clearly supports that the earth's climate is changing, that these changes are driven by greenhouse gas emissions resulting from human activity, and that without substantial mitigation of these emissions the scale and pace of climate change will pose substantial risks to the earth. It is the Panel's view that, both for Canada and for the world in general, the risks arising from climate change justify significant and accelerated efforts to reduce greenhouse gas emissions over the course of the decades to come. This is no small challenge, and requires fundamental societal change.

In reality, the complexity of climate change as a technological and policy problem can be overstated. Both the problem of climate change and its potential solutions have been extensively studied and are now well understood, and the technologies and policies needed to mitigate emissions are increasingly being employed. Keeping this progress in mind, the Panel has assembled an accessible though by no means exhaustive summary of the relevant literature. Our goal was to strategically clarify issues and distill ideas that are understood and accepted by energy and climate experts, as supported by the literature. The Panel was also guided by a systems lens recognizing the interconnectedness of society and the natural environment supporting it, and the importance of highlighting lessons learned from the design and implementation of climate change policies around the globe.

It is clear that a low-emission future is possible, but it will depend on the collective will and ambition of federal and provincial governments. Canada is in a particularly advantageous position to meet stringent cutbacks in greenhouse gas emissions, with its abundance of natural energy resources and technological expertise. Accordingly, in the Panel's view Canada can achieve meaningful change if appropriate policies are implemented. Optimal strategies and policies for moving forward will need to be adaptive, evolving as necessary in response to emission trends, new technological developments, and other social, economic, and political changes. They will also need to be based on system level principles of resilience, sustainability, fairness, and integration across jurisdictions and disciplines.

As Co-Chairs, we are most grateful to our fellow Panel members, representing a rich range of disciplines, for contributing their time, knowledge, wisdom, and considerable experience to ensure the report is comprehensive, insightful, balanced, and of an overall quality that meets Council standards. Panel deliberations were always engaging, constructive, and helpful for moving the project forward and it was a pleasure to witness differing views converge to a consensus.

On behalf of the Expert Panel, we are deeply appreciative of the opportunity to explore this important question and we thank Magna International Inc. for requesting the Council to undertake the assessment. In particular, we thank Mr. Donald Walker, Chief Executive Officer, and Mr. David Mark Pascoe, Vice-President of Engineering and R&D, at Magna International Inc. for providing background on the work of their organization as well as guidance on the motivation for the assessment and potential ways to scope the Panel's charge. The Panel also wishes to thank the report reviewers for volunteering their time to make valuable suggestions, which improved the quality, balance, and comprehensiveness of the Panel's work. The final report would not have been the same without their sage advice.

Finally, the Panel is most grateful for the outstanding research support that it received from staff members of the Council of Canadian Academies. They were full partners in this endeavour and deserve to be recognized as such.

Keith W. Hipel Paul R. Portney

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The Expert Panel on Energy Use and Climate Change

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Report Review

This report was reviewed in draft form by the individuals listed below — a group of reviewers selected by the Council of Canadian Academies for their diverse perspectives, areas of expertise, and broad representation of academic, industry, policy, and non-governmental organizations.

The reviewers assessed the objectivity and quality of the report. Their submissions — which will remain confidential — were considered in full by the Panel, and many of their suggestions were incorporated into the report. They were not asked to endorse the conclusions, nor did they see the final draft of the report before its release. Responsibility for the final content of this report rests entirely with the authoring Panel and the Council.

The Council wishes to thank the following individuals for their review of this report:

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The report review procedure was monitored on behalf of the Council's Board of Governors and Scientific Advisory Committee by **Jean Gray, C.M., FCAHS,** Professor of Medicine (Emeritus), Dalhousie University (Halifax, NS). The role of the report review monitor is to ensure that the Panel gives full and fair consideration to the submissions of the report reviewers. The Board of the Council authorizes public release of an expert panel report only after the report review monitor confirms that the Council's report review requirements have been satisfied. The Council thanks Dr. Gray for her diligent contribution as report review monitor.

Janet W. Bax
Interim President, Council of Canadian Academies

Executive Summary

A reliable energy system is essential for a functioning society, and improvements in humanity's capacity to harness energy from a range of sources have helped raise living standards around the world. Canada, like many countries, relies on fossil fuels for most of its energy. Coal, oil, and natural gas together account for 72% of Canada's energy supply, and they are the dominant sources of energy used for transportation, space heating, many industrial processes, and electricity generation in some provinces. The burning of these fuels is increasing the amount of carbon dioxide in our atmosphere and causing pervasive changes in the Earth's climate. The resulting widespread and substantial risks to society and ecosystems justify significant, accelerated efforts to reduce greenhouse gas emissions from human activity over the coming decades.

The Council of Canadian Academies (the Council) was tasked with synthesizing the evidence on select energy sources and technologies, as well as public policies, that would be involved in a transition to a low-emission energy system in Canada. This charge came in response to frustration among some business leaders that stemmed from a lack of clarity about key facts relating to energy technologies and climate change, and policy options to address this challenge. To address this charge, the Council convened a multidisciplinary, eight-member expert panel (the Panel) comprising people with expertise in economics, public policy, engineering, and energy systems and technologies. From its discussion and review of the evidence, the Panel identified three key findings.

Finding 1: Canada could achieve major emission reductions with the adoption of commercially available technologies.

Over the course of the next several decades, a transition to a low-emission energy system would involve three main strategies: improvements in energy efficiency, a shift from high-emission to low-emission energy sources (i.e., energy substitution), and possibly the adoption of carbon capture and storage (CCS) technologies. Improvements in energy efficiency can result in early gains and provide a foundation for the cost-effective introduction of low-emission technologies, but deeper emission reductions will require energy substitution and potentially the application of CCS in conjunction with continued fossil fuel use. Taking advantage of existing technologies in these areas and across the transportation, building, and industry sectors could result in emission reductions on a large scale. Promising options for reducing emissions include:

- *Transportation:* Ongoing efficiency gains for all vehicles, increasing reliance on low-emission electricity for passenger transportation, expanding use of biofuels in freight transportation, and long-term urban planning and investments in transportation infrastructure.
- *Buildings:* Ongoing efficiency gains in new buildings or in conjunction with building renovations, transitioning to electricity for space heating in highly energy-efficient buildings, and selective adoption of community heating systems that capture and use waste heat and/or rely on renewable energy sources.
- *Industry:* Ongoing efficiency gains in industrial processes, reduction of fugitive emissions, application of CCS in suitable industrial processes, and electrification and enhanced use of biomass in applicable industrial applications.

However, given the higher cost of these technologies relative to conventional options, they are unlikely to be widely adopted unless stringent, compulsory policies are introduced. Further innovation and technological development is also essential for reducing the costs of low-emission energy technologies over time.

Finding 2: Low-emission electricity is the foundation for low-emission energy systems.

Switching to low-emission electricity eliminates carbon dioxide emissions from power generation and allows for further emission reductions as the transportation, building, and industry sectors gradually increase their use of electricity as an energy source. Many Canadians live in jurisdictions that already benefit from low-emission electricity; however, future emission reductions will require a transition in provinces that still depend on emission-intensive electricity sources such as coal, as well as expanding low- and non-emitting generation in all provinces to meet growing demand. This expansion will require careful planning to integrate higher shares of electricity generation from intermittent renewable sources (such as solar, wind, and run-of-river hydro) with additional energy storage capacity and other dispatchable energy sources (such as hydropower, nuclear, geothermal, biomass, and coal or natural gas with CCS). Investments in electricity transmission lines, interconnections, and grid modernization can also enhance flexibility and enable greater reliance on low-emission generation technologies. The costs of low-emission electricity generation technologies, while still generally higher than those for fossil fuel-fired power plants, have been falling rapidly. Given the relatively low electricity prices in Canada in most jurisdictions, the increased cost of electricity from low-emission energy sources is not likely to pose a major burden for most consumers and businesses.

Finding 3: A transition to a low-emission energy system is achievable with the right combination of stringent and flexible policies.

There is no one right policy for reducing energy-related emissions. However, experience to date has shown that voluntary measures alone are insufficient, and policies that focus exclusively on further technological progress offer no guarantee of emission reductions. Stringent, compulsory, economy-wide emission reduction policies are therefore essential if Canada is to successfully undertake an energy system transition. Carbon taxes, cap-and-trade systems, and other regulations are all possible approaches. Regardless of the instrument, certain design features can improve performance of such policies across a range of criteria. These include linking policies to binding and increasingly stringent emission limitations, or to binding and increasingly high carbon prices; including appropriate monitoring and penalty provisions; providing extensive compliance flexibility; treating new and existing firms fairly; harmonizing policies across Canada and establishing international linkages; compensating groups that are adversely impacted by policies (at least on a transitional basis); and involving the public in decision-making. In addition to compulsory policy, enabling policies are very important for supporting emission reductions. These include direct government investment, adjustment of subsidies, enabling infrastructure, innovation support, and making regulatory processes more efficient. Support for energy innovation can accelerate the adoption of low-emission technologies by making them more affordable. With flexible economy-wide policies in place, individuals, businesses, and other decision-makers can choose the technology and energy responses that are right for their context and adjust these choices over time to adapt to further scientific progress, technological developments, and emission reduction trends.

MOVING FORWARD

Addressing climate change will ultimately require globally coordinated action to protect a common resource — the Earth's atmosphere — and society must be willing to pay now for benefits that accrue largely to future generations. However, climate change as a technological and policy problem may not be as complex as is often assumed. Both the consequences of climate change and its potential solutions have been extensively studied and are now well understood. While energy system transitions typically require many decades due to the long-lived nature of infrastructure and massive investments required, they can be accelerated with strategic policy support, and they are already under way in many jurisdictions across Canada. Due to the risk of getting locked in to new emission intensive capital and infrastructure, delaying mitigation increases the cost of meeting emission reduction goals over time. Ensuring that transitions are fully realized will require policies that are adaptive to changing economic, technological, and environmental conditions and persistent over time. With appropriately stringent and flexible policies in place, large emission reductions from Canada's energy system are achievable over the course of several decades. This transition will not be without cost for consumers, businesses, or the economy as a whole. It can, however, be achieved without jeopardizing Canada's long-term economic growth and competitiveness.

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List of Acronyms and Abbreviations

BEV	battery electric vehicle
CANDU	Canada Deuterium Uranium
CCEMF	Climate Change and Emissions Management Fund
CCS	carbon capture and storage
CEM	community energy management
CEPA	*Canadian Environmental Protection Act*
CHP	combined heat and power
CNG	compressed natural gas
CO_2	carbon dioxide
CO_2eq	carbon dioxide equivalent
COSIA	Canada's Oil Sands Innovation Alliance
DME	dimethyl ether
FCV	fuel cell vehicle
FIT	feed-in-tariff
GDP	gross domestic product
GHG	greenhouse gas
HEV	hybrid electric vehicle
IEA	International Energy Agency
IGCC	integrated gasification combined cycle
IPCC	Intergovernmental Panel on Climate Change
kWh	kilowatt hour
LCOE	levelized cost of electricity
LDV	light-duty vehicle
LNG	liquefied natural gas
LUCF	land-use change and forestry
MJ	megajoule
Mt	megatonne
MW	megawatt
NEB	National Energy Board
NEUD	National Energy Use Database
NIR	National Inventory Report
OECD	Organisation for Economic Co-operation and Development
PC	pulverized coal
PHEV	plug-in hybrid electric vehicle
PJ	petajoule
PV	photovoltaic
QUEST	Quality Urban Energy Systems of Tomorrow
R&D	research and development
RPS	renewable portfolio standard
SDTC	Sustainable Development Technology Canada
UNFCCC	United Nations Framework Convention on Climate Change

1

Introduction and Charge to the Panel

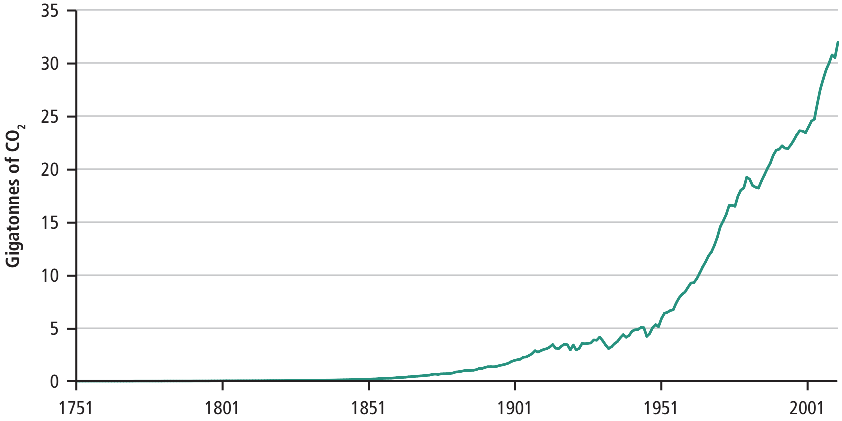
- The Charge to the Panel
- The Scope of the Assessment
- Climate Change Science: The State of the Evidence
- Canada in the Global Context
- Report Overview

1 Introduction and Charge to the Panel

A reliable energy system is essential for a functioning society. Energy powers our computers, lights our homes, drives our transportation systems, heats our buildings, and fuels our industry. Increasing access to energy was instrumental to the massive improvements in living standards that have occurred in much of the world since the Industrial Revolution, and it continues to be important in alleviating the burdens of poverty in low-income countries. Fossil fuels such as coal, oil, and natural gas played a major role in the unprecedented expansion of humanity's access to energy, and they are now the dominant global energy source, a result of their wide availability, energy density, portability, and compatibility with existing infrastructure.

Burning fossil fuels, however, is also the largest source of greenhouse gases from human activity. Fossil fuel combustion now accounts for over 70% of global greenhouse gas emissions (WRI, 2014). Between 1751 and 2010, the combustion of coal, oil, and natural gas is estimated to have released approximately 1,300 gigatonnes (billion tonnes) of carbon dioxide into the Earth's atmosphere (Boden *et al.*, 2013). Atmospheric concentrations of carbon dioxide are therefore increasing over time, and they are now 42% higher than in 1750 (WMO, 2014). As shown in Figure 1.1, carbon dioxide emissions from fossil fuel combustion are rising at a nearly exponential rate and are now equal to approximately 32 gigatonnes per year. Cumulatively, roughly half of all carbon dioxide emissions from fuel combustion have occurred since the mid-1980s (Boden *et al.*, 2013). Abundant scientific evidence strongly indicates that the Earth's climate is changing as a result of these emissions. Average global surface temperatures are increasing (Figure 1.2), and changes are extensively documented in sea levels, ocean acidity, snow and ice cover, geographic ranges of many species, and the frequency and duration of droughts, heat waves, and heavy precipitation events (IPCC, 2013b).

Emissions from fossil fuel combustion are expected to grow in coming years in parallel with increasing global demand for energy. The International Energy Agency (IEA) estimates that if business as usual prevails, worldwide energy demand will increase 37% by 2040, and that fossil fuels will still account for three-quarters of the world's energy needs 25 years from now (IEA, 2014d). Without a combination of substantial policy change, extensive shifts to alternative energy sources, or the widespread adoption of carbon capture and storage (CCS) technologies, global carbon dioxide emissions will continue to rise and the world will remain on course for further temperature increases (IPCC, 2014b).



Data Source: Boden *et al.*, 2013

Figure 1.1

Global Carbon Dioxide Emissions from Fossil Fuel Combustion, 1751–2010

Annual carbon dioxide emissions from the combustion of fossil fuels have increased steadily since the Industrial Revolution and are now equal to approximately 32 gigatonnes per year. Data do not include any non-energy emissions (including those from cement production).

Avoiding this scenario and stabilizing the climate in the long term will require a transition to energy systems — the resources, processes, and technologies involved in the production, conversion, distribution, and use of energy — that have low greenhouse gas emissions and therefore limited ongoing influence on the Earth's climate. Such systems feature technologies and subsystems on multiple scales, ranging from a single automobile to the entire combination of technologies and infrastructure involved in electricity generation and distribution. Realizing a transition to a low-emission energy system will require choices about the energy sources and technologies available to society. It will also require choices about the policies that governments can use to support energy system transformations while ensuring that these transitions occur at minimal cost to society and take into account the full range of relevant costs and benefits. However, the contentious nature of public debates on climate change, the complexity of the energy and climate systems, and the abundance of often conflicting information have made it challenging for policy-makers, businesses, and the public to know what information they can trust in seeking to understand these issues.

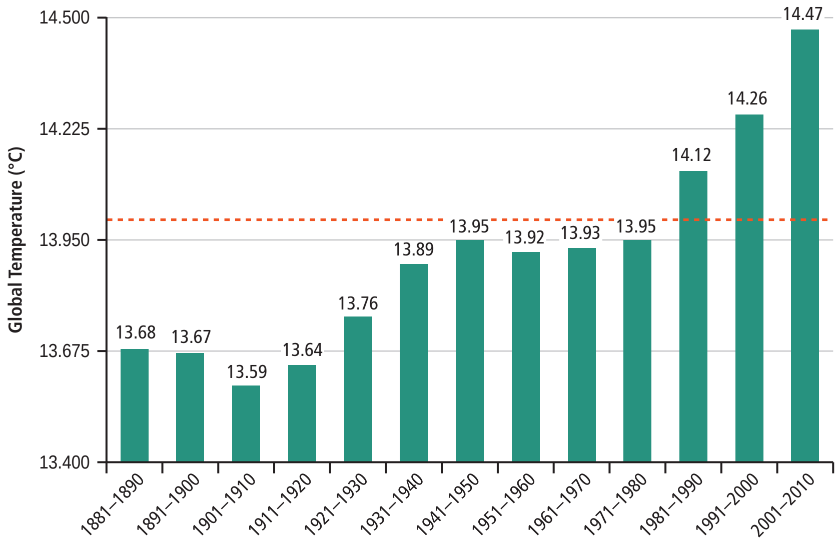


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Figure 1.2

Decadal Average Surface Temperatures, 1881–2010

The decade from 2001 to 2010 was the hottest since records began. The figure shows global average combined surface-air temperatures over land and sea-surface temperatures obtained from averages of three independent datasets: the U.K. Met Office Hadley Centre and the Climatic Research Unit, University of East Anglia, in the United Kingdom (HadCRU); NOAA-National Climatic Data Center (NCDC); and the U.S. National Aeronautics and Space Administration-Goddard Institute for Space Studies (NASA-GISS). The horizontal orange line indicates the long-term average for 1961–1990 (14°C).

1.1 THE CHARGE TO THE PANEL

In the fall of 2014, Magna International Inc. approached the Council of Canadian Academies (the Council) about sponsoring an assessment on energy and climate change. The motivation for doing so was growing frustration among Canada's business leaders over a lack of clarity about energy technologies and climate change, as well as policy options to address the latter. As a result, Magna was interested in supporting the development of an assessment that would:

- provide an overview of Canada's energy system and related opportunities and challenges in transitioning to a low-emission energy system;
- provide an analysis of different energy sources and technologies that could be involved in transitioning to low-emission energy systems, taking into account their relative strengths and weaknesses and their performance on a range of economic, environmental, and social criteria;

- identify the public policies available to support a shift toward low-emission energy sources and technologies, and discuss what has been learned about these policies through their introduction in Canada and elsewhere; and
- characterize how this evidence can inform the policy and investment decisions that will shape the development of Canada's energy system in the coming decades.

The goal of the project is to address these objectives in an accessible report that will be a useful guide to policy-makers, businesses, and the public, based on a rigorous, independent appraisal of the best available evidence.

In response to this inquiry, the Council convened a multidisciplinary, eight-member expert panel (the Panel) comprising individuals with expertise in economics, public policy, engineering, business, and energy systems and technologies. The Panel met six times (virtually and in-person) over the course of 2014 and 2015 to review evidence and deliberate the charge. The Panel's report was also subjected to an extensive peer review by energy and climate experts from Canada and other countries.

1.2 THE SCOPE OF THE ASSESSMENT

The focus of this assessment is on the energy sources, energy technologies, and public policies that can enable and support a transition to low-emission energy systems. While climate change is a global issue, Canada is the focus of the Panel's report, which is meant to be an accessible summary of the literature. Evidence was drawn primarily from recent synthesis literature published in peer-reviewed scientific journals or by independent international organizations, though reports published by governments and other organizations and primary studies were also considered where necessary. Search strategies varied across different topics in the report, and they evolved as the Panel assessed the most recent information. The peer review process also helped identify new evidence for the Panel's deliberations. The assessment is not meant to be exhaustive, nor is it based on primary research. Rather, most of the topics discussed in the report, and the evidence used to support these discussions, were identified as: (i) important for clarifying issues the public generally does not know or may be confused about; and (ii) widely understood and accepted by energy and climate experts and supported by the literature. The Panel was also guided by a systems thinking approach, recognizing the interconnectedness of society, energy and environmental systems, and different technology and policy options (Hipel *et al.*, 2007). This report offers insights into key systemic considerations that constrain or enable emission reduction opportunities across the economy, as well as lessons learned from the design and implementation of climate change policies.

The Panel's mandate touches on many topics pertaining to energy, the economy, the environment, and climate change; however, a number of areas were deliberately excluded at the outset from the assessment's scope. These were:

- *Climate change science.* Beyond basic background information provided in Section 1.3, this assessment does not include an original review of the scientific evidence pertaining to climate change, because this evidence has been extensively surveyed and analyzed elsewhere. Readers seeking more discussion of the evidence or how increasing greenhouse gas concentrations are affecting the climate system should turn to the *Fifth Assessment Report* from the Intergovernmental Panel on Climate Change (IPCC, 2013a). The Royal Society in the United Kingdom and the National Academies of Science in the United States have also produced a short summary (RS & NAS, 2014) that provides an overview of the science on climate change.
- *Non-energy greenhouse gas emissions.* Land-use change, agriculture, waste management, and industrial processes account for around 30% of global greenhouse gas emissions, including both carbon dioxide and other greenhouse gases such as methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, and sulphur hexafluoride. The Panel's focus on energy systems precludes detailed analysis of these emission sources and approaches to mitigating them. Agriculture emissions are also excluded due to the prevalence of non-energy emissions in that sector and the fact that energy-related agricultural emissions account for a small share (~3%) of Canada's total energy-related emissions.
- *Climate engineering.* With the exception of bioenergy technologies, the Panel did not explore technologies that remove carbon dioxide from the atmosphere. Nor did the Panel explore the potential for technologies and industrial applications that sequester atmospheric carbon dioxide into value-added products (e.g., carbon fibre), though these could ultimately play an important role in climate change mitigation by providing commercial incentives for carbon sequestration. Similarly, the Panel did not review the possibility of injecting aerosols into the stratosphere to deflect solar radiation. Such large-scale climate engineering solutions warrant a separate examination, as they entail different risks and challenges. For recent reviews of these challenges, see the National Research Council (NRC, 2015a, 2015b).
- *Climate adaptation.* Evidence on climate change adaptation strategies and activities was also excluded from the scope of the assessment due to its focus on mitigation. The Working Group II report of the *Fifth Assessment Report* from the IPCC provides an extensive review of evidence on climate impacts and adaptation (IPCC, 2014c).
- *International climate negotiations.* Finally, the Panel did not explore evidence relating to international climate negotiations, focusing instead on the domestic energy system in Canada and the policies involved in shaping that system.

1.3 CLIMATE CHANGE SCIENCE: THE STATE OF THE EVIDENCE

The relationships among atmospheric greenhouse gases, the climate system, and the effects that changes in climate impose on ecosystems and societies encompass extraordinarily complex domains of scientific inquiry. The evidence accumulated over the past several decades nonetheless strongly supports three general conclusions: (i) the Earth's climate is changing; (ii) the observed changes are driven primarily by greenhouse gas emissions from human activity; and (iii) without considerable emission mitigation, the expected scale and pace of climate change pose substantial risks to human communities and the Earth's ecosystems.

1.3.1 Climate Observations

There is a large and growing amount of evidence documenting changes in the Earth's climate that are occurring at a pace unprecedented in recorded history. Climate change is happening everywhere in the world and is affecting all parts of the global climate system, including water cycles, the cryosphere (the portions of the earth's surface covered in ice or snow), and marine and terrestrial ecosystems (IPCC, 2013a).

Surface temperatures are increasing around the world. The decade from 2001 to 2010 was the warmest since modern meteorological records began in the mid-19th century (WMO, 2013), and 2014 was the 38th consecutive year that global mean surface temperatures have been above the long-term historical average (NOAA, 2015). Surface temperatures are warming above both land and ocean, and over all continents. Most regions of the globe are experiencing an increasing number of hot days and a decreasing number of cold days (Hartmann *et al.*, 2013). Some types of extreme weather are also becoming more common, though these trends vary by region. Heavy precipitation events are increasing in frequency in some areas (such as North and Central America and Europe), and the frequency of drought has increased in some regions (such as the Mediterranean) and decreased in others (such as central North America) (Hartmann *et al.*, 2013).

Climate change is affecting the oceans, which are warming, rising, and becoming more acidic due to increased absorption of carbon dioxide from the atmosphere (Pörtner *et al.*, 2014). Climate change increases sea levels through the melting of freshwater resources such as glaciers and ice sheets on land, and through the expansion of seawater as it warms. Sea levels rose 19 centimetres on average over the course of the 20th century and are now rising at approximately 3.2 millimetres per year (Pörtner *et al.*, 2014). Rising sea levels, however, are not evenly distributed around the world. Since the early 1990s, some areas in the western Pacific have experienced rates of sea level rise up to three times greater than the global average (Church *et al.*, 2013).

Ice and snow cover is declining in many regions. The extent of sea ice in the Arctic has decreased in every season and in every successive decade since 1979 (Vaughan *et al.*, 2013). Declining Arctic ice cover likely accelerates the warming trend, as the surface of the ocean absorbs more heat than does ice. The thickness of Arctic sea ice is also decreasing, from an estimated mean winter thickness of 3.64 metres in 1980 to 1.84 metres in 2008 (Vaughan *et al.*, 2013). Warmer surface temperatures are causing glaciers around the world to recede (WGMS, 2013), and more than 600 have disappeared in recent decades (Vaughan *et al.*, 2013). The Greenland and Antarctic ice sheets are losing mass, and their rates of ice loss are accelerating (Vaughan *et al.*, 2013). The extent of summer snow coverage in the Northern Hemisphere has also been declining, with consequent impacts on seasonal runoff and water availability. Permafrost is melting in many areas, potentially accelerating climate change through additional releases of methane (Vaughan *et al.*, 2013).

Climate change is affecting ecosystems and species. Changes in the ranges of terrestrial and freshwater plant and animal species have been documented, including migratory birds, trees and other plants, and insects, with ranges shifting toward higher latitudes and altitudes in response to warming (IPCC, 2014d). In marine environments, northward shifts in the distribution of fish, seabirds, and other organisms have also been observed (Porter *et al.*, 2014). Such shifts are expected to continue as the climate warms, and many species will likely struggle to adapt to the rapid pace of warming (Settele *et al.*, 2014).

Many of these climatic shifts have been observed in Canada, often to a greater degree than the global average. For example, surface temperatures are increasing in Canada at approximately double the rate of the global average, with the average temperature over land having risen 1.5°C over the last 60 years (NRCan, 2014f). Precipitation patterns in Canada are also changing. Annual average precipitation is increasing in most regions, and several parts of southern Canada have also experienced a shift in the form of precipitation, with rainfall increasing and snowfall declining (NRCan, 2014f). Glaciers in both western Canada and the high Arctic are declining, with those in Alberta having lost 25% of their surface area between 1985 and 2005 (NRCan, 2014f). Most of the country, particularly western Canada, has seen trends toward earlier melting of ice on lakes and rivers. These changes have implications for hydrological cycles: earlier spring runoff can increase risks of flooding, while reduced winter snowpack leads to less surface water availability in the summer months and increased water flow variability. Canada's ecosystems and species are also responding to temperature changes with shifts in their traditional ranges. Maple trees, for example, have exhibited a significant northward shift since 1971 (Woodall *et al.*, 2009; NRCan, 2014f).

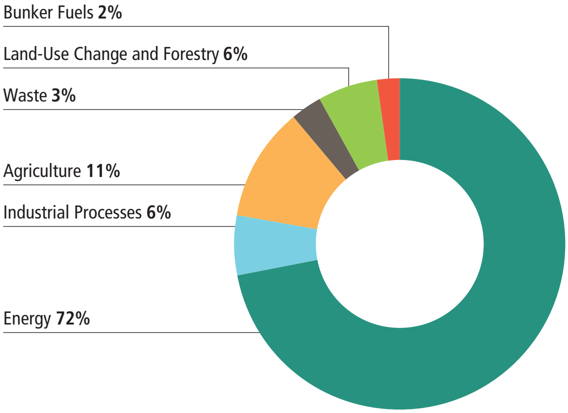
1.3.2 The Drivers of Climate Change

The available scientific evidence indicates that increasing atmospheric concentrations of greenhouse gases originating from human activity are the main driver of current changes in the Earth's climate, likely accounting for more than half of the increases in global average surface temperatures between 1951 and 2010 (IPCC, 2013a). Climate reconstructions suggest that global surface temperatures and carbon dioxide concentrations are highly correlated, and samples from ice cores indicate that the current concentration of carbon dioxide in the atmosphere is higher than it has been any time in the last 800,000 years (Lüthi *et al.*, 2008).

Greenhouse gases increase the amount of energy retained by the atmosphere by capturing outgoing thermal radiation emitted by the earth's surface and atmosphere. According to recent estimates, the atmosphere is retaining significantly more solar energy than it did in pre-industrial times, due primarily to increased concentrations of carbon dioxide (IPCC, 2013b). Other potential drivers of climate change include aerosols (small particles that can reflect radiation in the upper atmosphere, such as sulphur, nitrous oxide, black carbon, and organic carbon) and changes in the amount of radiation emitted by the sun due to solar cycles. However, aerosols introduced by human activity are generally exerting a cooling effect on the climate, and direct satellite measurements do not indicate a historical pattern of solar radiation that could be linked to the current increases in global temperatures (Myhre *et al.*, 2013).

Recent studies have found that there is a correlation between cumulative carbon dioxide emissions and global average temperature changes, with total carbon dioxide emissions over time closely associated with an expected level of warming (IPCC, 2013b; Friedlingstein, 2014). Such studies have implications for the design of climate policies and emission reduction targets. For example, the currently agreed-upon threshold for dangerous climate change, and the basis for ongoing international negotiations, is cumulative emissions associated with maximum climate warming of 2°C. Research suggests that two-thirds of these emissions have already been released, and the rest will occur in the next 15 to 30 years (Friedlingstein, 2014). If emissions continue to evolve along current trajectories and no further mitigation efforts are undertaken, recent modelling suggests the Earth's climate will most likely warm by between 3.7°C and 4.8°C by 2100 (IPCC, 2014e). Another implication of this relationship between cumulative emissions and temperature increases is that limiting temperature increases to 2°C would require that a large share of proven fossil fuel reserves remain undeveloped. McGlade and Ekins (2015) estimate that one-third of known oil reserves (including nearly three-quarters of Canada's proven oil reserves, which are mostly bitumen), half of known natural gas reserves, and over 80% of known coal reserves would need to remain in the ground in order to limit warming to less than 2°C.

Fossil fuel combustion is not the only source of greenhouse gas emissions. Others include land-use changes and deforestation (which can release carbon dioxide stored in soils and forests), agricultural processes (which can result in methane releases), waste decomposition, cement production (which releases carbon dioxide both through a chemical conversion involved in the production of lime from limestone as well as via combustion of fossil fuels), and other industrial processes that release greenhouse gases such as methane, nitrous oxide, and fluorinated gases (used in aluminum production and semiconductor manufacturing). These emissions are not insignificant. The estimated *net* greenhouse gas emissions (i.e., including both emissions and absorption from terrestrial sources) from land-use change and forestry (LUCF) in Canada vary from year to year and are sometimes negative (when terrestrial sinks absorb more carbon dioxide than is released); however, these emissions can account for a sizeable share of Canada's total emissions. With over three million square kilometres of forest, Canada has the third-largest forest area in the world, after Russia and Brazil (The World Bank, 2015). Extensive amounts of carbon dioxide are stored in these forests, which either absorb or release carbon dioxide depending on environmental conditions and management practices. Climate-related stressors such as fires, insect outbreaks, disease, and drought can all threaten forest health and potentially lead to additional carbon dioxide releases. As indicated in Figure 1.3, however, globally energy-related emissions account for over 70% of all greenhouse gas emissions (IPCC, 2014e; Le Quéré *et al.*, 2014). The share of emissions caused by land-use change and deforestation has also declined in the last decade. Energy-related emissions are accounting for a progressively greater share of global emissions over time (Le Quéré *et al.*, 2014). In Canada, energy-related emissions accounted for 74% of total greenhouse gas emissions in 2012, including those from LUCF (Environment Canada, 2015c).



Data Source: WRI, 2014

Figure 1.3

Share of Global Greenhouse Gas Emissions by Source, 2012

The figure shows a breakdown of world greenhouse gas emissions by source. *Land-Use Change and Forestry* is based on net emissions after accounting for terrestrial carbon sinks and sources. *Bunker Fuels* refers to emissions from international aviation and marine transport, also based on fossil fuel combustion.

1.3.3 Climate Change Impacts and Risks

Climate change is expected to result in a wide range of impacts on natural and social systems. These may include both positive and negative impacts for society. Warming temperatures, for example, may have positive effects on agricultural systems in some regions, leading to economic benefits (Porter *et al.*, 2014). In high-latitude regions (including Canada), warmer temperatures may alleviate some health burdens associated with colder climates (Martin *et al.*, 2012); however, studies generally suggest that in most locations, the health impacts from more frequent heat extremes outweigh the benefits of fewer colder days (Smith *et al.*, 2014a). Climate change risks are not equally distributed among countries. Some may be affected more negatively or positively than others. Nonetheless, the majority of the evidence suggests that the expected extent and pace of climate change pose significant and widespread risks to human communities and the Earth's ecosystems.

Rising temperatures and changing climate conditions create a range of risks for society, some of which are already evident based on recent trends. Temperatures may rise in some places to levels that threaten crops, livestock, and outdoor workers. The frequency and duration of heat waves will also likely increase in the future, with negative impacts on cities, and extreme precipitation events will likely become more intense and frequent in many countries (IPCC, 2014d). Agricultural systems are affected by both temperature and precipitation patterns. There is evidence that climate change has already adversely affected global wheat and maize production due to the sensitivity of crops to climate extremes, and global temperature increases of 4°C or more are likely to pose large risks to global food security (Porter *et al.*, 2014).

Marine ecosystems and species will be increasingly threatened by ocean acidification, and coastal communities are at risk because of the combined effects of sea level rise and potential storm surges (Pörtner *et al.*, 2014). Coral reefs are particularly vulnerable (Pörtner *et al.*, 2014), as are communities that depend on their ecosystems for tourism or fisheries. A large percentage of terrestrial and freshwater species are thought to be at increased risk for extinction due to climate change (IPCC, 2014c), in part due to the interactions between climate change and other stressors such as habitat loss and degradation. Most plant species cannot naturally shift their geographic ranges quickly enough to keep up with the pace of warming expected by current models (Settele *et al.*, 2014). Evidence from fossil records suggests that past episodes of climate change, which occurred much more gradually than the current rate, were nevertheless associated with major extinction events (Settele *et al.*, 2014).

Climate-related extremes such as heat waves, droughts, floods, cyclones, and wildfires can pose major risks for vulnerable communities. Climate change is projected to increase the displacement of people globally, potentially stimulating conflicts over resources and exacerbating problems such as poverty and environmental degradation (Adger *et al.*, 2014). Climate change may also harm human health, though these risks are not well quantified (Smith *et al.*, 2014a). Health impacts from climate change can occur due to direct influences, such as increases in heat-related morbidity and mortality (e.g., increasing incidence of heat strokes from heat waves), as well as from changes in disease vectors associated with malaria, dengue fever, and tick-borne diseases such as Lyme disease (IPCC, 2014a; Smith *et al.*, 2014a).

Canada specifically and North America in general are exposed to many climate change risks (NRCan, 2014f; Romero-Lankao *et al.*, 2014). Sectors of the Canadian economy susceptible to weather- or climate-related shocks include traditional natural resource industries such as agriculture, forestry, fisheries, and electricity generation from hydropower (NRCan, 2014f). The tourism industry also stands to be affected by changing climate and weather conditions (Arent *et al.*, 2014). Climate warming may enable more economic activity in Canada's Far North; however, melting ice roads and permafrost and less predictable ice conditions may jeopardize infrastructure and businesses there. Risks associated with heavy precipitation, flooding, or other extreme weather events may be rising, not only because of the changing climate, but because exposure to these risks is growing in tandem with population growth and development in hazardous regions. Rising property values and infrastructure development can also increase exposure to these risks and result in larger economic losses. Economic losses due to extreme weather events have increased in Canada over the past 10 years; in 2013 alone, flooding in and around Calgary and Toronto resulted in over $2.5 billion in damage claims (NRCan, 2014f).[1]

Many of the risks associated with climate change cannot be precisely quantified yet, and climate models currently provide only rough guidance as to the likelihood and potential scale of impacts. Estimates of the economic damages associated with future climate change are also highly uncertain (Arent *et al.*, 2014). The possibility that climate change could lead to catastrophic consequences for humanity in the long term also makes the usefulness of conventional cost-benefit analysis methods questionable (Weitzman, 2009, 2011; Wagner & Weitzman, 2015). When economists have weighed the costs and benefits of taking action to mitigate emissions, the conclusions reached in nearly all cases are that substantial emission reductions are warranted due to the risks and potential damages of climate change, the costs of climate mitigation increase the longer reductions are delayed, and climate-related risks and damages increase in proportion to cumulative emissions and expected increases in global temperatures (Nordhaus & Boyer, 2000; Stern, 2006; Nordhaus, 2008, 2013; Tol, 2009; Hope, 2011; Tol, 2014). The Panel's view is that for Canada and the world in general, the risks arising from climate change justify significant and accelerated efforts to reduce emissions from human activity over the course of this century.

1.4 CANADA IN THE GLOBAL CONTEXT

Climate change is a globally shared challenge. Greenhouse gases mix freely in the atmosphere, and emissions from any single country have implications for the entire global climate system. Climate change also exemplifies a "tragedy of the commons"[2] and the difficulties inherent in managing a commonly held resource — in this case the Earth's atmosphere. Faced with the shared goal of averting dangerous climate change, all countries have an incentive to free ride on emission reductions in other jurisdictions and avoid undertaking their own reductions (Nordhaus, 2015). However, reducing emissions on the scale necessary to avert dangerous climate change

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[1] All dollar amounts are in Canadian dollars, unless otherwise noted.

[2] A *tragedy of the commons* occurs where a commonly-held resource such as a pasture is overexploited by individuals acting in their own self-interest (Hardin, 1968).

will require action from all major emitters, including both developed and developing countries. Motivating the needed reductions will likely require internationally coordinated efforts to ensure that countries effectively allocate responsibility for the required cuts under the auspices of a transparent and enforceable framework.

Efforts have been under way for over two decades to develop a binding international agreement on climate change. Canada has actively participated in these efforts, having been a signatory to the Kyoto Protocol and the Copenhagen Accord. Negotiations are now under way to develop a successor agreement to the Kyoto Protocol under the auspices of the United Nations Framework Convention on Climate Change (UNFCCC). In the 2009 Copenhagen Accord, the international community collectively endorsed the goal of taking action to limit temperature increases to less than 2°C. Despite this commitment, global emissions have continued to rise, and meeting this objective becomes more challenging and more costly with each successive year. Canada's Copenhagen target included a commitment to a 17% reduction in greenhouse gas emissions below 2005 levels by 2020. In 2015, as part of ongoing international negotiations, Canada also announced a pledge to cut emissions 30% below 2005 levels by 2030 (its Intended Nationally Determined Contribution). Bilateral agreements may also be the basis for future international cooperation on climate change, with the United States and China, the world's two largest sources of emissions, having announced a joint agreement on climate change on November 11, 2014.

Canada's contributions to global emissions are substantial. As of 2013, Canada ranked 12th out of 219 economies in terms of total carbon dioxide emissions and accounted for 1.4% of the world's total (Boden *et al.*, 2013). Among Organisation for Economic Co-operation and Development (OECD) countries, only the United States, Russia, Japan, Germany, and South Korea have higher emissions, and only three OECD countries (Australia, Luxembourg, and the United States) have higher per capita emissions (The World Bank, 2015). Canada's greenhouse gas emissions have declined in the wake of the global financial crisis, and emission growth has slowed due to new provincial policies, such as British Columbia's carbon tax, and the closure of coal-fired power plants in Ontario (CESD-OAG, 2014). However, emission growth is resuming, and Canada will likely fail to meet its reduction goal for 2020 (Environment Canada, 2013c; CESD-OAG, 2014). This continues a long-standing pattern. Canada has set national emission reduction targets four times since 1988 without implementing policies capable of achieving these targets.

As noted in Section 1.3.2, Canada is also a potentially large source of future emissions from the carbon dioxide stored in its fossil fuel reserves. Canada has the third-largest proven reserves of oil in the world, after Saudi Arabia and Venezuela (EIA, 2014a), is the world's fourth-largest producer of natural gas (NRCan, 2014b), and is a significant exporter of coal (NRCan, 2014b). Canada's National Energy Board (NEB) also projects that fossil fuels will comprise three-quarters of Canada's energy needs in 2035 based on current trends, with hydropower and nuclear power accounting for most of the rest (NEB, 2013). Canada will likely continue to be a significant exporter of fossil fuels in the business-as-usual case, with Canadian oil production potentially growing from roughly four million barrels per day in 2015 to five or six million barrels per day between 2020 and 2030 (CAPP, 2014; IEA, 2015a). Due to the potential emissions represented by these resources, the development of Canada's fossil fuel industries has major implications for future emission trends both within and outside of Canada. This continues to prompt discussion, debate, and analysis on whether Canada's extensive fossil fuel resources could be developed more sustainably, particularly given the importance of the oil and gas industry to the Canadian economy (e.g., CAE, 2012a, 2014). Given that the oil sands have been the dominant source of Canada's emission growth in the past decade (Environment Canada, 2013b, 2015c), managing it will be critical to stabilizing and eventually reducing national emissions.

Canada, like all countries, can contribute to mitigating global climate change in many ways. Canadian governments can support the development of new international climate agreements, participate in regional emission reduction efforts in North America, support development of low-emission energy technologies, and take action to reduce domestic emissions from fossil fuel combustion and other sources. Governments can also apply trade measures to ensure a level playing field for firms facing competition from other jurisdictions whose climate policies are less stringent. Independent of government, businesses and consumers can also take steps that contribute to emission reductions by conserving energy, adopting more efficient technologies, and seeking energy from less emission intensive sources.

Ultimately, achieving substantial greenhouse gas reductions on a global scale will require most countries — Canada included — to transition to low-emission energy systems. This represents a substantial challenge given the pervasive dependence on emission intensive energy sources and technologies in most countries. Canada's prospects for successfully completing this transition therefore mirror those of other countries in many ways. While Canada is the focus of this assessment, much of the discussion and analysis is applicable to other jurisdictions.

1.5 REPORT OVERVIEW

The existing literature on energy use and climate change ranges from short and widely accessible educational documents to large, multi-year, multi-author synthesis reports. The Panel made efforts to provide a credible and concise synthesis of what is known about the technologies and policies that could support a transition to a low-emission economy. References provided throughout the report can be consulted for further details on specific topics. In addition, while the technologies and policy tools available to limit emissions from energy systems are globally applicable, this report draws out the aspects and considerations that are most relevant in the Canadian context. The report is intended as a tool to inform private sector decision-makers who are continually anticipating future developments that could affect their business decision-making. It is also relevant for government departments and agencies at the federal, provincial, territorial, and municipal levels considering options for motivating further emission reductions, and to members of the public at large as they consider the challenges of climate change and potential strategies to address them. It is the Panel's hope that this report will contribute to the continuing dialogue across Canada and internationally, and across many sectors, on the strategies necessary for transitioning to a low-emission energy system.

The rest of the report is structured as follows:

Chapter 2 provides an introduction to energy systems in general and an overview of Canada's in particular. It highlights facts about how energy is produced, distributed, and used to provide a range of basic services. It also reviews energy demand and supply in Canada, trends in energy-related greenhouse gas emissions, and evidence concerning energy system transitions.

Chapter 3 reviews energy sources and technologies in four sectors implicated in transitioning to low-emission energy systems: electricity generation, transportation, buildings, and industry. It identifies efficiency-improving measures, as well as opportunities for carbon capture and storage and energy substitution, and discusses systemic barriers to more widespread adoption of alternative low-emission energy technologies.

Chapter 4 discusses the public policy tools available to support a transition to low-emission energy sources and technologies. An analysis of different policies based on key evaluative criteria is provided, and lessons learned from the design and implementation of these policies in Canada and in other regions and countries are summarized.

Chapter 5 concludes the report by offering the Panel's reflections on the prospects for a transition to a low-emission energy system in Canada, and the most critical elements for encouraging and enabling such a transition in the coming years.

2

Understanding Canada's Energy System

- Understanding Energy Systems
- Canada's Energy System
- Canada's Energy-Related Greenhouse Gas Emissions
- Energy System Transitions
- Summary

2 Understanding Canada's Energy System

Key Findings

- The energy system consists of the resources, technologies, processes, and applications involved in the conversion of energy into useful services such as lighting, transportation, space heating and cooling, and material processing.
- Large amounts of energy are lost in conversions throughout the energy system. These losses present opportunities for improving efficiency, in some cases by integrating processes and technologies.
- Canada has high rates of energy use per capita due to high incomes, extensive endowments of energy resources and low energy prices, a large land mass, variable climate, and industrial composition. Demand for energy is expected to continue to grow in Canada in the coming decades, particularly in industry.
- Canada relies on fossil fuels to meet most of its energy needs, and dependence on these energy sources will continue without some combination of major technological and policy change. The production and processing of fossil fuels for export also affect Canada's ability to reduce emissions.
- Energy system transitions typically require decades, due to the long-lived nature of infrastructure and massive investments required. However, energy transitions can be accelerated with aggressive policy support. Minimizing the costs of energy transitions requires taking advantage of the natural turnover rates associated with different capital stocks.

Canada, like most countries, relies on fossil fuels to meet most of its energy needs. As a result, many of the ways Canadians use energy on a daily basis, including driving cars, heating homes and buildings, and cooking meals, are implicated in greenhouse gas emissions. Departing from a course of continued dependence on a high-emission energy system will involve changes to many aspects of how energy is produced, distributed, and used. In the Canadian context, it also requires taking into account the defining characteristics of Canada's energy system and changes in energy demand and emissions.

This chapter provides an overview of energy systems and Canada's energy and emission landscape. The first section highlights fundamental facts and concepts needed to understand energy systems, such as the distinction between primary and secondary energy sources. The second section identifies key features of Canada's energy system, including basic facts about energy supply and demand in Canada and recent trends pertaining to emission growth. The final section summarizes evidence on energy system transitions and the implications of this evidence for governments hoping to facilitate shifts toward low-emission energy systems.

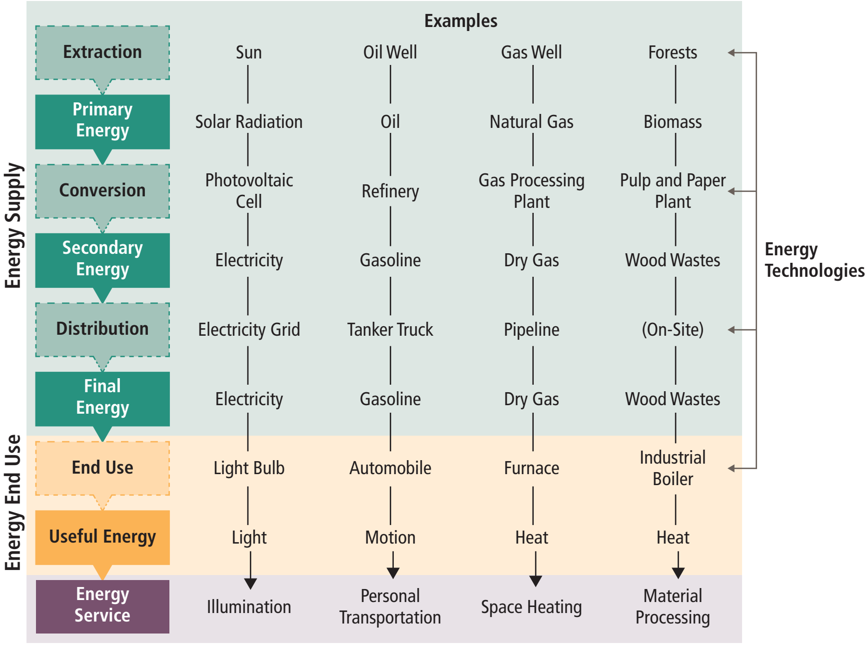
2.1 UNDERSTANDING ENERGY SYSTEMS

The *energy system* is composed of all the resources, processes, technologies, and applications involved in the production, conversion, distribution, and use of energy. Energy systems link together natural and social systems, and they have geological, biological, economic, and technological components. Figure 2.1 provides a schematic diagram of the energy system, showing how energy is generated and transformed through a series of conversions as it moves from its original sources through to its final applications. Demand for energy is ultimately driven by the need for basic energy *services* such as lighting, transportation, space heating and cooling, and material processing. These services are provided by end-use *technologies* such as light bulbs, automobiles, furnaces, and industrial boilers, which convert energy into a useful form such as light, motion (kinetic energy), or heat.

2.1.1 Primary and Secondary Energy Sources

Fundamental sources of energy in the system are referred to as *primary energy* sources. They consist of energy embodied in resources in their natural state, such as chemical energy contained in fossil fuels and biomass, solar radiation from the sun, kinetic energy inherent in the movement of wind and water, or energy within the bonds that bind together the nucleus of an atom (Grubler *et al.*, 2012c). Primary energy sources sometimes exist in the form of energy stocks, which are extracted by natural resource industries (such as in an oil well or a uranium mine). In other cases, energy is captured from naturally occurring *flows* such as incoming solar radiation or water flowing through a watershed. Stocks are, by definition, exhaustible, whereas energy flows are constantly renewed. For fossil fuel stocks, the size of the resource is assessed by considering the total amount that could be extracted with current technologies and economic conditions — referred to as *proven reserves.* The primary energy sources used in most modern energy systems are fossil fuels (coal, oil, and natural gas), nuclear power, and renewable flows from hydropower, biomass (such as wood), solar, wind, geothermal, and tidal (Grubler *et al.*, 2012c).

Primary energy sources, however, are rarely used in their original form. More often they are converted into more convenient and usable forms of energy, which are referred to as *secondary energy* sources or energy carriers. For example, crude oil (a primary energy source) is refined to produce petroleum-based fuels such as gasoline (a secondary energy source), and solar radiation is converted



Adapted with permission from the International Institute for Applied Systems Analysis (IIASA); see Grubler *et al.*, 2012c

Figure 2.1

The Energy System: Sources, Stages, and Conversions

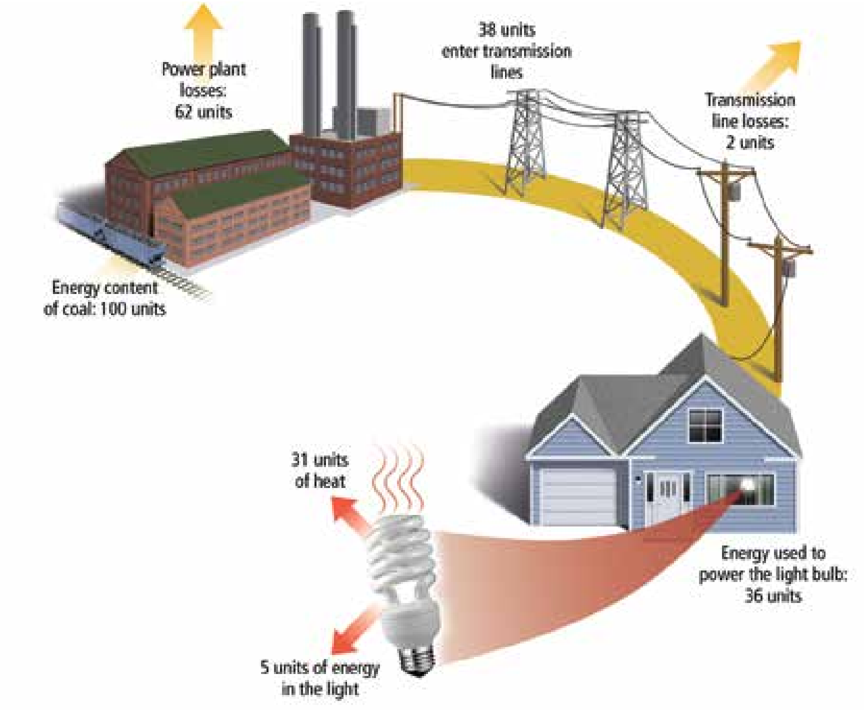
The figure shows a schematic depiction of the energy system, highlighting how energy flows from primary sources through multiple stages and conversions toward end use and the provision of energy services. Note that energy resources often have separate transmission and distribution systems, and that transmission systems also often occur prior to conversion (e.g., oil pipelines).

with a photovoltaic (PV) cell to create electricity. Secondary energy is used to distribute energy to the place where it is finally used. Refined petroleum products (such as gasoline, diesel, and jet fuel) are the dominant energy source in transportation. Electricity is a versatile energy carrier produced by many conversion technologies (such as wind turbines, hydropower plants, and coal-fired power plants), and it is used in a wide range of applications, from computers and home appliances to street lights and industrial equipment. Secondary energy sources are transported throughout the energy system and distributed to end-users via various modes, including electricity grids, pipelines, trucks, tanker ships, and trains. Not all energy carriers are subject to extensive processing prior to end use. For instance, resources such as biomass or solar energy can in some cases be consumed directly, as in the case of traditional biofuels used for cooking or the sun used to passively heat a home.

2.1.2 Energy Conversions and Losses

Because energy is converted from one form to another and distributed throughout the system, much of it is lost, typically in the form of waste heat. The useful energy produced at the end of these conversions is therefore often a small percentage of the energy contained in the primary source. For example, as shown in Figure 2.2, when electricity from a coal-fired plant is used to power a typical compact fluorescent light bulb, only 5% of the energy is transformed into useful light. Only around one-third of the world's primary energy supply is converted into useful services with existing technologies and conversion processes (Grubler *et al.*, 2012c).

Losses from conversions at all stages collectively affect the overall efficiency of the energy system and are dependent on the technologies and processes involved. These conversions offer opportunities for efficiency gains, and they



Adapted with permission from National Academy of Sciences; see NRC, 2008

Figure 2.2

Energy System Efficiency of Lighting from a Coal-Fired Power Plant

Most of the energy provided in primary sources is lost in the process of conversion at various stages in the energy system. The figure shows the energy chain and system losses associated with powering a typical compact fluorescent light bulb with electricity from a coal-fired power plant. Only 5% of the energy contained in the coal is captured as useful energy in the form of light.

therefore represent an energy resource that can be harnessed. Efficiency can be improved directly through the adoption of improved conversion (such as more efficient solar cells), distribution (such as high-efficiency transformers), and end-use technologies (such as energy-efficient appliances). Energy losses from fuel combustion in electricity generation and from the transportation sector are particularly large, whereas losses in electricity transmission and distribution are minor in comparison.

Switching to alternative energy sources associated with more efficient technologies and conversion pathways can also result in efficiency gains, and enhancing the integration of energy systems can also improve efficiency if waste heat can be captured and repurposed as useful energy. One example of this is cogeneration, in which heat from electricity plants is used for residential or industrial purposes (see Sections 3.3.1 and 3.4.1). Opportunities for improving energy efficiency are widespread; however, technological, economic, and behavioural barriers often partially limit the ability to realize these gains. Fundamental thermodynamic constraints, for example, mean that some energy is inevitably lost in all energy conversions. Energy efficiency gains can also trigger a rebound effect in which energy consumption can rise as consumers buy more of a relatively less expensive service and have more income available to purchase other energy-using goods and services.[3]

2.2 CANADA'S ENERGY SYSTEM

Patterns in energy production and consumption are influenced by each country's natural and built geography as well as other factors such as energy prices, income levels, and industry structure. Climate variability, natural resource endowments, and geographic and ecological characteristics affect energy flows from renewable sources and can influence energy demand for space heating and cooling. The characteristics of existing infrastructure, such as electricity grids or pipelines, transportation networks, and cities also influence energy demand and serve to differentiate countries and regions. Canada's energy system reflects an abundance of energy resources as well the country's status as a major energy exporter. Figure 2.3 provides an overview of this system, tracing the flows of energy from production (and imports) through energy conversions and ultimately to its transformation into useful energy and services. Energy production is portrayed on the left side of the figure, and end use is on the right. The top line in the figure, for example, shows the energy in the

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[3] The extent of the rebound effect is heavily debated. According to the InterAcademy Council (2007) "[b]oth theory and empirical studies have shown that in general only a small portion of the energy savings is lost to increased consumption." However, others have discussed the theory that efficiency gains can backfire completely, ultimately increasing overall production and consumption (see Alcott, 2005; Sorrell, 2007 for discussion of the Jevons Paradox).

uranium produced in Canada. Most of that uranium is exported; however, approximately 15% is directed to Canada's nuclear reactors and used to generate electricity (NRCan, 2014d). That electricity is then distributed to users in all sectors as well as exported to the United States. Conversion losses, which significantly exceed the amount of total useful energy captured in the system, are also shown in the bottom right corner of the figure. The data underlying the figure is calculated in petajoules (PJ), though other units are also often used in measuring energy flows.[4]

2.2.1 Energy Resources and Production

An extensive endowment of energy resources, including fossil fuels and low-emission energy sources, is a defining feature of Canada's energy landscape. Canada is one of the five largest energy producers in the world, behind China, the United States, Russia, and Saudi Arabia (EIA, 2014a). Canada is the world's fifth-largest producer of oil (with the third-largest proven oil reserves), the fourth-largest producer of natural gas, and the second-largest producer of uranium (NRCan, 2014b). As seen in Figure 2.3, Canada exports large volumes of these resources. Canada is also the third-largest producer of hydropower in the world, after China and Brazil (EIA, 2014a).

While Canada's energy resources are abundant, they are not evenly distributed across the country. Canada's oil reserves are concentrated in the west, with the oil sands now accounting for 98% of Canada's proven reserves. Oil production also occurs in offshore oil fields in Atlantic Canada, and in conventional resources in the Western Canada Sedimentary Basin. This area also holds most of Canada's natural gas reserves, though other areas with significant reserves include offshore fields around Newfoundland and Nova Scotia, the Arctic region, and the Pacific coast. The shale oil and gas revolution (see Box 2.1) has also contributed to expanding oil and gas development in Canada, in the process instigating a dramatic shift in North America's energy landscape. Canada's existing hydropower capacity is concentrated mainly in five provinces: British Columbia, Manitoba, Quebec, Ontario, and Newfoundland and Labrador. All Canadian provinces aside from Prince Edward Island, however, have considerable untapped hydropower potential (CAE, 2012b; TEFP, 2013).

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[4] Energy is most often measured in joules, where one joule is formally defined as the work done when a force of one newton is applied over a distance of one metre. However, other units are often used as well when discussing energy. *Power* is the rate at which energy is transferred, and it is measured in watts, where one watt is one joule per second. Kilowatt hours (kWh) are used to measure electricity (1 kWh is equal to 3.6 megajoules). In international statistics, tonnes of oil equivalent (toe) are often used, where 1 toe is equal to 42 gigajoules. The imperial system uses British thermal units (BTUs), where 1 BTU equals 1,055 joules. For more on energy units and measures, see the *Global Energy Assessment* (GEA, 2012).

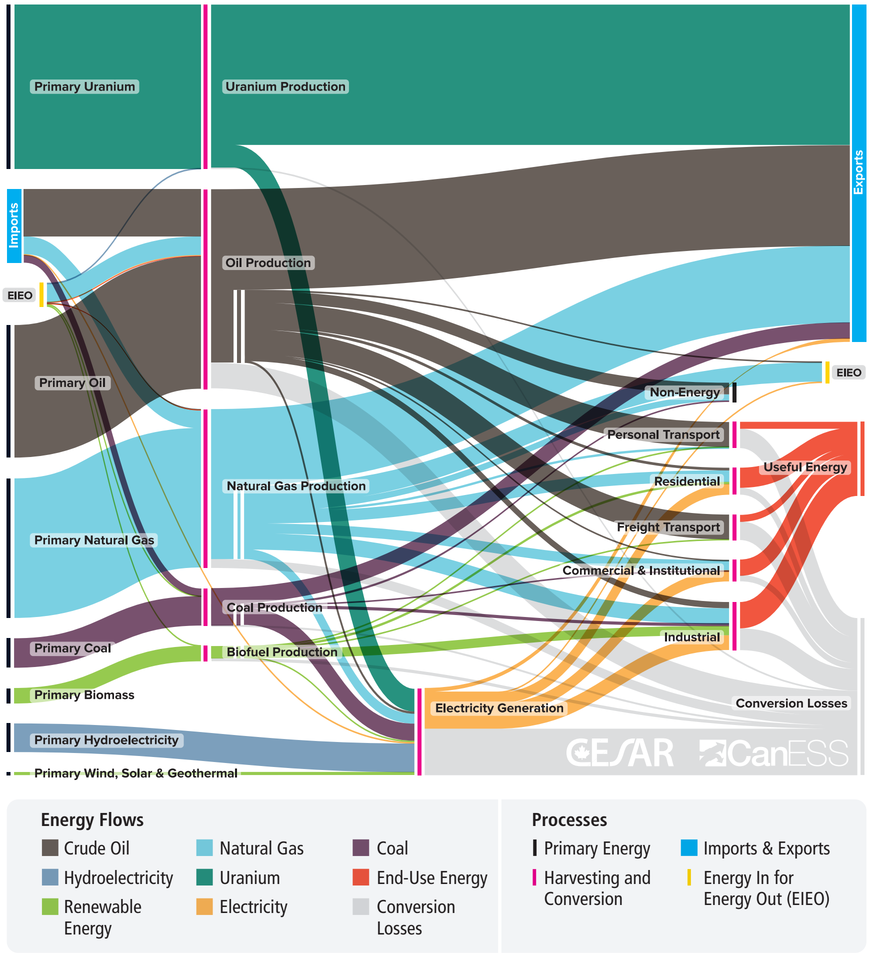

Image created by CESAR (www.cesarnet.ca) using data from the CanESS model (www.caness.ca)
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Figure 2.3

Canada's Energy Flows, 2010

Canada's energy system can be visualized as the flow of energy between production (and imports) and energy consumption (and exports). Fossil fuels still dominate Canada's energy system, accounting for most energy production and consumption. Canada's status as an energy exporter is also readily apparent, as are the extensive energy losses associated with conversions throughout the system. EIEO (energy in for energy out) reflects the energy consumed in the production of usable energy such as natural gas burned in the production of oil from Alberta's oil sands.

Box 2.1
The Shale Oil and Gas Revolution in North America

New technological advances for extracting oil and gas from shale deposits have led to a major shift in North America's energy supply over the past decade. A combination of technologies such as extended-reach horizontal drilling, multi-stage hydraulic fracturing, and pad drilling have allowed development of resources that were previously considered technically impossible or not profitable (NRCan, 2012a). In Canada, new shale gas development, primarily in the Horn River basin and Montney shales in northeastern British Columbia, has partially offset declining production of conventional gas reserves (NRCan, 2012a; NEB, 2015). New technologies have also led to shale (tight) oil development in the Bakken formation and other shale oil plays in Saskatchewan, Manitoba, and Alberta (NRCan, 2014e). In the United States, natural gas production rose 35% between 2005 and 2013, largely from shale gas development (EIA, 2014b), and U.S. oil production rose 44% in the same period (EIA, 2015). As a result of these trends, North America is expected to go from being a net energy importer to a net energy exporter in 2015 (BP, 2015). In addition to implications for regional and global energy trade, this development also has implications for energy-related carbon dioxide emissions. The increased abundance of natural gas in North America is facilitating a shift to natural gas as a preferred fuel for electricity generation. To the extent that it replaces existing coal-fired power plants, this could result in reductions in carbon dioxide emissions. At the same time, increasing reliance on natural gas without CCS technologies risks new investments in energy-related infrastructure that can lock in substantial future emissions for decades to come.

The capacity to extract energy from these resources and transport it to consumers depends on existing energy-related infrastructure. Energy complexes such as Alberta's Industrial Heartland, northeast of Edmonton, and the Sarnia-Lambton Petrochemical and Refining Complex, in Ontario, serve as hubs for refining and processing petroleum products and developing related industrial co-products (CAE, 2012b). As of 2012, 19 refineries throughout Canada collectively had a capacity to process over two million barrels of oil per day, though the number of refineries in Canada has been declining over time (CAE, 2012b). Canada's oil and gas pipeline networks extend over 700,000 kilometres and are used to transport crude oil and natural gas to refineries and processing plants in eastern Canada and the U.S. Midwest (CAE, 2012b). Canada also has a uranium corridor, with uranium mined in Saskatchewan transported to Blind River and Port Hope in Ontario for processing, and substantial experience with the development of nuclear power technologies such as the Canada

Deuterium Uranium (CANDU) reactor (see Box 2.2). In the case of hydropower, Quebec's James Bay development provides substantial power for export to the United States, and British Columbia's Columbia River development provides substantial water control benefits to downstream electricity generators in the United States.

Electricity systems play a key role in distributing energy to end-users. Management of electricity systems in Canada is under provincial jurisdiction, and the energy sources used for electricity generation differ among provinces, depending on regional resource availability. The regulatory regimes for electricity systems also vary by province. In most provinces, electric utilities have historically been vertically integrated Crown corporations that operate as regulated monopolies. However, there has been a general evolution toward partial market liberalization, the extent of which varies by province (IEA, 2009b). Ontario and Alberta, for example, have adopted full retail competition in electricity markets.

Box 2.2
Canada's CANDU Nuclear Reactors

Canada has amassed considerable expertise in nuclear power technologies through the development of the CANDU reactors. These reactors are pressurized heavy-water reactors of a type first developed by Atomic Energy of Canada Limited in the late 1950s and 1960s. CANDU reactors have several distinctive features compared to conventional light-water reactors. They can use natural rather than enriched uranium (as well as thorium) as a fuel, and they can also be refuelled while operating at full power — advantages that result in lower fuel and refuelling costs relative to other reactor designs. These cost savings, however, are partially offset by the costs of producing the heavy water used as a moderator and coolant. CANDU reactors have evolved through several generations of plant designs. The latest reactors built are based on Enhanced CANDU 6 (EC6) technology, and a Generation III Advanced CANDU Reactor (ACR-1000) is also in development. There are 31 operational CANDU reactors worldwide as of 2015, in Canada as well as South Korea, Romania, India, Pakistan, Argentina, and China.

World Nuclear Association (2015); CAE (2012b); TEFP (2013)

How electricity markets are structured can have implications for managing greenhouse gas emissions from this sector. Adoption of smart grids and systems concepts could improve the efficiency, reliability, and sustainability of Canada's electricity services (Luiken, 2014, 2015).

Wind energy, solar power, and bioenergy do not currently play a big role in Canada's energy system, but could provide large amounts of energy in the future. Many regions in Canada have average wind speeds sufficient for viable wind power, with the strongest wind regimes found in northern Quebec, Labrador, Newfoundland, Cape Breton, Prince Edward Island, and offshore regions of Atlantic Canada (TEFP, 2013). Solar power potential varies depending on local climate conditions and average solar radiation; however, it could be widely deployed in southern Canada. With huge forests and vast agricultural lands combined with a low population density, many Canadian regions have significant potential to produce bioenergy in the form of solids (wood chips), liquids (ethanol, biodiesel), or gases (bio-methane).[5]

2.2.2 Energy Exports and North American Energy Integration

Canada's status as a major energy exporter and the high degree of integration between the Canadian and American energy systems are other key features of the Canadian energy system. Canada is a net exporter of many energy commodities, most of which are shipped to the United States. Canada is the largest foreign supplier of energy to the United States, and together the United States and Canada form the largest integrated energy market in the world (EUS, 2015). The two countries share interconnected electricity grids and cross-border electricity markets, an integrated network of oil and gas pipelines, joint ownership of some energy assets and infrastructure by Canadian and American firms, cross-border partnerships and collaborations in energy technology development, and joint reliance on key energy storage facilities (EUS, 2015). Due to the lack of infrastructure connecting western Canadian oil supplies to eastern markets, Canada also imports oil and natural gas from the United States (NEB, 2014). In 2014, the United States displaced Algeria as the largest source of Canada's crude oil imports (NEB, 2014).

The electricity grid has more connections between Canada and the United States than among the provinces, and interprovincial connections tend to have lower capacity than those linking provinces to states (CAE, 2012b). New investments in interprovincial transmission connections could facilitate more electricity

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[5] According to the *Global Energy Assessment*, Canada accounts for 6.5 and 2.6%, respectively, of the world's theoretical bioenergy and biomass potential in 2050 from energy crops, forest residues, crop residues, municipal solid wastes, and animal wastes (Rogner *et al.*, 2012).

trade within Canada and potentially lead to emission reductions for some provinces (CAE, 2012b, 2014). However, to date, north-south electricity trade between Canadian provinces and American states has been more economical in most circumstances, because electricity exports command higher prices (Goodman, 2010).[6]

Concern about overdependence on a single export market, however, along with global market conditions and resurgent oil and gas production in North America, have prompted Canada's federal government and some provincial governments to pursue a goal of expanding oil and gas exports to overseas markets. Proposed pipeline projects for shipping bitumen from Alberta's oil sands to tanker terminals on the west and east coasts, such as Enbridge's Northern Gateway Pipeline, Kinder Morgan's expansion of its Trans Mountain Pipeline system, TransCanada's Energy East Pipeline Project, and the Line 9 reversal (Eastern Canadian Refinery Access Initiative), are seen as critical infrastructure investments in order to gain access to growing Asian and European markets. British Columbia is also anticipating the export of liquefied natural gas (LNG). While these projects would facilitate Canada's ability to export energy commodities to Asian and European markets, they have also raised concerns about their potential environmental impacts (Palen *et al.*, 2014).

2.2.3 Domestic Energy Supply and Use

Like in most countries, Canada's energy needs are currently met mainly by fossil fuels. As shown in Figure 2.4, oil and natural gas each account for around a third of Canada's total primary energy supply, defined as domestic production plus imports minus exports; coal provides a smaller share at 7%. Hydropower and nuclear power also play a significant role, with hydropower providing most of Canada's electricity, and nuclear power being a large source of electricity in Ontario. Biomass is used as an energy source mainly by the forestry industry in the production of pulp, paper, and lumber (NRCan, 2014g). Renewable energy sources such as solar and wind play only a minor role in Canada's energy supply, though they have experienced rapid growth in recent years. While the role of natural gas in Canada's energy mix has gradually increased over time and the role of coal has declined, Canada's overall dependence on fossil fuels has remained relatively stable for the past 40 years.

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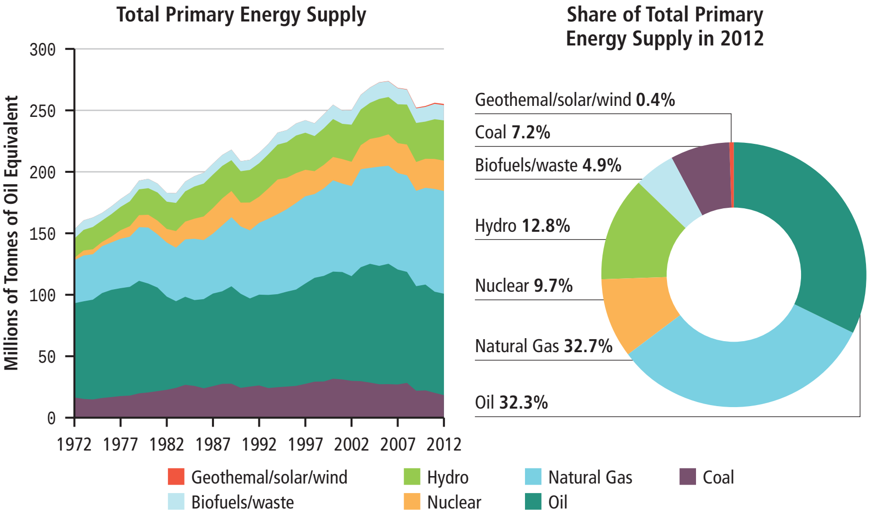
[6] Historically, one of the drivers of electricity exports was also the fact that Canada experienced peak electricity demand in the winter, while the U.S. demand peaked in the summer, leading to favourable conditions for trade. This may be less true in the future, however, if more Canadian regions experience peak demand in the summer due to increased demand for air conditioning (Goodman, 2010).



Total Primary Energy Supply

Share of Total Primary Energy Supply in 2012

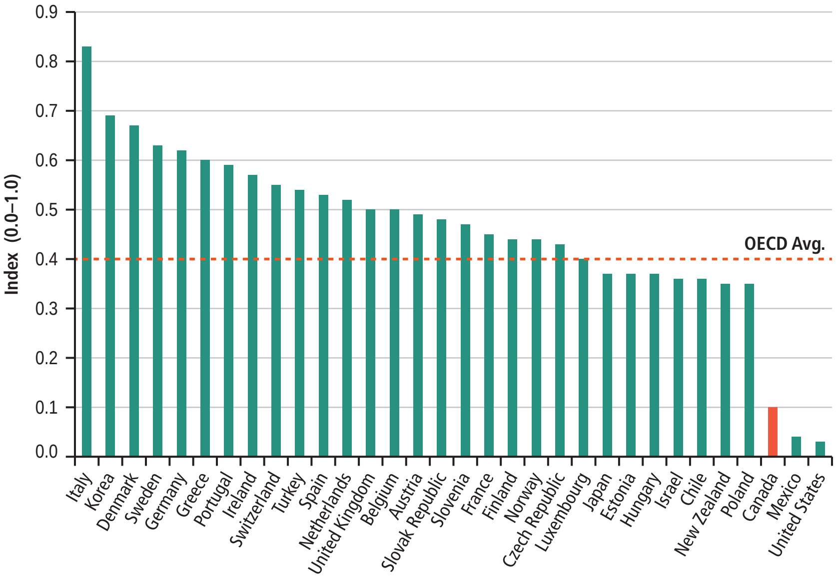
Based on IEA (2014b) data from the IEA Energy Statistics Service © OECD/IEA 2014, IEA Publishing; modified by Council of Canadian Academies. Licence: http://www.iea.org/t&c/termsandconditions/

Figure 2.4

Total Primary Energy Supply in Canada by Source, 1972–2012

Like most countries, Canada has long relied on fossil fuels to meet most of its energy needs. Significant changes in Canada's energy mix during this period include the gradually increasing reliance on natural gas and the introduction of nuclear power throughout the 1970s and 1980s. Renewable energy sources such as solar, wind, and geothermal still provide only a small fraction of Canada's energy supply. Total primary energy supply is calculated as domestic production plus imports minus exports, and excludes electricity trade. Peat and oil shale are aggregated with coal where relevant. Units are millions of tonnes of oil equivalent (Mtoe). 1 Mtoe is equal to 42 petajoules (PJ). For presentational purposes, shares of under 0.1% are not included and consequently the total may not add up to 100%.

Canada has relatively high levels of energy consumption on a per capita basis. Canada currently has the highest energy use per capita of all OECD countries aside from Luxembourg and Iceland (The World Bank, 2015). Relatively high per capita incomes coupled with abundant energy resources and low energy prices are a significant factor driving higher levels of energy consumption. Canada's electricity, natural gas, and gasoline prices are among the lowest of all OECD countries (see Figure 2.5). Price differentials are particularly large in the residential sector, where households in European countries such as Denmark and Germany face electricity prices that are more than triple the average residential electricity rates in Canada (IEA, 2014a).



Data Source: Panel calculations based on IEA, 2013, 2014a

Figure 2.5

Energy Prices in OECD Countries (Index), 2013

Canada, along with the United States and Mexico, has some of the lowest energy prices in OECD countries. The figure shows an energy price index based on prices for diesel fuel, unleaded gasoline, natural gas for industry, natural gas for households, electricity for industry, and electricity for households. Data are based on prices for 2013, with the exception of Canadian electricity price data, which are based on prices from 2012.

Other factors, however, also influence Canada's demand for energy. A variable climate requires substantial energy consumption for space heating and air conditioning. Canada's industrial structure, with a large share of resource industries (e.g., oil and gas, mining, and agriculture and forestry) is comparatively energy-intensive. Transportation energy needs reflect Canada's extensive landmass. Policy choices by successive federal and provincial governments (such as climate policies, federal fuel economy standards, and provincial building codes) have also shaped trends in energy use in Canada over time.

Energy Demand Growth in Canada

Projections of future growth in energy demand are subject to large uncertainties and so should be used with caution. Changes in technologies, public policy, economic conditions, social and cultural norms, and global markets for energy commodities can all have large and unforeseen impacts on future energy demand. Forecasts for Canada may also be sensitive to how future economic conditions and climate policies affect industrial growth, particularly with respect to energy-intensive export industries such as the oil sands. However, current projections suggest that overall energy demand in Canada will continue to increase in the coming years. Both the NEB and the United States Energy Information Administration expect overall demand for energy in Canada to grow at a rate of 1 to 1.1% per year, which is roughly double the projected average for OECD countries (EIA, 2013; NEB, 2013).

Economic growth and population growth are fundamental drivers of energy demand. Projections of future demand in Canada are based on the assumption that the economy will continue to grow at around 2% per year (NEB, 2013). In recent years Canada's economic growth has exceeded that of other G7 countries (The World Bank, 2015), contributing to Canada's comparatively high rate of growth in energy consumption. Changes in the structure of Canada's economy are also affecting energy demand over time — though opposing trends are partially counteracting each other, as expanding activity in the energy-intensive oil and gas industry has been offset by declining output in energy-intensive manufacturing industries. As a result, changes in Canada's economic structure have exerted modest downward pressure on overall energy consumption (NRCan, 2013). Canada also has relatively high population growth compared to most developed countries, reflecting high levels of immigration. At the same time, Canada's population is aging, and the proportion of the population that is working age is expected to decline in the coming decades, which will moderate economic growth and growth in energy demand in the future (NEB, 2013).

2.3 CANADA'S ENERGY-RELATED GREENHOUSE GAS EMISSIONS

Canada's greenhouse gas emissions have increased substantially since 1990, despite governments adopting a series of successive emission reduction targets and climate policies. In 2013, Canada's total greenhouse gas emissions (excluding land-use change) were 18% above 1990 levels (Environment Canada, 2015c). Canada has missed emission reduction targets agreed to at the 1988 G7 meeting, the 1988 World Conference on the Changing Atmosphere, the 1992 Earth Summit, and in the Kyoto Protocol (Rivers & Jaccard, 2009). Recent analysis suggests that this trend will continue, as Canada is unlikely to achieve its current target under the Copenhagen Accord, which is 17% below 2005 levels in 2020 (Environment Canada, 2013c; CESD-OAG, 2014).

Carbon dioxide emissions associated with fuel combustion account for a majority of Canada's total greenhouse gas emissions, and they have risen steadily in parallel with increasing energy demand (NRCan, 2013; Environment Canada, 2015c). Growth in energy-related emissions reflects multiple underlying drivers, including population increase, economic growth, the energy intensity of the economy, and the emissions intensity of energy use (Kaya, 1990). All these factors affect emissions, though some are more amenable to policy. Governments are typically averse to manipulating population growth, per capita incomes, and the structure of the economy for the purposes of mitigating emissions (Rivers & Jaccard, 2009). Most policy attention is therefore focused on the energy intensity of the economy and the emission intensity of energy use.

Figure 2.6 shows long-term energy and emission intensity trends in Canada. There has been a substantial reduction in the energy needed to produce a dollar of gross domestic product (GDP) since 1970, reflecting energy efficiency improvements and changes in the structure of the economy (such as shrinking energy-intensive industries and a growing service sector). An analysis conducted by NRCan (2013) found that energy efficiency improvements were responsible for cutting the growth of energy use in half between 1990 and 2010, and that these savings were of a much greater scale than savings from changes in the structure of the economy. During that same period, the amount of emissions per unit of energy declined modestly, reflecting changes in the mix of energy sources away from fossil fuels toward less-emitting sources. As a result of these trends, the overall emission intensity of the Canadian economy is now roughly half of what it was in 1970. However, both total energy use and carbon dioxide emissions in Canada consistently increased over that same period, because growing energy demand and continued reliance on relatively high-emission energy sources more than offset any reductions. Moderating energy-related emission growth will likely remain a challenge due to comparatively high rates of population growth and economic growth (Rivers & Jaccard, 2009).

Trends in Canada's energy use and emissions are not uniform across the economy. Energy use and emissions can be divided into four general sectors: electricity, transportation, buildings (which encompasses residential, commercial, and institutional energy use), and industry. Figure 2.7 shows the total Canadian energy demand in the three energy end-use sectors (transportation, buildings, and industry) for 1990 and 2012, while Figure 2.8 shows energy-related greenhouse gas emissions for all four sectors for the same period.[7]

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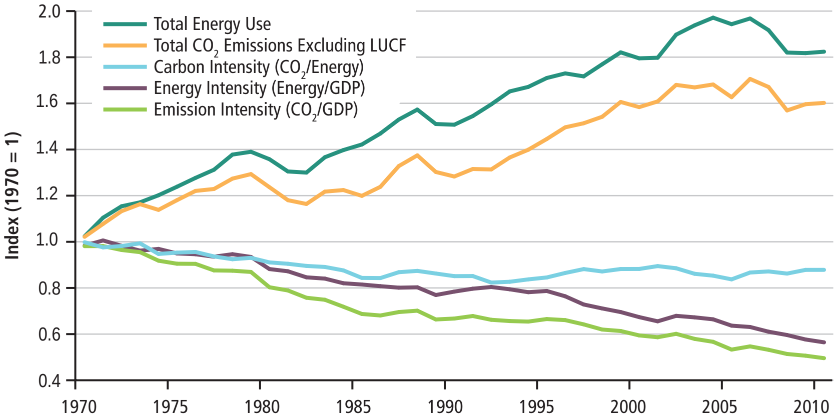
[7] Data for these figures is drawn from Natural Resources Canada's *National Energy Use Database* (NEUD), which provides a consistent set of energy and emissions data across the end-use sectors. NEUD data captures emissions from energy-related combustion but does not include other sources such as fugitive emissions or industrial process emissions. As such, it differs from the official emissions data provided in Environment Canada's *National Inventory Report* (NIR). Differences in the attribution of emissions between sectors create further discrepancies (NRCan, 2014c). Readers looking for the latest official emissions data for Canada should consult Environment Canada (2015c).

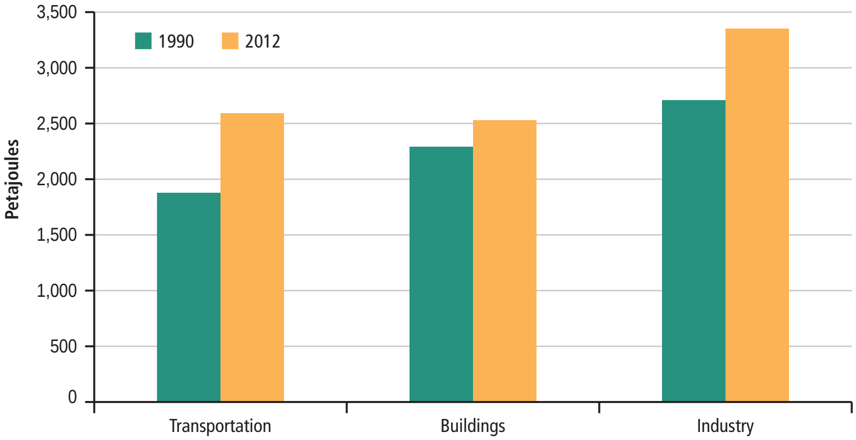


Data Source: WRI, 2014

Figure 2.6

Canadian Energy and Emission Trends, 1970–2011

Over the past four decades, the amount of energy required to produce a dollar of economic output has fallen steadily, as have carbon dioxide emissions per unit of energy and, consequently, per dollar. At the same time, total energy use and total emissions continue to rise as economic growth outpaces efficiency gains. *LUCF* refers to land-use change and forestry.

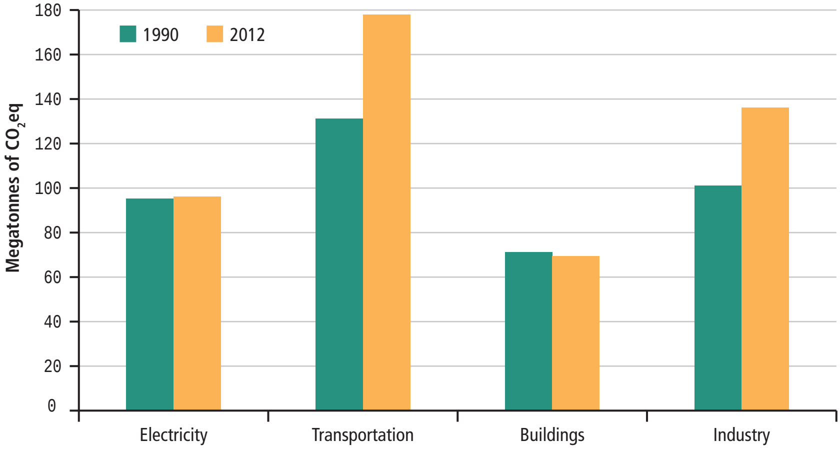


Data Source: NRCan, 2014h

Figure 2.7

Final Energy Use by Sector in Canada, 1990 and 2012

Energy use in Canada can be roughly divided into three nearly equal sectors: transportation, buildings (i.e., residential, commercial, and institutional), and industry. Growth in energy demand has been higher in the transportation and industrial sectors.



Data Source: NRCan, 2014h

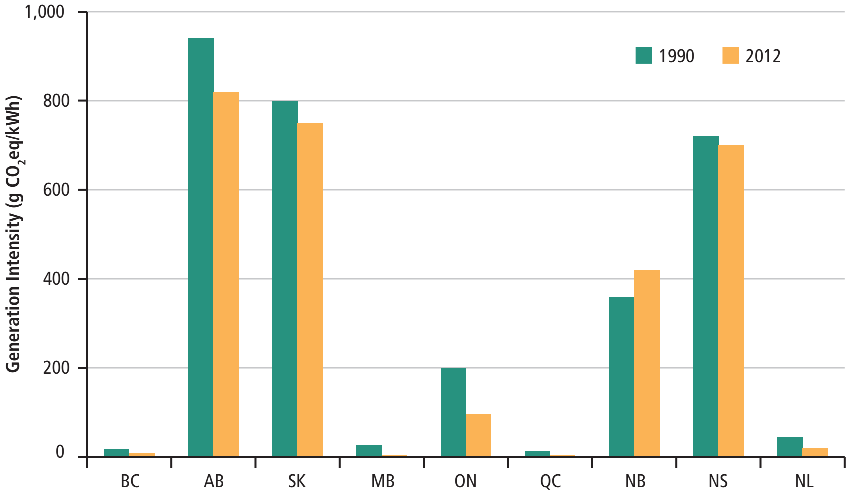
Figure 2.8

Energy-Related Greenhouse Gas Emissions by Sector, 1990 and 2012

Energy-related greenhouse gas emissions have increased in transportation and industry since 1990. However, emissions due to energy use in the buildings sector declined over the same period.

2.3.1 Electricity

Greenhouse gas emissions for electricity generation peaked in 2003 in Canada and have been declining slowly since then, due to large decreases in reliance on coal and oil (Environment Canada, 2015c). Electricity grids in British Columbia, Manitoba, and Quebec are almost entirely dependent on hydropower. Prince Edward Island now relies heavily on wind power along with electricity imports. Ontario's electricity sector has become much less emission intensive due to the provincial government's decision to shut down its coal-fired power plants. As a result, emissions associated with electricity generation are at approximately the same level as they were in 1990 and are increasingly concentrated in four provinces: Alberta, Saskatchewan, New Brunswick, and Nova Scotia (Figure 2.9).



Data Source: Environment Canada, 2014

Figure 2.9

Greenhouse Gas Intensity of Electricity Generation by Province, 1990 and 2012

Most Canadian provinces generate their electricity from low-emission sources. Only Alberta, Saskatchewan, New Brunswick, and Nova Scotia still rely on coal for significant shares of their electricity. Ontario's emissions from electricity generation have declined steadily in recent years due to the closure of coal-fired power plants, and more recent figures would show additional declines, as the last plant was closed in 2014. The emissions intensity for PEI is not shown as the province imports most of its electricity from New Brunswick.

2.3.2 Transportation

Transportation is the fastest-growing source of energy consumption and greenhouse gas emissions in Canada. Transportation energy consumption includes road, aviation, rail, and marine modes of transportation, and virtually all current transportation systems rely on fossil fuels for energy.

Growth in transportation-related energy consumption and emissions in Canada reflects several trends. Energy demand for freight transportation by road, in particular, has grown rapidly in recent years, with most of that demand stemming from increased use of heavy-duty trucks (NRCan, 2013). Demand for diesel fuel increased 73% in Canada between 1990 and 2010; freight transportation emissions increased by 77% over the same period. One of the main drivers of this increased reliance on trucking is the adoption of just-in-time delivery and stocking schemes by many businesses (NRCan, 2013). Energy efficiency improvements in freight transportation, however, have partially offset these increases (NRCan, 2013).

Energy use and emissions for passenger transportation have also grown, though less rapidly, and reflect a variety of underlying trends. In general, for light-duty vehicles (LDVs; the dominant mode of passenger transportation), large increases in transportation demand (reflected by an increase in the total passenger kilometres travelled), have been partially offset by increasing vehicle efficiency. However, more Canadians are also driving larger vehicles. In 2010, light trucks composed 46% of new vehicles sold, compared to 26% in 1990 (NRCan, 2013). Canadians are also travelling by air more (NRCan, 2013). The net effect has been continued growth in energy consumption and emissions. Passenger transportation emissions increased by 9% between 1990 and 2010 (NRCan, 2014h).

2.3.3 Buildings

Building energy use is driven by applications such as space and water heating, air conditioning, lighting, refrigeration and cooking, and devices such as computers, televisions, and appliances. The mix of energy sources in this sector varies by end use and by region, depending on local resource availability. Electricity is a source of energy for many applications, but natural gas is the main fuel used for space and water heating (which account for most energy use in buildings). Building emissions showed little change between 1990 and 2010 due to counterbalancing trends. Population growth, increased floor space from larger house sizes, smaller households, increased use of air conditioning, and increased uptake of computers, photocopiers, and other equipment all contributed to upward pressure on energy and emissions. However, improvements in energy efficiency (such as increased uptake of high-efficiency gas furnaces) and changes in fuel mix (such as reduced use of coal and heating oil as fuels) resulted in downward pressure on energy consumption and emissions (Environment Canada, 2015c). The net result was a modest increase in energy consumption but a slight decline in emissions from residential buildings (NRCan, 2013).

2.3.4 Industry

Industry energy use is dominated by energy-intensive industries such as iron and steel, aluminum, cement, chemicals and fertilizers, pulp and paper, mining and quarrying, and oil and gas extraction, which together account for 80% of industrial energy demand (NEB, 2013). In industry, energy is used primarily to produce heat and steam, or as a source of motive power. Energy sources for industry vary. Natural gas is the main fuel, but others include electricity, biomass, and other fossil fuels such as still gas and petroleum coke.

Industry energy consumption and emissions both grew by approximately 20% between 1990 and 2010 (NRCan, 2013). But trends in industrial energy use and emissions vary by industry. Some industries, such as coal mining, upstream oil and gas (which includes oil sands production), and smelting and refining saw substantial increases in energy use due to expanding production, while others, such as the pulp and paper industry, the wood products industry, and other manufacturing industries, saw declines (NRCan, 2013). Large improvements in energy efficiency across most industries have also moderated energy demand and emission growth over time (NRCan, 2013).

Emission trends in industry, however, have been heavily impacted by increasing oil sands development (Environment Canada, 2015c). Bitumen from oil sands is extracted either through surface mining or in situ production, which involves injecting steam into subsurface deposits, and the heavy oil that is extracted this way must be either upgraded or diluted with light hydrocarbons for transportation. Production of bitumen from oil sands is energy and emission intensive. Upstream emissions per barrel of crude oil produced from Alberta's oil sands are about the same as other global heavy crude oils, but are significantly higher than for conventional crudes (Gordon *et al.*, 2015) — though emissions vary depending on the quality of the reservoir. Greater reliance on in situ extraction in the future will likely increase both absolute emissions and emissions per barrel of oil extracted.

The expansion of oil production in Canada has led to both growing demand for energy and growing emissions associated with the extraction, processing, and transportation of this resource. While the oil sands account for 9% of total greenhouse gas emissions in Canada, they accounted for 42% of the total growth in Canada's emissions between 1990 and 2013 (Environment Canada, 2015c). No other industry had comparable emission increases, and emissions in most of Canada's industries declined over the same period (NRCan, 2014h). The impact of oil sands development is also evident in the regional distribution of emissions across Canada: emission growth has been concentrated in Saskatchewan and Alberta. In contrast, emissions have declined in Quebec and Ontario since 1990, increased slightly in British Columbia, and been relatively stable in the Atlantic provinces (Environment Canada, 2015c). The extraction and processing of oil from the oil sands have had a large role in overall emission growth, so energy and technology choices in this sector will play an important part in whether Canada achieves deep national emission reductions (see Section 3.4 for more discussion).

2.4 ENERGY SYSTEM TRANSITIONS

Energy system transitions typically require many decades due to the involvement of long-lived capital such as buildings, equipment and machinery, and public infrastructure, and because once people become used to certain technologies and behaviours, it is often hard for them to change course (Grubler, 2012; Bruckner *et al.*, 2014). The average lifetime of a fossil fuel power plant, for example, is between 30 and 40 years (Davis *et al.*, 2010). Power plants and other capital stock can be retired before the end of their economic life, though this increases the costs of emission abatement. Not all energy-related capital, however, is long-lived, and turnover rates vary widely (Jaccard & Rivers, 2007). Many changes in fuel sources can be achieved within a few decades, as this is all the time needed for transforming industrial boilers, building heating systems, and vehicle propulsion systems. Likewise, some retrofits can occur quickly and with profound impacts on emissions. As shown by the Boundary Dam power plant in Saskatchewan, an individual coal-fired power plant can be retrofitted with CCS technology within a span of 5 to 10 years. Relatively rapid transitions to low-emission energy sources are achievable with sufficiently aggressive government policies, though the pace and cost of emission reductions will vary depending on the sector, region, context, technologies, and capital stocks involved.

In the past, two notably rapid energy system transitions were precipitated by a combination of energy price shocks and government policies. The oil shocks of the 1970s prompted dramatic energy system changes in France, where electricity generation was at the time largely dependent on imported petroleum (PBS, 1997). Faced with sharply increased oil prices and minimal domestic energy resources, the government at the time aggressively pursued nuclear energy. Over the next 15 years, France built 56 nuclear reactors, and nuclear power rapidly became the country's dominant source of electricity (PBS, 1997; IEA, 2014b). The oil crisis also launched a major energy transition in Brazil. In response to increased oil prices and decreased sugar prices, the government aggressively supported the development of sugar cane ethanol as an alternative transportation fuel. Encouraged by policies such as mandated ethanol/gasoline blends and supports for auto manufacturers, ethanol production quintupled between 1975 and 1979 (Meyer, 2012). In 1979, the first automobile was introduced in Brazil that could run on pure ethanol, and by 1985 virtually all new vehicles sold in Brazil ran on pure ethanol (Furtado *et al.*, 2011; Meyer, 2012). Currently, most sales of new vehicles in Brazil are for flex-fuel vehicles, allowing consumers to operate on either gasoline or ethanol depending on market conditions (Meyer, 2012).

In the Canadian context, Ontario's closure of its coal-fired power plants is an example of a rapid change that resulted in a major reduction in emissions. In 2003, Ontario generated roughly a quarter of its electricity from coal-fired power plants; however, that year the provincial government committed to phasing out these plants — which was accomplished in 2014 with the closure of the Thunder Bay Generating Station. To replace the lost generation capacity, new natural gas plants were constructed (natural gas releases roughly half of the carbon dioxide emissions of a coal-fired power plant per unit of energy produced), and the provincial government's 2009 *Green Energy Act* also accelerated the development of wind power and other renewables throughout the province. Carbon dioxide emissions from electricity generation declined as a result, by roughly 85% over the course of 10 years, and are projected to remain low (Figure 2.10). Residential electricity rates increased 2.86% per year in real terms between 2000 and 2010, partially reflecting the increased cost of adding new generation capacity. However, price increases also reflect transmission and distribution system investments and are consistent with long-term trends in Ontario as the province continues to expand beyond its low-cost legacy generation sources such as hydropower (Dewees, 2012).

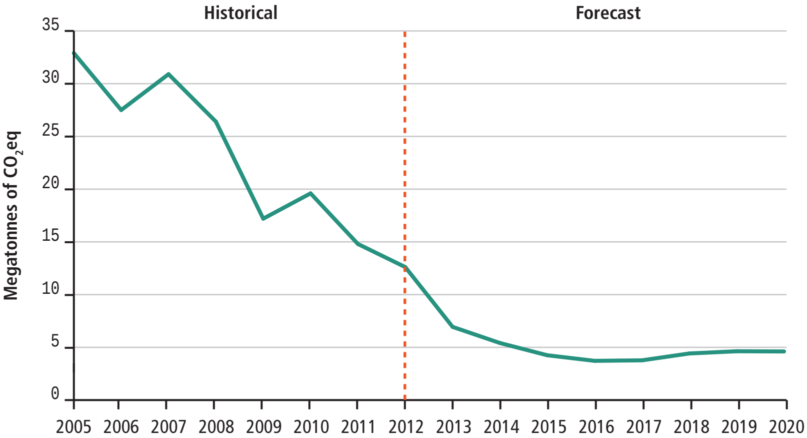


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Figure 2.10

Ontario Historical and Forecast Electricity Emissions

The decision by the Ontario government to close all coal-fired power plants in the province initiated a sharp decline in electricity-related emissions over the course of a decade.

Past energy transitions offer other lessons relevant to reducing emissions. Historical transitions most often occurred in response to technological and institutional changes relating to energy end use and demand (Grubler, 2012). Technological developments that enabled entirely new or greatly improved energy services (e.g., electric lighting over candles, automotive transportation over human- or animal-powered transportation) triggered changes in energy consumption and in energy supply systems (e.g., the development of electricity grids and power plants, the development of oil production and refining industries). Because new technologies may initially be more costly and less versatile than conventional alternatives and relegated to niche markets (Grubler, 2012), sustained transitions typically occur only when a new technology becomes less expensive than the incumbent technology (Fouquet, 2010; Fouquet & Pearson, 2012). One implication for mitigating emissions is that technologies offering tangible benefits to end-users are more likely to trigger energy transitions than supply-side technologies with no perceptible benefits for end-users (Grubler, 2012). History also indicates that regions and economies are prone to skipping energy transitions due to lock-in-related effects. In Europe, those countries slowest to adopt coal as a leading energy source in the 19th century moved more rapidly toward the adoption of electricity, oil, and gas in the 20th century (Grubler, 2012). Developing countries today may similarly be able to more rapidly adopt low-emission energy sources and technologies, as the role of fossil fuels in their energy systems is less entrenched.

For governments looking to promote energy system transitions, Grubler (2012) argues that three factors are especially critical for effective policy: persistence, alignment, and balance. Policies must be persistent due to the often decades-long nature of energy system transitions. Ambitious but erratic stop-and-go policies are unlikely to successfully foster a sustained transition over the long term — a fact particularly important in urban energy systems due to the long periods needed to change the built environment (see Box 2.3). Delays in adopting mitigation policy, however, increase the costs of emission reduction by encouraging continued investment in emission intensive infrastructure. Policy alignment is required due to the large number of sectors, institutions, technologies, and stakeholders involved in the energy system. The frequent co-existence of subsidies for both fossil fuel industries and emerging renewable energy technologies is a prime example of a policy alignment failure. Finally, balance is necessary due to the inherent technological uncertainty and associated risks that often feature in energy system transitions. No single low-emission energy source or technology will result in reductions across all contexts, and the relative difficulty of reducing emissions depends on the number and cost of alternative technologies. In the face of such uncertainties, prudent governments often need to support a diverse portfolio of technologies and transition strategies.

Box 2.3
Energy Transitions and Urban Planning

Most of the world's population now lives in urban areas, and that share is growing rapidly as populations in developing countries migrate from rural areas to larger cities (Grubler *et al.*, 2012b). As a result, cities account for an increasingly large amount of energy consumption; experts estimate that between 60 and 80% of all energy use occurs in cities. Many aspects of the configuration of cities, including transportation systems, zoning policies, urban planning, municipal services, housing stock, building codes, and community densities, all have implications for urban energy use and energy supply systems. Recognizing the spatial and social relationships between these dimensions can facilitate transitions to more efficient — and potentially more resilient — energy systems.

Urban planning that promotes relatively dense communities co-located with key services can improve energy efficiency on a macro scale and reduce transportation-related energy demands. The concentration of services required in cities yields economies of scale and makes new energy technologies viable. District heating systems, for example, depend on shared demand for an energy service (heat) within a limited area. Cities also cluster waste, which can increase the viability of energy-from-waste technologies such as harvesting biogas from municipal wastewater. More effective public transportation systems can reduce air pollution and associated health impacts, as well as traffic congestion, thereby improving the productivity and quality of life of urban residents. Improving the efficiency of urban water and wastewater systems can result in significant energy savings. Finally, cities can sometimes use distributed electricity generation systems, potentially improving the resilience of local electricity grids and reducing losses associated with the transmission system. See Grubler *et al.* (2012b) for a review of urban energy systems.

2.5 SUMMARY

Energy systems in industrialized societies are composed from a wide range of resources, processes, and technologies that convert energy from primary sources into useful services such as light, motion, and heat. Large amounts of energy are lost during these conversions, and improving efficiency throughout the entire energy system can moderate growing energy demand and reduce emissions associated with meeting that demand.

Canada's energy system is similar to those of other industrialized economies in that it relies on fossil fuels to meet most of its energy needs, and it releases large amounts of carbon dioxide into the atmosphere when these fuels are combusted. In Canada, fossil fuels play a dominant role in providing energy for transportation systems (through refined petroleum products such as gasoline and diesel), space heating (through natural gas furnaces), and heat and power for some industrial processes. Canada, however, benefits from a comparatively low-emission electricity system that is highly reliant on hydropower and, in the case of Ontario, nuclear power.

Canada has relatively high rates of energy consumption per capita, which reflects the relative wealth of Canadians, comparatively low energy prices, and other factors such as a variable climate, a large land mass, and a resource-based economy with significant exports. Robust economic and population growth and expanding oil sands production have driven emission increases in Canada in recent decades, contributing to the failure to meet a succession of national emission reduction targets. Energy-related emissions in Canada are projected to continue to rise due to these drivers in the absence of widespread adoption of low-emission energy technologies and more stringent greenhouse gas mitigation policies.

3

Toward a Low-Emission Energy System: Energy and Technology Options

- Electricity
- Transportation
- Buildings
- Industry
- Summary

3 Toward a Low-Emission Energy System: Energy and Technology Options

Key Findings

- Low-emission electricity is the foundation for economy-wide emission reductions in transportation, buildings, and industry. While Canada already benefits from relatively low-emission power generation, remaining high-emission generation facilities will need to be replaced, and all provinces will need to expand low-emission electricity generation capacity to meet growing demand and enable further reductions.
- In Canada, particularly promising options for reducing transportation emissions include ongoing efficiency gains for all vehicles; increasing reliance on low-emission electricity for passenger transportation; expanding use of biofuels in freight transportation; and long-term urban planning and transportation infrastructure investments.
- Improved building design can reduce heating and cooling energy demand by 60 to 90% over conventional construction, and can facilitate a transition to low-emission electricity for space heating. Such buildings feature passive solar design; enhanced use of insulation; and air-, ground-, and water-source heat pumps.
- In industry, improved equipment maintenance, industrial integration, and reduced use of energy for material processing can all contribute to reductions in emissions. Electricity, biomass, and fossil fuels with CCS can all be used as low-emission energy sources, depending on the industrial context.

Canada's energy system remains dependent on emission intensive energy sources; however, low-emission technologies are now available in all major sectors and for most energy-using applications. As a result, the possibility of reducing emissions in most domains is increasingly real. There are three main strategies to reduce emissions:

- *Energy efficiency* improvements can lower emissions by reducing demand for energy and the amount of fossil fuels used to provide it. This can be accomplished in several ways. Technological efficiency can be improved, energy conservation can be encouraged, and energy systems can be better integrated. Efficiency gains can also be realized through changes in how services are provided, such as by shifting from cars to mass transit.
- *Carbon Capture and Storage* (CCS) technologies allow the use of fossil fuels as a low-emission energy source by capturing carbon dioxide emissions, then transporting and storing them in a suitable geological repository such as a deep saline aquifer or an existing oil field. The application of CCS is particularly suited to large, stationary sources of emissions such as power plants, oil sands upgrading facilities, fertilizer plants, and petrochemical and cement manufacturing plants.

- *Energy substitution* involves switching from fossil fuel sources to renewable and other low-emitting energy sources. Energy substitution can result in emission reductions at multiple points in the energy supply chain. For example, switching from fossil fuel-fired power plants to renewable technologies lowers emissions directly during power generation, whereas in transportation, switching to biofuels or electricity can enable emission reductions at the point of use.

This chapter reviews the energy sources and technologies most likely to be involved in implementing these strategies in four sectors: electricity, transportation, buildings, and industry. It also identifies the energy technologies viewed by the Panel as most promising in the Canadian context, describes systemic considerations that affect the prospects for these technologies, and identifies modifications to energy infrastructure and systems that could facilitate wider adoption of low-emission energy sources and technologies in the future.

3.1 ELECTRICITY

Key Findings

- About 80% of the Canadian population lives in jurisdictions already benefiting from low-emission electricity systems. Future emission reductions will require a transition to low-emission generation in all provinces.
- Efficiency improvements in fossil fuel-fired power plants and electricity transmission and distribution systems can reduce emission intensity but are unlikely to provide large reductions in emissions.
- CCS technologies, now being tested on a commercial scale in Canada, could play an important role in achieving emission reductions. Widely scaling up CCS would require addressing barriers related to high capital costs, reduced plant efficiencies, and the need for supporting distribution and storage infrastructure.
- The switch to low-emission electricity sources must be informed by impacts on electricity costs and system reliability. In the absence of emission mitigation policy, low-emission technologies generally remain more costly than fossil fuel generation options in most contexts. However, gradually transitioning to a portfolio of low-emission technologies over several decades would not impose a major burden on most consumers or businesses.
- System management challenges associated with integrating higher shares of electricity generation from intermittent sources mean that integrated planning will be needed, focused on developing a flexible mix of energy sources and additional energy storage capacity for the grid. Investments in electricity transmission and distribution systems — including transmission lines, interconnections, and grid modernization — can also enhance grid flexibility and enable greater reliance on low-emission generation technologies. Experience points to the importance of community engagement in energy planning and development.

Developing low-emission electricity systems is critical for facilitating widespread emission reductions for two reasons. First, where electricity grids depend on fossil fuels and conventional thermal power plants for energy, power generation represents a large share of total emissions. For example, in Alberta and Saskatchewan, electricity generation accounts for approximately 18 and 21%, respectively, of greenhouse gas emissions in those provinces (Environment Canada, 2015c). Second, availability of low-emission electricity enables emission reductions in other sectors by allowing them to switch from fossil fuels to electricity as an energy source (such as by switching from a gasoline-powered vehicle to an electric one). Models exploring deep emission reduction scenarios, for example, often find that electrification of energy use across all sectors is instrumental in achieving system-wide reductions (J&C Nyboer and Associates Inc., 2008; Bataille *et al.*, 2014; IPCC, 2014b; Sachs *et al.*, 2014).

Nationally, Canada's electricity generation is already dominated by low-emission sources. Due to abundant hydropower, nuclear power in Ontario, and provincial electricity policies, approximately 80% of the Canadian population lives in jurisdictions that already benefit from relatively low-emission electricity systems (Statistics Canada, 2014; Environment Canada, 2015c).[8] As noted in Chapter 2, however, energy sources for electricity generation vary by region. For Canada, the challenge will be to transition to low-emission electricity systems in provinces that still depend on emission intensive sources and to expand low-emission generation in all provinces to meet growing demand. This section reviews energy sources and technologies that can be used to develop low-emission electricity systems, focusing on efficiency gains, CCS technologies, and alternative low-emission energy sources. It also explores systemic considerations and challenges associated with increasing the penetration of low-emission electricity generation technologies in existing electricity systems.

3.1.1 Improving Electricity System Efficiency

Changes in the technologies used in electricity generation, transmission, and distribution can reduce energy losses and carbon dioxide emissions.[9]

In electricity generation, newer fossil fuel-fired power plants offer improved conversion efficiencies over conventional plants. The efficiency of a sub-critical conventional pulverized coal (PC) power plant is around 38% (i.e., 62% of the

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[8] This calculation is based on the population of all provinces aside from Nova Scotia, New Brunswick, Saskatchewan, and Alberta. Ontario's inclusion as a low-emission jurisdiction is justified, in the Panel's view, by the closure of the province's coal-fired power plants and the banning of future coal plants.

[9] Efficiency gains from reducing final demand for electricity and adopting cogeneration technologies are discussed in Sections 3.3 and 3.4.

energy in the coal is lost during combustion as waste heat) (Larson *et al.*, 2012). Advanced coal power plants use steam at higher pressures and temperatures to achieve greater efficiencies. Supercritical and ultra-supercritical plants, for example, can achieve efficiencies of 40 to 42% and 42 to 45%, respectively (Larson *et al.*, 2012). Coal can also be gasified and combusted in integrated gasification combined cycle (IGCC) plants, which achieve efficiencies between 38 and 41% (Larson *et al.*, 2012). Efficiency tends to decline over a plant's lifetime, but a number of improvements can be made to existing PC plants to enhance their efficiency as they age (Campbell, 2013). For gas-fired power plants, combined-cycle gas turbines are significantly more efficient than simple gas turbines. By combining a steam heat-recovery cycle with a gas turbine, combined-cycle plants can reach efficiencies up to 55% (Larson *et al.*, 2012).

Improvements in transmission and distribution technologies can also reduce electricity system losses. In OECD countries, around 6.5% of total electricity generated is lost to transmission and distribution combined (IEA, 2003a; Bruckner *et al.*, 2014). Technologies that reduce these losses include high-efficiency transformers, high-voltage direct current transmission lines, and, in the future, the potential wide-scale use of superconductors in transformers and transmission lines (IEC, 2007; Bruckner *et al.*, 2014). Grid configuration can also have implications for efficiency. Congestion losses result when electricity is transmitted from power plants to consumers. Reducing the distance electricity travels from the point of generation to the point of consumption can improve efficiency, and these reductions could be facilitated by distributed generation. Alternatively, integrating power generation from sources farther from population centres can increase losses. This can be a challenge for renewable power generation when optimal sites are far from the sources of demand.

The overall potential emission reductions from efficiency gains in electricity generation, transmission, and distribution systems, however, are relatively modest. Increasing the efficiency of fossil fuel-fired power plants leads to emission reductions roughly proportional to the increase in efficiency (i.e., a 2% efficiency gain leads to approximately 2% reduction in emissions) (Linn *et al.*, 2013).[10] Efficiency improvements associated with advanced coal-fired power plants are also largely irrelevant in the Canadian context due to federal regulations that effectively prevent the construction of new plants that

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[10] Minor departures from this equivalence result from differences in the carbon content of various coal types, as well as from plant characteristics such as size, age, firing technology, and the rate of utilization (Linn *et al.*, 2013).

do not incorporate CCS.[11] Potential emission reductions from grid efficiency improvements are also modest and limited to provinces now using fossil fuels for electricity. While more efficient coal and natural gas plants and upgrades to transmission and distribution systems could reduce the emission intensity of electricity generation in Canada over time, these improvements are likely insufficient to offset growing demand for electricity and continued growth in emissions.

3.1.2 Carbon Capture and Storage in Electricity Systems

CCS is often regarded as a relatively mature technology, as all of the components involved have been used for decades — primarily in gas processing and enhanced oil recovery, where carbon dioxide is injected into existing oil wells to increase the amount of oil that can be extracted (Bruckner *et al.*, 2014). A complete CCS system involves four elements:

- capture and compression of carbon dioxide from a large, stationary source;
- transportation of carbon dioxide to a location for long-term geologic storage;
- injection of compressed carbon dioxide into a deep underground geological formation; and
- use of measurement, monitoring, and verification technologies to ensure the safety and permanence of storage (Bruckner *et al.*, 2014).

Systems for all four of these activities have been developed, tested, and deployed in various contexts. While CCS has not yet been widely adopted for emission mitigation in any jurisdiction, the world's first commercial-scale application of CCS in a coal-fired power plant began operations in Saskatchewan in the fall of 2014 (see Box 3.1). CCS is also being explored in Canada as a way to reduce emissions from upgrading bitumen from the oil sands (see Box 3.5).

CCS has sometimes prompted concern about accidental releases of stored carbon dioxide over time and the impacts of such releases on the climate. Studies have calculated, for example, that the leakage rate for CCS projects would need to be less than 1% of stored carbon dioxide per thousand years to be comparable to a low-emission future, as even very small leaks can result in large cumulative releases over long periods of time (Shaffer, 2010). However, assessments suggest the risk of substantial leakage is low and declines once injection has ceased (IPCC, 2005; Benson *et al.*, 2012; Bruckner *et al.*, 2014). In reviewing evidence on the long-term geological stability of CCS, Benson (2012) concludes that "…appropriately selected and managed

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[11] Federal regulations adopted in 2012 require coal-fired plants to meet natural gas emission standards by the end of the useful life of the plant. Unless they are retrofitted with CCS, most coal-fired plants in Canada will retire by 2030, with the two newest supercritical plants closing by 2057 (Government of Canada, 2012).

Box 3.1
The Boundary Dam Carbon Capture Project

In 2014, a CCS facility integrated into the Boundary Dam power plant in Saskatchewan became the world's first operational commercial-scale CCS project for a coal-fired power plant. By retrofitting one of its generation units with post-combustion carbon capture technology, the plant now has the capacity to produce 110 megawatts (MW) of low-emission electricity while capturing approximately one million tonnes of carbon dioxide per year. Carbon dioxide is captured from flue gas after combustion using an amine solvent, and is then compressed and either transported by pipeline to oil fields in southern Saskatchewan for use in enhanced oil recovery, or stored 3.4 kilometres underground in a deep saline aquifer. The retrofit took approximately four years, and the total cost of the project was $1.3 billion, of which $800 million was for the CCS facility, though SaskPower believes that capital costs could be reduced by 20 to 30% on the next unit. The Boundary Dam project builds on the province's earlier experience with CCS at the Weyburn-Midale carbon storage and monitoring project. Between 2000 and 2012, some 22 million tonnes of carbon dioxide from a coal gasification plant in North Dakota were permanently stored and monitored in two depleted oil reservoirs in southeastern Saskatchewan. Both Boundary Dam and Weyburn-Midale demonstrate the feasibility of large-scale CCS using current technologies, and future applications of CCS to coal-fired power plants in Canada and other countries are likely to benefit from lessons learned in these projects.

SaskPower (2014b, 2014a); MITei (2015)

geological storage reservoirs are very likely to retain nearly all the injected CO_2 for very long times, more than long enough to provide benefits for the intended purpose of CCS." The risk of leakage can also be mitigated through long-term monitoring of storage facilities, and equipment for this purpose has been tested in existing sequestration operations, including those in Saskatchewan (Benson *et al.*, 2012).

CCS could play a large role in reducing electricity-system carbon dioxide emissions globally and in Canada. Incorporating current CCS technologies into power plants reduces direct emissions by roughly 85 to 90% depending on the technology employed (Schlömer *et al.*, 2014). Globally, assessments indicate CCS could account for a large share of the emission reductions required to stabilize the climate over the next century, roughly equal to those arising from energy efficiency and energy substitution (IPCC, 2005; Benson *et al.*, 2012).[12] In assessing the potential for a 65% reduction in emissions in Canada by 2050, a study for the National Round Table on the Environment and the Economy found that CCS represented the largest single source of emission reductions and accounted for most of the predicted emission reductions in electricity generation (J&C Nyboer and Associates Inc., 2008; NRTEE, 2009). According to an inventory of carbon sequestration potential in North America, the estimated geological carbon storage capacity across all Canadian provinces and territories is 132 gigatonnes, enough for 600 years of Canadian emissions based on current levels — though the location and accessibility of these opportunities varies by region (NACSA, 2012).

CCS, however, faces substantial barriers to widespread deployment. Incorporating CCS into power plants entails significant cost increases relative to conventional coal and natural gas plants (see Section 3.1.3), driven primarily by additional capital costs and increased energy requirements that can reduce electricity generation output by 15 to 30% (Benson *et al.*, 2012). CCS is more economical in new power plants, and it may not be technically or economically viable to retrofit older power plants with CCS depending on factors such as their age, size, existing flue gas treatment, space for equipment, and access to carbon storage and transportation options (IEA, 2012b). Widespread penetration and scaling up of CCS would require development of supporting infrastructure such as pipelines and other distribution systems as well as injection sites. Regulatory and legal barriers to geological storage may also need to be addressed (Herzog, 2010). Finally, public acceptance of CCS may be a barrier in some contexts, due to concerns over perceived safety and potential environmental impacts (see Section 3.1.4). Due to these challenges, CCS is unlikely to be widely deployed in Canada (or elsewhere) without relatively stringent emission mitigation policies or other types of government support.

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[12] It is also possible to produce electricity with net *negative* carbon emissions using a combination of biomass and CCS. Biomass absorbs atmospheric carbon, which is then captured during combustion and stored geologically. Global integrated assessment models suggest this bioenergy with CCS could be critical to limiting future temperature warming to 2°C or less by allowing atmospheric concentrations of greenhouse gases to be gradually reduced over time (IPCC, 2014b).

3.1.3 Energy Substitution in Electricity Systems

Energy substitution will be critical for eliminating carbon dioxide emissions from electricity systems in the long term. Replacing coal and natural gas-fired power plants with low-emission technologies could eliminate most remaining emissions from electricity generation in Canada while also meeting growing demand for electricity (Bataille *et al.*, 2014).

A range of energy sources and technologies are available for electricity generation. Coal and natural gas play a dominant role in providing energy for electricity in many jurisdictions. Oil is also occasionally used as a fuel for electricity generation — both in oil-fired turbines and in diesel generators, which are commonly used in communities not connected to the grid. Commercially available, low-emission generation options include hydropower (reservoir and run-of-river), nuclear power, biomass, onshore and offshore wind, and solar PV and concentrated solar power systems. Tidal power generation (and other ocean power technologies) rely on the movements of marine tides and currents to power turbines. With the exception of some forms of tidal power, all of the low-emission generation options identified here have been widely deployed and integrated into existing electricity systems in recent years.

All electricity generation options lead to a range of social and environmental impacts. These impacts arise at multiple points in energy supply chains, including resource extraction and processing, infrastructure development, power generation, power transmission and distribution, and electricity grid management and design. The nature and scale of the impacts varies significantly depending on the local context and parameters specific to the site or project. As a result, choices about alternative power generation technologies are context specific. No single generation option is preferable in all situations, and it is not the place of this Panel to prescribe specific electricity generation choices for any Canadian jurisdiction. The emission mitigation benefits associated with alternative power generation technologies, however, need to be weighed against increases in the cost of electricity generation and implications for the flexibility and resilience of electricity systems. Many of the impediments to expanding electricity generation stem from challenges in integrating new generation capacity into existing power transmission and distribution systems.

Carbon dioxide emissions are directly related to the carbon content of the fuel used in power generation. Table 3.1 provides average greenhouse gas emissions per kWh of electricity for selected fossil fuel energy sources and technologies. Coal is the most emission intensive fuel. Natural gas is approximately half as emission intensive, with a modern combined-cycle natural gas plant releasing approximately 50% of the carbon dioxide emissions of a PC plant per kWh of electricity generated. Natural gas plants can therefore play a role as a transitional energy source in moving to low-emission electricity systems, and a complementary role in providing load-following and peaking power for electricity systems with large amounts of intermittent renewables. Non-carbon energy sources for electricity (e.g., hydro, nuclear, geothermal, wind, solar, and tidal) have zero direct greenhouse gas emissions. Power plants running purely on biomass are typically considered to have net-zero direct greenhouse gas emissions, as emissions from fuel combustion are presumed to be offset by carbon dioxide previously absorbed from the atmosphere (Smith *et al.*, 2014b). Co-firing power plants relying on a combination of biomass and coal can achieve emissions equivalent to natural gas plants and are now widely used in Europe (Al-Mansour & Zuwala, 2010).

Table 3.1

Direct Greenhouse Gas Emissions for Selected Electricity-Generation Technologies (gCO_2eq/kWh)

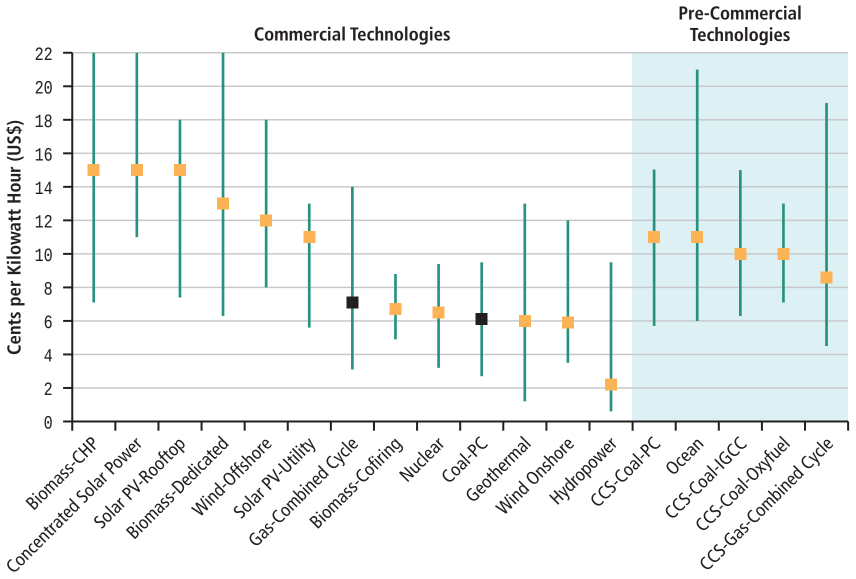
	Median	Min–Max
Coal-PC	760	670–870
Gas-Combined Cycle	370	350–490
CCS-Coal-PC	120	95–140
CCS-Gas-Combined Cycle	57	30–98
Nuclear, Hydro, Wind, Solar, Biomass, and Tidal	0	

Data Source: Schlömer *et al.* (2014)

The table shows direct greenhouse gas emission estimates for selected technologies. *Coal-PC* is a pulverized coal power plant.

Studies have also estimated the indirect or life-cycle emissions of electricity generation technologies, including emissions from supply chains, facility construction, and land-use impacts for biomass. The analysis of indirect greenhouse gas emissions, however, is methodologically challenging and subject to large uncertainties. Indirect emission estimates are also inherently problematic for energy modelling as they combine static analysis (the indirect emissions in the current fossil fuel-dominated system) with dynamic analysis (indirect emissions with the gradual penetration of new technologies across all sectors that have near-zero emissions).

The standard indicator used to compare the costs of power generation technologies is the *levelized cost of electricity* (LCOE). LCOE is an estimate of the cost of electricity produced by a new plant over its expected lifetime, and it factors in capital costs, operation and maintenance costs, financing costs, fuel costs, and facility decommissioning costs. Figure 3.1 shows median LCOE estimates for various energy sources as well as ranges between minimum and maximum estimates. The estimates shown here are illustrative, and are based on global averages from the literature. They may not accurately reflect costs in North America and also do not factor in costs imposed by emission mitigation policies.



Data Source: Schlömer *et al.*, 2014

Figure 3.1

Levelized Cost of Electricity Estimates for Selected Technologies

LCOE estimates the cost of electricity produced by a new plant over its expected lifetime and factors in costs related to capital, operation and maintenance, financing, fuel, and facility decommissioning. Data here are based on an international literature review and reflect global averages (IPCC, 2014b). Data are also based on a 5% weighted average cost of capital and high full load hours (i.e., baseload generation). The costs for some options (e.g., nuclear, hydropower, solar power) may not be accurate for North America due to variation in costs associated with regulation, capital and construction, and resource availability. The lines show the range between the minimum and maximum estimate for each technology, and the square marks the median estimate. The maximum estimates for Biomass-CHP and Biomass-Dedicated are not shown. LCOE estimates for fossil fuel sources (without CCS) are shown in black. *Biomass-CHP* is biomass combined heat and power. *Coal-PC* is pulverized coal. *IGCC* is an integrated gasification and combined cycle plant.

LCOE estimates can provide a general comparison of electricity generation costs for different technologies, but they have several limitations. First, they do not take into account variation in the market price of electricity associated with changes in demand, and so they overestimate the value of intermittent renewable technologies such as wind and solar relative to dispatchable power plants (that is, those that can be quickly cycled on or off and can therefore provide power at peak demand times). This limitation also means that LCOE calculations overestimate the value of wind relative to solar power, which is more likely to be generated during the day when demand for electricity is higher (Joskow, 2011). A more accurate cost comparison accounts for fluctuations in the market value of the electricity produced, or adding storage costs to non-dispatchable electricity. Second, LCOE estimates do not factor in system integration costs such as new transmission or distribution infrastructure or additional costs associated with maintaining the balance between supply and demand in the grid (Bruckner *et al.*, 2014). Third, LCOE estimates do not account for externalities (costs to society that are not captured in market prices) from traditional fossil fuel energy sources, such as health costs associated with air pollution or the costs of climate change. Correcting for externalities with emission pricing policies or other measures makes renewable power generation technologies more cost-competitive with fossil fuels (NRC, 2010; IMF, 2014).

The costs of electricity generation for any technology range widely depending on project-specific factors and the regional context. The lowest-cost power generation option for any situation varies as a result. Large-scale hydropower, larger geothermal projects, onshore wind, and some off-grid PV applications can be cost competitive with fossil fuel options in favourable conditions. However, most low-emission generation options remain more expensive than fossil fuel options, especially when costs of storage for non-dispatchable technologies are factored in (Schlömer *et al.*, 2014).

CCS also increases the cost of electricity generation, though CCS costs may be comparable to those of other low-emission sources depending on the context. For PC plants, incorporating CCS in a new plant results in a cost increase of approximately 80% (from 6.1¢/kWh to 11.0¢/kWh). For combined-cycle natural gas plants with CCS, the estimated cost increase is 21% (from 7.1¢/kWh to 8.6¢/kWh). These costs could decline over time due to continued technological development, particularly developments in carbon capture technologies. CCS costs also depend on the distribution and storage of carbon dioxide; however, these account for a relatively small share of total CCS costs.[13]

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[13] LCOE estimates here assume distribution and storage costs equal to US$10/tonne CO_2. Most studies suggest transportation and storage costs in CCS deployment scenarios are unlikely to exceed US$15/tonne CO_2 (Bruckner *et al.*, 2014).

The allocation of costs across different types of expenditures and plant lifetimes varies, which can affect the commercial prospects of various plant designs. Technologies such as nuclear, geothermal, and large hydropower have high upfront investment costs and comparatively low operating costs (Bruckner *et al.*, 2014; Schlömer *et al.*, 2014). Financing challenges may therefore be more acute for these options. Alternatively, technologies such as concentrated solar power systems and offshore wind turbines tend to have higher operation and maintenance costs relative to initial capital costs. Fuel costs for power plants are also variable. With the exception of biomass, renewables have zero fuel costs. For nuclear power, fuel costs are a relatively small contributor to total costs. Fuel costs for gas-fired power plants are more significant, though the recent increases in natural gas production in North America and lower gas prices have contributed to a gradual shift away from coal-fired power plants.

These costs are also not static. The costs of some electricity generation options are rapidly changing in response to technological development and changes in market conditions. For example, the cost of crystalline silicon PV systems fell by 57% between 2009 and 2013 (Bruckner *et al.*, 2014). The LCOEs of onshore wind, landfill gas, municipal solid waste, and biomass gasification systems also declined between 15 and 26% in this period (Bruckner *et al.*, 2014). Expected future trends vary depending on the technological maturity of the option in question. Technological developments in solar and wind technologies are expected to result in ongoing cost reductions. Hydropower, in comparison, is a relatively mature technology, and costs are not expected to change significantly, though there is relatively little information available about how hydropower costs have been evolving over time (Kumar *et al.*, 2011). Additional technological development will likely continue to lower the costs of low-emission generation options (including CCS); however, these trends coincide with declining prices for fossil fuels as well, due to technological developments (such as new technologies for extraction of unconventional oil and gas) and reduced demand driven by climate policies (Sinn, 2008).

In Canada, a transition to low-emission electricity sources is likely to increase costs for consumers, though these increases are likely to occur over several decades as individual power plants are gradually retired and replaced. Natural gas increasingly represents the default option for new generation facilities in North America, and the levelized cost of low-emission options ranges from considerably below that of a combined-cycle natural gas plant, in the case of hydropower and onshore wind, to 50 to 70% higher in the case of utility-scale solar PV and offshore wind. Canadians can voluntarily pay a private company a premium of 2.5 cents per kWh to ensure that an amount of low-emission electricity equivalent to what they consume is fed into the grid, though this premium does not necessarily factor in additional costs associated with electricity transmission and distribution systems and increased reliance on intermittent energy sources.[14] Given the relatively low electricity prices in Canada in most jurisdictions, the increased cost of electricity from low-emission energy sources is not likely to pose a major burden for most consumers and businesses.

3.1.4 Systemic Considerations for Electricity

Electricity systems are large, complex, and capital intensive. While emission reductions can be achieved by changes in technologies and energy sources at the level of individual power plants, systemic factors relating to how these systems are managed can significantly impede or enable emission reductions. The Panel identified three key sets of systemic considerations involved in reducing emissions from electricity systems:

- addressing public concerns about localized environmental impacts arising from expanded generation capacity;
- managing load balancing and system management challenges associated with integrating new generation sources; and
- improving electricity transmission and distribution systems to more effectively enable reliance on low-emission sources.

Localized Environmental Impacts and Public Concerns

Low-emission generation technologies are critical for climate change mitigation and so have global benefits. They can also have adverse local impacts, however, on the environment and nearby communities, including visual intrusion in the landscape; noise, land, and water degradation; ecosystem disturbances; and introduction of new sources of air, water, and land pollution (Walker, 1995). The nature of local impacts from power generation technologies varies by technology and fuel source. Table 3.2 lists a range of environmental impacts and other sources of public concern for selected generation technologies.

Among renewables, these challenges are most acute for hydropower, wind turbines, and biomass. Hydropower projects result in disruptions of the affected aquatic and terrestrial ecosystems by creating impediments for fish migration, changing sedimentary transport patterns, and affecting nutrient transport to downstream areas (Kumar *et al.*, 2011). Such impacts have led to public opposition to new large hydropower facilities (particularly those with reservoirs) in recent decades (Jaccard, 2006a; TEFP, 2013). Wind turbines result in localized land disturbance and ecological impacts and have land-use implications, with bird and bat mortality being a particular cause for concern (NRC, 2007).[15] The aesthetic

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[14] Based on 2015 rates provided by Bullfrog Power. See https://www.bullfrogpower.com/index.cfm.

[15] These mortality rates should be considered in the context of the overall number of bird fatalities due to human activity (such as from driving and pet ownership) and structures (glass buildings), which are an order of magnitude higher (Wiser *et al.*, 2011).

impact of wind turbines on the landscape is another source of public opposition, as are concerns that noise from turbines could pose health risks (NRC, 2007; CCA, 2015a).[16] More intensive agricultural production for biomass energy can exacerbate pollution concerns related to fertilizer and pesticide use, degrade soil quality, and have adverse impacts for nearby ecosystems and species (Chum *et al.*, 2011). Biomass production can increase water consumption in some areas, intensifying water stresses. More far-reaching public concerns arise in relation to using food crops for fuel, which could increase food prices and exacerbate food and income insecurity for vulnerable populations (Smil, 2010).

Table 3.2

Environmental Impacts and Sources of Public Concern for Selected Low-Emission Electricity Technologies

Technology	Local Environmental Impacts and Sources of Public Concern
Hydropower	• Impacts on hydrological systems (e.g., water flows and levels, sediment and nutrient transport, water temperature) • Impacts on affected aquatic and terrestrial species and ecosystems (e.g., through habitat disruption, barriers to fish migration) • Potential displacement of people and communities • Conflicts about sharing benefits and costs in affected communities
Wind	• Impacts on local and migratory species (e.g., birds and bats) • Aesthetic imposition on the landscape • Wind turbine noise and concerns about health impacts
Nuclear	• Risk of major accident • Waste management and storage • Proliferation risks • Water use in power plant
Biomass	• Air pollution from combustion • Environmental impacts associated with expanded/more intensive agricultural production (e.g., soil degradation, pesticide use, fertilizer use, nitrogen runoff) • Impacts on local biodiversity associated with agricultural production • Increased water consumption • Impacts on food prices with fuels derived from food crops
Concentrated Solar Power	• Land disturbance from construction
Solar PV	• Some hazardous materials used in production
Geothermal	• Land disturbance impacts from construction • Potential for land use conflicts (e.g., barriers to development near tourist areas, national parks)

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[16] Definitive causal links between wind turbine noise and adverse health impacts have not been established; however, turbines do produce sound at multiple frequencies, which can cause annoyance and be a potential source of stress (CCA, 2015a).

Nuclear power faces major challenges in relation to public acceptance and the siting of new plants. Concerns about nuclear power stem from factors that include the challenges and risks associated with long-term storage of nuclear wastes, the risks of nuclear accidents, and security-related concerns about nuclear proliferation and the potential weaponization of nuclear material. While such risks can be mitigated in various ways (such as through improved reactor designs, appropriate engineering safeguards, and the development of secure, long-term storage facilities for nuclear waste), they remain a barrier to broad public acceptance. Fifty-three percent of Canadians report being either strongly or somewhat opposed to the development of nuclear power; in comparison, only 37% are supportive. Nuclear accidents amplify these concerns (Kim *et al.*, 2013); Canadian support for building new reactors and upgrading and refurbishing existing ones dropped following the Fukushima nuclear disaster in 2011 (CNA, 2010, 2011; as cited by EEUC, 2015). Public perceptions of risk, however, are not necessarily consistent with the actual safety records of alternative electricity generation technologies. Fatality rates from accidents for nuclear power in OECD countries are relatively low compared to coal, oil, and hydropower, which have resulted in significantly more deaths per kWh of electricity generated (Sathaye *et al.*, 2011; Bruckner *et al.*, 2014).

Public concerns about power generation technologies sometimes manifest only when development occurs in the immediate vicinity of residents or a community, resulting in localized opposition. Wind power, for example, has broad public support according to polling data, but wind turbine development projects are often met by local opposition. Some research suggests that local opposition occurs primarily in the project planning phase, but projects tend to achieve greater levels of acceptance and support once they are complete (Krohn & Damborg, 1999). Experience in Canada and other jurisdictions also suggests that how communities are engaged in energy planning and development processes can influence the extent to which local concerns impede or prevent new plants being developed (Wiser *et al.*, 2011; CCA, 2015a).

Public acceptance may also be a challenge for CCS in some cases due to localized concerns about the safety risks associated with a carbon dioxide leak, the risk of contaminating groundwater, the impacts of seismic surveying, and environmental impacts from construction of pipelines and storage facilities. Globally, studies suggest the overall level of understanding and support for CCS among the public is low (Benson *et al.*, 2012). Attitudes toward CCS among Canadians, however, do not suggest major opposition. In a 2009 study, Canadians were found to be moderately supportive of CCS as a climate change mitigation strategy and viewed it as less risky than normal oil and gas industry operations, nuclear power, and coal-fired power plants (Sharp *et al.*, 2009). Concerns about local environmental impacts from power plants are also not limited to low-emission generation choices: the development of new fossil-fuel power plants — particularly coal plants — is also frequently met by public opposition due to environmental concerns (Box 3.2).

In the face of these impacts, attempts to rapidly expand low-emission generation capacity can engender land-use conflicts and public opposition if policy-makers and regulatory agencies do not effectively anticipate and respond to public concerns (Jaccard *et al.*, 2011). This points to the need for institutional mechanisms (e.g., energy planning, land-use planning, and public consultation and engagement strategies) that respond to these concerns at different scales of decision-making. Given the imperative to expand low-emission generation capacity for climate change mitigation, standard mechanisms such as individual

Box 3.2
Local Environmental Impacts of Fossil Fuel Electricity Generation Plants

Fossil fuel-fired power plants result in negative environmental impacts at the plant site and at the source of resource extraction. Air pollution from the combustion of coal for electricity is associated with a significant public health burden and related costs to affected individuals and communities (Markandya & Wilkinson, 2007; Smith *et al.*, 2012; Bruckner *et al.*, 2014). Coal mining and natural gas extraction also result in the physical disturbance of affected land areas and can have adverse impacts on terrestrial and aquatic ecosystems. Large quantities of water are used to remove impurities from coal during production, and acid mine drainage can occur when acidic water from mines leaks into rivers and streams. Coal mining is associated with the potential introduction of toxic substances such as heavy metals into the environment through tailings ponds and other sources (NRC, 2010). Natural gas extraction affects land and ecosystems through well drilling and road and pipeline construction, and terrestrial impacts can also increase erosion and affect local streams and rivers (NRC, 2010). Unconventional gas extraction methods such as hydraulic fracturing (fracking) may exacerbate these impacts due to higher water consumption and a greater density of wells, leading to increased risks associated with surface water and groundwater contamination (CCA, 2014). These impacts have resulted in public opposition to coal and gas extraction in many jurisdictions and contributed to high levels of public opposition to coal in Canada. One poll has suggested that 68% of Canadians are opposed to producing electricity from coal-fired power plants (CNA, 2012).

environmental impact assessments may not effectively (or expeditiously) address these concerns. Energy planning mechanisms also need to be designed to balance global and local impacts in planning future capacity expansions. See Section 4.4.3 for additional discussion of approaches governments can take to address these challenges.

Load Balancing and Electricity System Flexibility

Electricity systems must continuously balance supply with fluctuations in demand. They do so by relying on dispatchable or partially dispatchable generation sources, which can be turned on in response to increased demand and shut off when demand decreases. Not all electricity generation technologies are suited to this use. Renewables such as wind and solar are dependent on environmental conditions (e.g., wind speed, cloud cover, solar radiation) and are only partially dispatchable. These sources can be ramped down, if necessary, but not ramped up beyond what environmental conditions support. Thermal generation sources such as coal-fired power plants and nuclear plants can be used as flexible generation sources, but are not designed for this purpose (MIT, 2011) — using them this way lowers their profitability and increases physical wear. Power plants with the lowest marginal costs (i.e., operating and fuel costs) are typically used to provide baseload power; that is, these plants produce power most of the time. Plants with high capital costs (e.g., hydropower, nuclear, and large coal-fired plants) are more suitable for this function.[17] Hydropower facilities with reservoirs are dispatchable and can effectively complement intermittent generation from sources like wind (Acker, 2011), though like larger thermal plants, it may not always be economical to reserve hydropower capacity offline. Natural gas plants, in contrast, are frequently used to meet fluctuations in demand. Because of load-balancing needs, integrating larger amounts of intermittent, non-dispatchable electricity into electricity grids may require adding complementary dispatchable generation capacity as well.

Alternatively, energy storage technologies connected to the grid can also play a role in addressing this challenge. The ability to store excess electricity at off-peak times would be of significant value to electricity systems that rely heavily on intermittent sources. Current and potential grid storage technologies include compressed air systems, battery systems, hydrogen fuel cells, flywheels, and electrochemical capacitors (DOE, 2013b). Most existing electricity storage systems rely on hydropower reservoirs or pumped water storage systems, where energy is stored by pumping water up a gradient that is later released to power

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[17] These plants are often built with the expectation that they will be operating much of the time (i.e., have high capacity factors), and may therefore require more intensive operation to recover costs. In addition, when thermal power plants cycle on or off, they incur additional physical wear, and their efficiency is consequently reduced over time (MIT, 2011).

a turbine (DOE, 2013b). Battery systems from plug-in electric vehicles may eventually be used as a form of storage in the long term, though this would require modifications to existing distribution systems. Energy storage technologies, and related economic and technological challenges, vary depending on the context, scale of deployment, the amount of energy stored, and the duration for which that energy is stored (MIT, 2011; DOE, 2013b). Large battery systems for electricity storage for power grids are prohibitively expensive in most cases. However, the adoption of various grid-scale energy storage technologies is accelerating as they become more cost competitive in certain markets and applications (GTM Research and ESA, 2015). As energy storage costs continue to fall over time, these technologies could be more widely deployed as viable solutions to specific grid challenges.

Advanced sensors, control systems, and dispatch algorithms can also help manage electricity systems with more complex and variable mixes of generation sources (MIT, 2011). Current dispatch algorithms, for example, are not designed to "accommodate the uncertainties involved in forecasting wind, load, and other probabilities" (MIT, 2011). Another possibility is using electricity demand management and response strategies as a means of achieving system flexibility (IEA, 2003b; Depuru *et al.*, 2011; Cook *et al.*, 2012; Joung & Kim, 2013; Procter, 2013). Rather than adding generation capacity to meet peak demand, electricity providers can take steps to reduce demand or shift it to off-peak times. Traditional demand management programs coupled with time-of-day pricing and technologies such as smart meters may be able to moderate demand fluctuations and alleviate some of the burden associated with managing load.

The load-balancing challenges associated with integrating higher shares of power generation from intermittent sources require integrated energy system planning focused on developing a flexible mix of power generation sources and wider access to markets through interconnections. In the Canadian context, provinces must develop system flexibility through in-province generation capacity or through trade with other jurisdictions. In closing its coal-fired power plants, Ontario shifted to a model where nuclear and renewables account for most baseload generation capacity, while natural gas plants are used to meet fluctuations in demand. Alberta, Saskatchewan, New Brunswick, and Nova Scotia could follow a similar model. Alternatively, they could focus on developing electricity systems that are more reliant on fossil fuel power with CCS.

Transmission and Distribution Systems

Transmission and distribution systems affect the viability of different power generation technologies. Where optimal locations for certain types of power generation such as wind and geothermal are far from population centres, new transmission lines may be needed, resulting in additional costs and electricity losses (Sims *et al.*, 2011). For CCS plants, siting decisions need to balance the cost of transmission versus the costs of transporting carbon dioxide to storage sites. Bottlenecks or congestion points in transmission systems can make siting in particular regions more or less attractive. In Canada, if existing transmission lines are congested, it may be difficult to take advantage of power generation options in some regions without transmission system upgrades.

Investments in transmission lines and new interconnections also facilitate system flexibility and resilience. Greater geographic aggregation of intermittent renewables, for example, can reduce fluctuations in power output due to the variation in environmental conditions across a larger area (Sims *et al.*, 2011). In Canada, linking multiple high-wind regions together across the country with high-voltage direct current transmission lines could significantly reduce variation in wind power output (Harvey, 2013). Increasing grid interconnections between regions (whether among provinces or between provinces and states) also provides flexibility by allowing system managers to rely more heavily on electricity trade as a means of balancing supply and demand. In the Canadian context, Quebec, Newfoundland and Labrador, and Manitoba could sell more low-emission hydropower to Ontario if adequate east-west transmission lines were in place (CAE, 2012b, 2014).

Distributed generation refers to the use of widely distributed, small-scale generation, often integrated into communities or located close to demand. Greater uptake of distributed generation could decrease transmission costs and losses by reducing the distance travelled between the points of generation and consumption (Thomson & Infield, 2007; Sims *et al.*, 2011). Increased reliance on distributed generation, however, poses other challenges to system managers who may then face managing generation from a larger, more diverse set of facilities. Existing distribution systems are typically designed to facilitate the flow of electricity in one direction: from the generation source to the consumer. Enabling distributed generation technologies like residential solar panels to feed electricity back into the grid requires modifications to existing distribution systems. An implication is that *electricity grid modernization* (sometimes referred to under the umbrella of *smart grids*), defined by the Canadian Electricity Association as “the addition of two-way communications, control and automation capabilities to existing power grids” (CEA, 2015), can enable greater penetration of renewables and distributed generation while also facilitating optimal use of existing generating assets (CEA, 2014).

3.2 TRANSPORTATION

Key Findings

- Transportation systems are a large and growing source of Canada's greenhouse gas emissions. Freight transportation is the fastest-growing source in the sector. Current systems are almost entirely dependent on petroleum-based fuels and will likely remain so without more stringent emission mitigation policies.
- Energy-efficiency improvements for new vehicles and strategies that reduce demand can reduce transportation emissions in the near term; however, substantial emission reductions will require switching to low-emission fuels and vehicles.
- Low-emission fuel choices now used in commercially available transportation technologies include biofuels, electricity, hydrogen, and alternative fossil fuels such as diesel, natural gas, and propane. Due to their relative advantages and disadvantages, no one fuel or vehicle is better than others across all transportation contexts. Electricity is a more promising option for passenger vehicles, while biofuels may be a more viable choice in most freight transportation.
- Transportation systems depend on fuel production and distribution systems and the prospects of energy substitution may both hinge on the extent to which the required refuelling infrastructure is in place. Urban planning and public infrastructure investments can also support a transition to low-emission transportation systems and communities.

Globally, refined petroleum products account for 95% of energy consumed in transportation systems (Kahn Ribeiro *et al.*, 2012). Petroleum-based fuels such as gasoline, diesel fuel, and jet fuel have distinct advantages based on their portability and energy density, as well as the technological lock-in established by the dominance of internal combustion engines and current fuel production and distribution systems. They are also a large and growing source of greenhouse gas emissions. Approximately 38% of Canada's energy-related greenhouse gas emissions come from the transportation sector (NRCan, 2014h). Figure 3.2 shows current energy use and emissions for transportation in Canada by fuel and mode of transportation. Gasoline, diesel fuel, and aviation fuel provide the energy for over 90% of Canada's transportation needs (NRCan, 2014h). Ethanol (the only lower-emission fuel choice widely used in Canadian vehicles) accounts for only 3% of transportation energy use.[18] Road transportation dominates

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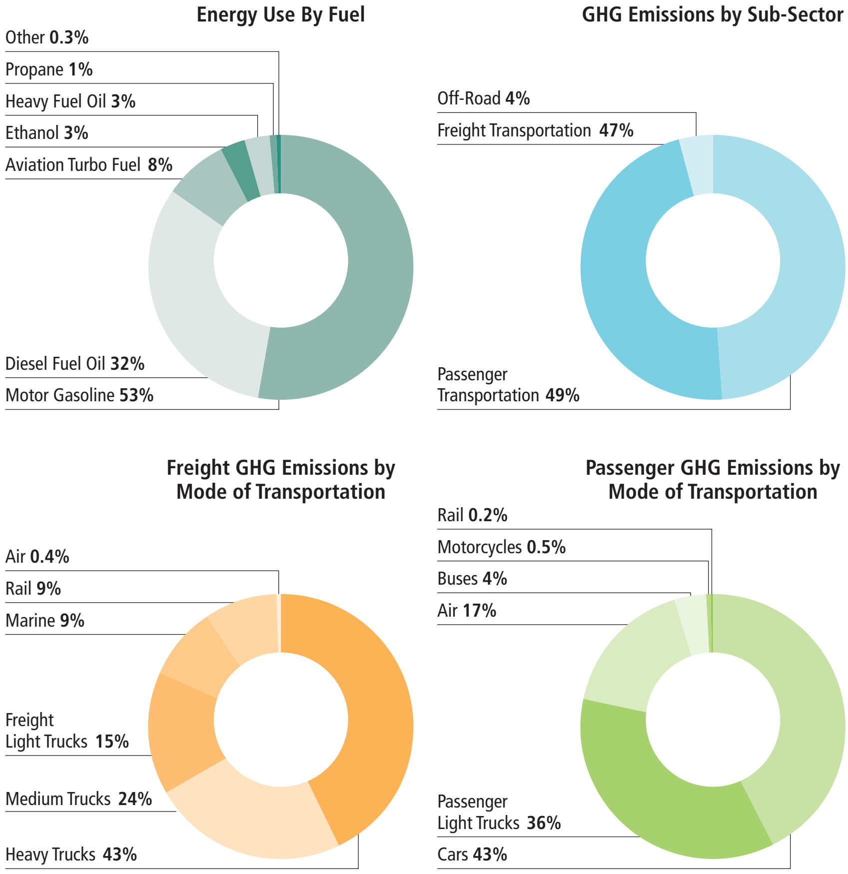
[18] Data was not available for Canadian biodiesel consumption.


Energy Use By Fuel

GHG Emissions by Sub-Sector

Freight GHG Emissions by Mode of Transportation

Passenger GHG Emissions by Mode of Transportation

Data Source: NRCan, 2014h

Figure 3.2

Canadian Transportation Energy Use and Greenhouse Gas Emissions, 2012

Transportation systems in Canada depend heavily on refined petroleum products as fuel sources and are therefore a large source of greenhouse gas emissions. Motor gasoline, diesel fuel, and aviation fuel together account for 93% of energy used in the sector. Emissions divide roughly equally between passenger and freight, though freight emissions are growing more rapidly. Totals may not add up to 100% due to rounding.

energy consumption and emissions from the sector. In passenger transportation, cars and light trucks account for over two-thirds of emissions, while in freight transportation, trucks account for 82% of emissions (NRCan, 2014h).

Transportation systems in Canada and elsewhere are evolving in response to shifts in the demand for transportation services driven by demographic, social, and economic trends. As the world's population becomes more concentrated in urban areas, passenger transportation requirements change, potentially enabling mass transit systems and non-motorized transportation, but also contributing to suburban growth and increasing demands for motorized transport (Kahn Ribeiro *et al.*, 2012). The balance between transportation demands related to passenger and freight services is also shifting. In Canada, energy demand from road passenger transportation is slowing and expected to decline (along with carbon dioxide emissions) in coming years, owing partially to more stringent fuel-economy standards adopted by the federal government (NEB, 2013). In contrast, freight transportation is growing and will account for a relatively larger share of transportation-related emissions over time (Environment Canada, 2013c; NEB, 2013).

This section reviews efficiency-enhancing improvements and alternative fuel and vehicle choices that could facilitate a transition to low-emission road transportation in two key areas: (i) urban LDV passenger transportation (the largest source of transportation emissions); and (ii) freight transportation (the fastest-growing source of transportation emissions). It concludes with a brief discussion of systemic considerations relating to transportation infrastructure and fuel production and distribution systems that pose challenges to widespread adoption of low-emission technologies.

3.2.1 Improving Transportation System Efficiency

Widespread opportunities for efficiency improvement exist in most transportation systems (IEA, 2012a; Kahn Ribeiro *et al.*, 2012; NRC, 2013; Sims *et al.*, 2014). Modelling studies indicate that vehicle improvements are important in driving short-term emission reductions (J&C Nyboer and Associates Inc., 2008; Sachs *et al.*, 2014) and, along with changing transportation modes and reduced travel needs, could significantly contribute to emission mitigation (Kahn Ribeiro *et al.*, 2012; Sims *et al.*, 2014). In Canada, key efficiency improvements could include more efficient passenger and freight vehicles (including adoption of hybrid electric vehicles (HEVs)), a shift to public transit, and a shift in freight transport from trucking to rail (Sachs *et al.*, 2014). For these reasons, the Panel has focused on two key areas for improving efficiency: improved vehicle technology and modal shifts that reduce the need for travel.

Vehicle Efficiency

Most studies indicate that efficiency of conventional internal combustion automobiles (both light and heavy duty) could be improved by about 30 to 50% by 2050 through:

- *Greater drivetrain efficiencies* using technologies such as automated manual transmission and continuously variable transmission;
- *Recapturing energy losses from engines, idling, and braking,* with advanced engine technologies such as variable valve timing and lift, turbocharging, direct fuel injection, cylinder deactivation, engine idling shutdown, and regenerative braking systems;
- *Reducing loads associated with vehicle weight, rolling, and air resistance,* with design changes and greater incorporation of lightweight materials (like carbon fibre), improved tire design and redesigned wheel bearings and seals, reduced frontal areas of vehicles, and smoothed-out body surfaces; and
- *Greater efficiencies in accessory system*s such as air conditioning, power steering, windshield wipers, and audio systems.

(IEA, 2012a; Kahn Ribeiro *et al.*, 2012; NRC, 2013; Sims *et al.*, 2014)

Changing driver behaviour to encourage slower acceleration, reduced idling, and maintenance of proper tire pressure can also complement technological improvements, further enhance efficiency, and provide cost savings to the consumer (IEA, 2012a). More revolutionary changes in vehicle technologies could also play a role in further enabling or delaying efficiency gains in passenger vehicles. The development of self-driving vehicles could lead to further efficiency gains stemming from improved traffic flow, reduced congestion, and vehicles travelling at more constant and slower speeds. Such vehicles, however, could also make driving more convenient, thereby encouraging more vehicle travel and out-competing public transportation (Fagnant & Kockelman, 2015).

HEVs represent a key opportunity for improving vehicle efficiency in light-, medium-, and heavy-duty vehicles. Through the combined use of an internal combustion engine and a battery and electric motor, HEVs can achieve approximately 35% higher fuel economies than a comparable vehicle with only an internal combustion engine (Sims *et al.*, 2014). Fuel consumption in HEVs is reduced in various ways, such as engines that turn off during idling, deceleration, and coasting; brakes that capture energy during use (called *regenerative braking*); downsized engines allowed by the addition of electric motors; easier electrification of accessory services such as power steering; engines that operate more efficiently at lower loads; and more efficient engine cycles (NRC, 2013). Changes in vehicle fuels can enable more substantial efficiency gains as well, as fully electric drivetrains in battery-electric vehicles and hydrogen fuel cell vehicles (FCV) are much more efficient than the drivetrains of vehicles with internal combustion engines (see Section 3.2.2).

Many vehicle efficiency improvements can be achieved at low or even negative costs, taking into account fuel cost savings over the lifetime of the vehicle (Sims *et al.*, 2014). For light-duty and long-haul heavy-duty vehicles, efficiency gains of up to 50% are possible by relying on very low or negative cost options (Sims *et al.*, 2014). Low costs do not mean, however, that such improvements will occur without supporting policy or regulation. Efficiency-enhancing improvements are frequently impeded by financial, behavioural, and institutional barriers. For example, consumers often do not attempt to minimize life-cycle fuel costs when making vehicle purchases, due to factors such as imperfect information, information overload, and uncertainty about future vehicle and fuel costs (Anderson *et al.*, 2011; Small, 2012; Allcott & Wozny, 2013). Consumers and businesses may also resist operational changes that can improve energy efficiency (such as operating vehicles at lower speeds), and may have preferences that run counter to efficiency maximization (like preferences for larger vehicles). Reducing the cost of travel by improving fuel economies can subsequently encourage more travel, thus partially offsetting emission reductions from efficiency gains. In North America, studies estimate that a 50% reduction in fuel costs results in a 2.5 to 15% increase in driving (Sims *et al.*, 2014). The pace and cost of potential efficiency gains are also partly limited by capital turnover rates associated with existing vehicles and fleets and by existing transportation infrastructure (such as rail lines and road networks).

Modal Shifts and Reducing Travel Needs

Transportation systems can reduce energy demand through modal shifts (changes in the type of transportation used) and avoided travel. Modal shifts from individually owned and operated vehicles to mass transit systems can improve efficiency of fuel consumption (assuming reasonable utilization rates), as can switching to active modes of transportation such as walking and cycling. Modal shifts can also lead to co-benefits in terms of reduced traffic volumes and congestion, reduced urban air pollution, and exercise-related health benefits (Kahn Ribeiro *et al.*, 2012; Sims *et al.*, 2014). In freight transportation, modal shifts from truck-based transport to rail can lead to substantial energy savings; the IEA (2009c) estimates that shifting half of the global truck transportation expected between 2010 and 2050 to rail would result in about a 15% reduction in energy consumption. Travel needs also could be reduced through strategies such as increasing the density of urban landscapes, restructuring freight logistics systems, and using information and communication technologies for online shopping and telecommunication (Sims *et al.*, 2014) (see Section 3.2.3 for a discussion of urban form in transportation systems). Car sharing also has the potential to improve travel efficiency, leading to lower emissions per passenger kilometre, and can be particularly relevant to lower-density areas less amenable to public transit.

3.2.2 Energy Substitution in Transportation Systems

Despite widespread opportunities to improve vehicle efficiency, modelling studies for Canada have found that deeper, medium- to long-term emission reductions for transportation are driven mainly by switching to alternative fuels (J&C Nyboer and Associates Inc., 2008; Sachs *et al.*, 2014). Many of the relevant fuels and associated technologies, including HEVs, plug-in hybrid electric vehicles (PHEVS), battery electric vehicles (BEVs), and hydrogen FCVs have benefited from intensive development efforts over the past two decades, and a wide range of choices are now commercially available in North America. Although alternative vehicles remain more expensive than vehicles with conventional internal combustion engines, the costs are expected to decline over time as technologies improve, vehicle production increases, and additional economies of scale are realized (NRC, 2013) (see Figure 3.3).

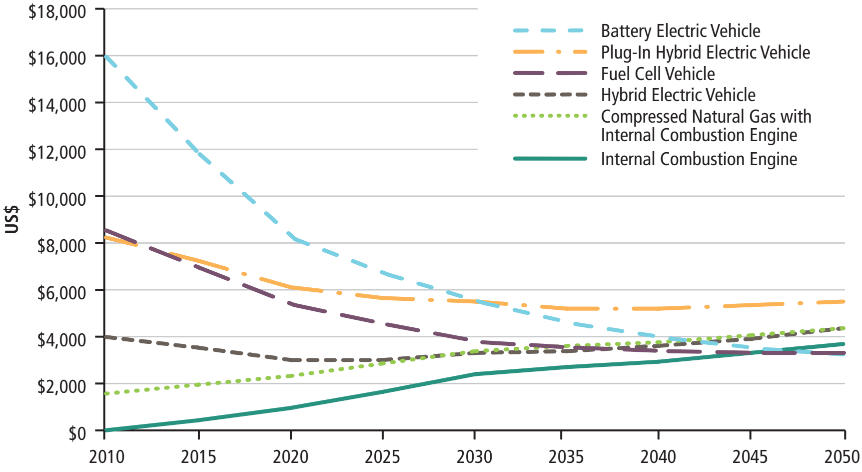


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Figure 3.3

Projected Additional Vehicle Cost Versus 2010 Baseline

While the costs of vehicles running on alternative fuels currently remain higher than those of gasoline-powered vehicles with conventional internal combustion engines, these costs are expected to decrease over time due to continued technological learning and economies of scale. Cost estimates above are in US$ for a light-duty vehicle, and represent direct manufacturing costs to the manufacturer over the baseline cost of a 2010 internal combustion engine vehicle with a US$26,341 retail price.

Alternative fuels can be divided into four main categories: lower-emission fossil fuels (i.e., diesel, natural gas, and propane), biofuels, electricity, and hydrogen. These fuels and associated vehicle technologies differ across key properties, such as their energy density, portability, and effects on vehicle performance. They also differ in their impacts on ambient air pollution and public health (see Box 3.3). No alternative fuel choice or technology is better than others across all contexts, and given the current state of technological development, it is difficult to predict whether and how much any of them will increase their share of transportation energy use over time. Table 3.3 compares technologies across a range of impacts, including well-to-wheel emissions, vehicle and fuel costs, driving range and refuelling impacts, and systemic barriers or constraints that might stand in the way of their adoption (discussed in Section 3.2.3). Given the relatively higher costs of alternative vehicles, as well as behavioural and institutional barriers, petroleum-based fuels and internal combustion engines are likely to remain dominant in the near to medium term unless substantial policy changes are implemented.

Box 3.3
Vehicle Emissions and Ambient Air Pollution

Vehicles relying on internal combustion engines have tailpipe emissions beyond greenhouse gases, and these too result in adverse impacts. Automotive emissions of other pollutants such as volatile organic compounds, nitrous oxide, benzene, carbon monoxide, and particulate matter are associated with a range of health effects, including increased mortality, respiratory disease, cardiovascular disease, and adverse reproductive outcomes (WHO, 2011). Studies that have monetized the cost to society of negative health impacts from vehicle fuel combustion have often found that non-greenhouse gas air pollution damages exceed the estimated damages expected from the impacts of climate change (Hill *et al.*, 2009; Michalek *et al.*, 2011; Tessum *et al.*, 2014). Researchers have also found that switching to low-emission technologies could result in large benefits to public health. For example, West *et al.* (2013) found that global greenhouse gas mitigation (including transportation and non-transportation emission sources) could result in between 1.4 and 3 million fewer premature deaths in 2100 due to co-benefits associated with air pollution reduction.

Table 3.3

Comparison of Alternative Vehicles and Fuels

	Well-to-Wheel GHG Emissions Relative to Gasoline Internal Combustion Engine (%)	Vehicle and Fuel Costs		Driving Range and Refuelling Impacts	Systemic Barriers and Challenges
		Fuel Costs (US$ per Gasoline Gallon Equivalent)	Additional Vehicle Cost		
Gasoline	100	$3.34	Not available*	• Range of average LDV is ~480 kilometres.	• Current infrastructure designed around these fuels.
Diesel	73	$3.38	Not available*	• Improved driving range relative to gasoline.	
Natural Gas	56–94	$2.16	+$1,921	• Reduced range; extra tanks can compensate in medium- and heavy-duty vehicles.	• Benefits from existing methane production and distribution infrastructure. • Expanded network of refuelling stations would be required. • Potential for fugitive emissions.
Biofuels	18–121 (high or low depending on indirect land-use impacts)	$4.07–$4.25 (E85,B100)	0 for drop-in biofuels	• High-ethanol blends have reduced fuel economy/range. • Biodiesel range comparable to petroleum diesel.	• Environmental and agricultural impacts increase with production. • Limited capacity to expand corn-grain ethanol production based on current yields.
HEVs	71	$3.34 (gasoline)	+$3,510	• Gasoline engine mitigates concerns about range and refuelling.	• Relies on existing infrastructure.

continued on next page

	Well-to-Wheel GHG Emissions Relative to Gasoline Internal Combustion Engine (%)	**Vehicle and Fuel Costs**		**Driving Range and Refuelling Impacts**	**Systemic Barriers and Challenges**
		Fuel Costs (US$ per Gasoline Gallon Equivalent)	**Additional Vehicle Cost**		
PHEVs	4–113 (near zero when operated with low-CO$_2$ electricity)	$1.24 (electricity only)	+$7,282	• Gasoline engine mitigates concerns about range and refuelling.	• Construction of high-speed charging stations. • Upgrades to transmission and distribution systems. • Grid expansion to meet additional demand.
BEVs	3–92 (near-zero when operated with low-CO$_2$ electricity)	$1.24 (electricity only)	+$11,809	• ~160-kilometre range. • Long charging times, or recharging requires dedicated high-speed charging stations.	
FCVs	6–57 (near zero when operated on hydrogen produced with CCS or electrolysis)	$3.68	+$6,954	• Comparable range and refuelling times to conventional vehicles.	• Expanded hydrogen production facilities. • Development of distribution infrastructure and refuelling stations.

Well-to-wheel emission ranges are based on Creutzig (2011) and Creutzig (2010), calculated based on gC0$_2$e/MJ delivered to the wheels; biofuel emissions include estimates of indirect and direct effects, though estimates of indirect effects vary significantly depending on methodological choices. Fuel costs are in US$ for gasoline gallon equivalents and based on average retail prices in the United States in 2014; hydrogen costs are an estimate by DOE (2012). Vehicle costs are estimated incremental additional vehicle costs for an LDV over a conventional gasoline-powered vehicle with an internal combustion engine in 2015 in US dollars, from NRC (2013). *Vehicle costs for diesel vehicles are not included here as NRC (2013) did not explore these costs based on the assumption that the efficiency and emission advantages of diesel vehicles over gasoline-powered vehicles are likely to diminish over time.

Lower-Emission Fuels from Fossil Sources[19]

Vehicles operating on diesel have higher fuel economies than gasoline and so can achieve lower carbon dioxide emissions. Diesel LDVs — which use more efficient compression ignition engines, as opposed to the spark ignition engines in gasoline-powered vehicles — have 12 to 15% lower greenhouse gas emissions per kilometre travelled than gasoline LDVs (Schlömer *et al.*, 2014). Vehicles operated on natural gas also have lower carbon dioxide emissions per kilometre than gasoline or diesel vehicles. Natural gas is used as a vehicle fuel in two forms: compressed natural gas (CNG) and liquefied natural gas (LNG). Propane, also known as liquefied petroleum gas or LPG, is another gaseous fuel that can be used to power light-, medium-, and heavy-duty vehicles. The driving range of natural gas vehicles is typically lower than for gasoline- or diesel-powered vehicles, due to the lower energy content of the fuel by volume; however, additional fuel tanks can partially compensate for this impact (DOE, 2015b). Propane vehicles have driving ranges that are comparable to conventional vehicles (DOE, 2015b). Refuelling can be done relatively rapidly with either of these fuel choices and poses no particular challenges to consumers, other than the current limited availability of fuelling stations. For gaseous fuels, CNG is a lower-cost option, while propane is a higher-cost fuel choice (DOE, 2015a).

While fuels such as natural gas offer reduced emissions compared with gasoline and diesel, these benefits may be partially offset by fugitive emissions from gas production and distribution (see Box 3.8 on fugitive emissions). As a result, while some estimates suggest that natural gas could achieve emission reductions over gasoline of nearly 50% (Creutzig, 2010; Creutzig *et al.*, 2011), analysis from the United States Argonne National Laboratory found that well-to-wheel emissions (including fugitive emissions) for LDVs operating on either CNG or LNG were only 6 to 11% lower than gasoline, with the emission reduction potential of the two forms of natural gas being nearly identical (DOE, 2015b). Other assessments suggest life-cycle emission reductions in the range of 10 to 15% (Sims *et al.*, 2014). Propane has been estimated to result in well-to-wheel emission reductions of approximately 10% compared to gasoline (DOE, 2015b).

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[19] Fossil fuels can also be used to produce methanol and other synthetic fuels. Methanol (wood alcohol) has similar properties to ethanol (see biofuels section) and also has lower carbon emissions than gasoline at the point of combustion. Dimethyl ether (DME) is a synthetic alternative to diesel fuel. DME can result in reductions of all particulate matter, though DME has approximately half the energy density of traditional diesel and therefore requires larger fuel tanks to achieve comparable driving ranges (DOE, 2015b).

Biofuels

Biofuels are any liquid fuels produced from organic feedstocks (i.e., biomass). Biofuel feedstocks, conversion pathways, and fuels are widely variable; however, only two biofuels, ethanol and biodiesel, are now widely produced on a commercial scale. Ethanol is produced from corn, wheat, or other plant materials through the fermentation of sugars by yeasts. Pure ethanol has approximately 30% less energy per litre than gasoline, which leads to lower fuel economies and reduced driving ranges in vehicles operating on high-ethanol blends (DOE, 2015b).[20] Biodiesel, a biomass-based analogue to conventional diesel, can be produced from a range of feedstocks such as soybeans, canola, waste cooking oil, and animal fats. Biodiesel has slightly less energy by volume (93%) than conventional diesel (DOE, 2015b) and can therefore lead to slightly lower fuel economies, but its use does not result in other significant changes to vehicle performance. A drawback of biodiesel — one shared with traditional diesel to a lesser extent — is the fuel's tendency to crystalize in cold temperatures.

Advanced biofuels may become important fuels in the future. These are fuels derived from lignocellulosic feedstocks (woody plant materials such as crop residues or forestry waste products) and algae (IEA, 2011). Lignocellulosic biofuels could alleviate concerns about reliance on food crops as feedstocks and improve the fuels' emission reduction potential and energy balance (the ratio of energy used in production to the energy available in the fuel) (Creutzig *et al.*, 2011; IEA, 2011; Kahn Ribeiro *et al.*, 2012).

For all biofuels, the choice of feedstock, conversion process, and associated impacts on land use and soil carbon have large impacts on final carbon dioxide emissions.[21] Emission reduction estimates for ethanol, for example, range from negative (e.g., corn grain ethanol could increase greenhouse gas emissions) to large reductions in the case of sugar cane and cellulosic ethanol (Creutzig *et al.*, 2011; IEA, 2011). Emission reductions from biodiesel are often greater than those associated with ethanol. Including indirect emissions, the use of biodiesel over conventional diesel likely results in emission reductions

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[20] Use of blended gasoline-ethanol mixes is widespread in North America (blending ethanol with gasoline helps both oxygenate the fuel and reduce tailpipe emissions).

[21] Biofuels were traditionally seen as having low net emissions, as carbon emissions released during combustion are offset by the absorption of carbon into the biomass feedstock from which the fuel was generated. However, this accounts only for direct emissions and does not include emissions involved in the production of biomass feedstocks (such as emissions resulting from fertilizer use), the operation of agricultural equipment, biomass transportation, or fuel production and distribution. This view also does not account for whether there are secondary (indirect) impacts on land use. The well-to-wheel (life-cycle) emissions of various biofuels is a contested and heavily researched topic, particularly with respect to emissions from indirect land-use change — see Smith (2014), Finkbeiner (2014), Wicke (2012), and NRC (2011) for discussions.

in the range of 20%, in the case of soybeans from the midwestern United States, to 80%, in the case of biodiesel produced from restaurant waste grease (Creutzig *et al.*, 2011).

Electricity — Plug-In Hybrid Electric Vehicles and Battery Electric Vehicles

Electricity can be used as an energy source in automotive transport through several vehicle designs. HEVs use electricity as an auxiliary power source to supplement energy from the combustion of a liquid fuel such as gasoline, diesel, or ethanol. PHEVs and BEVs, however, have the potential to operate solely on electricity. PHEVs are similar to HEVs, but have a built-in capability to charge their batteries using electricity, and they have larger battery packs to facilitate driving moderate distances relying only on electricity (DOE, 2015b). Current PHEVs can often travel 15 to 65 kilometres on electricity before the gasoline engine is needed. BEVs operate entirely on electricity, eliminating the need for an internal combustion engine and therefore offering savings in vehicle weight and efficiency. BEV manufacturers currently target a driving range of 160 kilometres on a fully charged battery (DOE, 2015b), and few affordable BEVs are expected to exceed this range in the near future (NRC, 2013). In comparison, the average conventional vehicle has a driving range of 480 kilometres on a tank of gasoline (NRC, 2013). BEVs must therefore be refuelled (recharged) more frequently than conventional vehicles and require longer refuelling (recharging) times, though they can be refuelled at home while you sleep or at work unlike gasoline vehicles.[22]

Batteries are a key component of all electric vehicles, and the characteristics of battery systems have large impacts on the weight, size, cost, and range of vehicles. Some current electric vehicles use nickel-metal hydride batteries; however, future vehicles will likely rely on lithium-ion batteries, which are more expensive, but also more compact and lightweight (NRC, 2013). Battery recharging times are a potentially significant barrier for consumers. Most PHEVs and BEVs can be charged by connecting to a standard 120 volt residential outlet. However, this method of charging adds only between 3 and 8 kilometres of range per hour of charging time (DOE, 2015b). Quicker charging times require higher-voltage direct-current connections and specialized charging stations, which can provide between 80 and 110 kilometres of driving range with 20 minutes of charging (DOE, 2015b).

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[22] The use of vehicle battery swapping systems is one approach being explored to resolve these challenges. This would involve creating dedicated stations that, using specialized equipment, would rapidly replace a depleted battery with a fully charged one. This approach, however, would require significant additional infrastructure and may face its own consumer concerns relating to battery quality, reliability, and longevity. A network of such stations is currently being developed in Israel (NRC, 2013).

BEVs have zero tailpipe emissions, and PHEVs have the potential to operate with near-zero tailpipe emissions when running primarily on electricity. However, the upstream emissions of carbon dioxide and other pollutants from electric vehicles depend on the source of electricity. BEVs powered by electricity from coal-fired power plants, for example, can increase greenhouse gas emissions relative to gasoline-powered vehicles (Tessum *et al.*, 2014). Alternatively, BEVs operated with electricity from low-emission sources have low carbon dioxide emissions and can result in large reductions of other air pollutants (Tessum *et al.*, 2014). In the Canadian context, electric vehicles would be able to take advantage of Canada's relatively low-emission electricity system in most areas. Electricity is also a relatively low-cost fuel choice due to both the greater efficiency of electric motors, which are roughly 3.4 times more efficient than standard gasoline internal combustion engines, and relatively low electricity prices in North America (DOE, 2015a). As of January 2015, the electricity needed in the United States to provide the amount of energy equivalent to a litre of gasoline was 47% cheaper than the gasoline (DOE, 2015b). Similar costs would likely apply in Canada, though gasoline and electricity costs vary by region.

Hydrogen — Fuel Cell Electric Vehicles

Hydrogen is also a potential low-emission fuel when used to produce electricity through hydrogen fuel cells. In fuel cell vehicles (FCVs), electricity used to power the motor is generated by a fuel cell and on-board hydrogen storage instead of a battery pack. The vehicle must be refuelled at a dedicated hydrogen refuelling station, and hydrogen is stored on board the vehicle, either as a compressed gas or as a liquid at low temperatures. Hydrogen storage is a key technical challenge for FCVs, and current vehicle designs rely on carbon-fibre reinforced composite tanks (NRC, 2013). FCVs also typically have battery systems in order to capture energy from regenerative braking, supplement fuel cell output, and warm up the fuel cell in cold weather (NRC, 2013). While hydrogen fuel cells have been used as power sources for a range of vehicles, from forklifts (where indoor tailpipe emissions are a safety risk) to crewed spacecraft, they have not been widely used in road transportation to date. However, companies including Hyundai, Daimler, Honda, and Toyota have plans to introduce their first commercial FCV models in select markets in 2015 (NRC, 2013).

FCVs have no tailpipe emissions other than water vapour and warm air (DOE, 2015b), but may entail upstream emissions depending on how the hydrogen is produced. Most current hydrogen production relies on steam reformation of natural gas (the lowest-cost option), which results in greenhouse gas emissions from both natural gas combustion and fugitive emissions. Running a FCV on hydrogen from such a source, however, still results in emission reductions of 40% over a vehicle operated on gasoline, due to the lower carbon content of natural gas and the higher efficiency of the fuel cell stack (DOE, 2012). When hydrogen is produced through low-emission sources such as cellulosic biomass or renewable natural gas, well-to-wheel emission reductions can be in the range of 83 to 85% (DOE, 2012). If electrolysis is used to produce hydrogen, emissions depend on electricity generation sources and can be near zero.

While hydrogen is not currently available as an automotive fuel in most locations, studies estimate the cost of fuel at the pump, excluding taxes, would likely range between US$0.92 and $1.53 for the equivalent of a litre of gasoline, with the lower end of the range corresponding to hydrogen produced from natural gas reformation and the higher end to hydrogen from distributed electrolysis (NRC, 2013). FCVs are approximately twice as efficient as conventional internal combustion engine vehicles; therefore, overall fuel costs may be relatively low once economies of scale are achieved. Assuming hydrogen production incorporates CCS technologies to reduce emissions, the NRC (2013) estimates that annual fuel costs for an FCV in 2030 would be approximately 65% of those for a gasoline-powered vehicle.

Energy Substitution in Passenger and Freight Transportation

The impacts of alternative fuel and vehicle choices on driving range and refuelling differ in their importance depending on travel type and mode of transportation. Urban passenger transportation occurs within a relatively concentrated geographic area, involves comparatively short trips separated by frequent intervals and vehicle downtime, and can be handled with smaller vehicle sizes. In comparison, long-haul freight transportation often requires vehicles to operate and travel over large geographic areas and to operate continuously or near-continuously for large amounts of time, and it requires larger vehicles capable of carrying heavy loads.

For long-haul freight trucking, a switch to an alternative propulsion system such as an electric motor powered by batteries or fuel cells would likely require large compromises in terms of driving range (Fulton & Miller, 2015). Current diesel trucks can achieve driving ranges of over 1,600 kilometres. Vehicles running on LNG and FCVs running on hydrogen can achieve ranges of 800 kilometres, but would require much larger fuel storage capabilities than traditional diesel trucks (Fulton & Miller, 2015). Battery electric trucks could theoretically be designed to achieve such ranges, but would require very large battery systems and would incur a significant weight penalty due to the size of the battery (Fulton & Miller, 2015). Charging times for electric trucks may be a barrier to adoption due to the additional time required for refuelling, especially in the absence of a high-speed charging station. Biodiesel represents the most attractive fuel choice for long-haul trucking in many contexts, because it does not reduce range or cause other operational changes. BEVs (along with HEVs), however, may be more applicable to light- and medium-duty trucks like delivery vans and garbage trucks, which have limited ranges and frequent stops and starts that facilitate energy savings through regenerative braking (Sims *et al.*, 2014). Transit buses can also be electrified with either battery systems or overhead wire systems.

For passenger transportation and LDVs, electricity is a more viable fuel choice, as range concerns are less acute. Commuter vehicles can be recharged at standard outlets while they are not in use. Development of rapid recharging stations can also focus more intensively on urban areas, whereas for long-haul trucking, charging infrastructure development would also need to occur along major trucking routes between cities. PHEVs allow passengers to rely predominately on electricity to meet urban travel needs, while preserving their ability to rely on gasoline to fuel longer, intercity trips.

3.2.3 Systemic Considerations for Transportation

People and businesses can contribute to emission reductions directly by investing in more efficient vehicles or vehicles running on low-emission fuels, switching to low-emission modes of transport such as mass transit or walking and cycling, or reducing their travel needs. The potential to pursue these strategies, however, is also influenced by systemic issues pertaining to transportation systems and their dependence on long-lived infrastructure. The Panel identified two key considerations affecting the potential for emission reductions:

- fuel production, distribution, and refuelling systems and infrastructure; and
- urban form and transportation infrastructure.

Fuel Systems and Infrastructure

Alternative fuels differ in the extent to which they require large-scale changes to fuel production and distribution systems and refuelling infrastructure. Natural gas and propane, for example, are widely available in North America and would require few changes to already well-established production and distribution systems. New investments would be needed to build additional refuelling stations and dispensing equipment; however, LNG and CNG fuelling stations are currently available in some areas of the United States, particularly in areas that service long-haul trucking (DOE, 2015b).

Electric vehicles benefit from existing infrastructure in the form of power plants and electricity grids. Widespread adoption of these vehicles, however, would be limited in part by the availability of dedicated high-speed charging stations. Expanding reliance on electricity to power transportation needs will place additional demands on electricity grids and could require modest grid expansion and new high-voltage transmission lines. Due to the greater efficiency of electric motors, however, the addition of electric vehicles has a relatively small impact on overall electricity demand. Hydro-Québec estimates that the electricity consumed by one million electric vehicles would amount to less than 2% of total electricity sales in Quebec in 2009 (Hydro-Québec, n.d.-b). Grid impacts of electric vehicles also vary over the course of the day or week (NRC, 2013). If vehicle recharging occurs during peak demand times, new flexible power plants may be required; alternatively, charging during low-demand hours such as at night may avoid this need.

Infrastructure requirements for hydrogen FCVs are extensive, as there are very few hydrogen refuelling stations in Canada — though approximately 50 stations are expected to be operating in the United States by the end of 2015 (DOE, 2015b). Hydrogen is used for a variety of industrial purposes, and expanded uptake of hydrogen as a transportation fuel may partially benefit from existing hydrogen distribution systems such as pipelines, high-pressure tube trailers, and liquefied hydrogen tankers (DOE, 2015b), but new production facilities and refuelling infrastructure will be needed if FCVs are widely adopted. The costs of new hydrogen production facilities would vary depending on the mode of production. A hydrogen development pathway focused on low-emission production (e.g., incorporating CCS, relying on electrolysis from low-emission electricity, or using biomass gasification) would entail higher costs than one relying on steam-reformation of natural gas (NRC, 2013). The development of a highly decentralized production system may eliminate the need to transport large amounts of hydrogen over long distances. According to the NRC (2013), hydrogen refuelling infrastructure would likely begin with truck delivery from local distribution points, and could eventually transition toward refuelling stations with on-site generation capabilities.

Biofuels pose unique challenges in terms of fuel production processes and scalability. Expanding biomass production would require new conversion facilities as well as harvesting and transportation equipment for transporting biomass from agricultural areas to production facilities (NRC, 2013). To be economical, conversion facilities must be relatively close to the site of biomass production, though some biofuels can use distribution systems that already exist for petroleum products (NRC, 2013). The amount of biomass that can sustainably be used for transportation fuels without adverse impacts on the environment, agricultural systems, and food prices is also a consideration, particularly for corn-grain ethanol (IEA, 2011; Kahn Ribeiro *et al.*, 2012; Sims *et al.*, 2014). Biomass production may be associated with adverse impacts such as soil erosion and high levels of nitrogen fertilizer use — a source of greenhouse gas emissions that can negatively impact nearby water bodies — and water consumption (Smil, 2010). While these impacts are particularly significant for corn-based ethanol, cellulosic biofuel production could also have adverse environmental and agricultural impacts. Crop residues are often used in agronomic management to recycle nutrients into the soil, replenish soil organic matter, and prevent soil erosion (Smil, 2010). Removing these residues from farms and using them for fuel production may hurt agricultural sustainability. The environmental impacts from biofuel production, however, can be managed by adopting sustainable agricultural and forestry practices, and by regulation where necessary.

Urban Form and Transportation Infrastructure

Transportation emissions are also a function of the built environment and urban form. In cities, per capita emissions from transportation fall as population density increases (Kennedy *et al.*, 2009; Rickwood & Searle, 2011; as cited in Sims *et al.*, 2014). Higher population densities can reduce travel needs and make mass transit and non-motorized transportation more viable. In contrast, mass transit systems are more costly and difficult to deploy in lower-density suburban communities (Sims *et al.*, 2014). Cities differ widely in their use of non-motorized transportation, reflecting the influence of urban form and planning (Naess, 2006; Merriman, 2009; Kahn Ribeiro *et al.*, 2012). The share of trips taken by walking, cycling, or mass transit is 50% or higher in cities in Asia, Africa, Latin America, and Western Europe. Cities such as Amsterdam, Copenhagen, Melbourne, Bogota, and Curitaba have demonstrated the role that deliberate land-use planning and coordination can play in supporting higher reliance on non-motorized transportation (Beatley, 2000; Bongardt *et al.*, 2010; Gehl, 2011; Kahn Ribeiro *et al.*, 2012). Investments in bus rapid transit, light rail transit, and metro and commuter rail systems can also enable mode shifts in urban and suburban areas, leading to emission reductions (Kahn Ribeiro *et al.*, 2012).

Regional and intercity transportation infrastructure can affect transportation system emissions. Investments in highway infrastructure, for example, can contribute to dominance of road-based transportation over other modes. In the United States, the development of the interstate highway system increased kilometres travelled on roads, contributed to ex-urban development, and played a role in the lack of passenger rail systems (Shalizi & Lecocq, 2009). In the Canadian context, development of a high-speed train system powered by low-emission electricity in the corridor between Toronto, Ottawa, and Montréal could reduce emissions substantially without increasing total travel times for most trips (Smil, 2014).

The long-lived nature of urban form and transportation infrastructure can lock in particular transportation systems and their associated emission trajectories for decades (Shalizi & Lecocq, 2009). Current infrastructure investments and urban planning decisions are consequently critical to determining future transportation modes. Over the medium and long term, investments in transportation infrastructure, along with transit-oriented development and urban planning that prioritizes denser communities, mass transit, and non-motorized transit, could decrease the global emission intensity of transportation by 20 to 50% below 2010 levels, assuming most vehicles remain powered by fossil fuels (Sims *et al.*, 2014). Alternatively, the importance of emission reductions associated with such shifts to public transit and avoided travel is reduced or eliminated if vehicle fleets transition to alternative, low-emission energy sources.

3.3 BUILDINGS

Key Findings

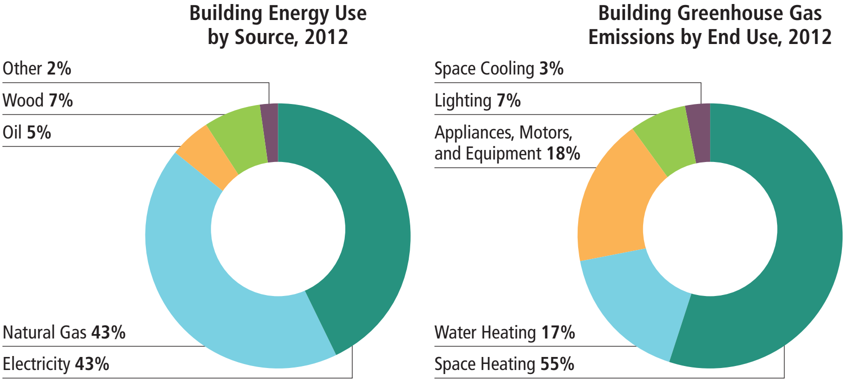
- Space and water heating account for most energy use and carbon dioxide emissions in the buildings sector in Canada.
- Buildings that incorporate features such as passive solar design; enhanced use of insulation; and air-, ground-, and water-source heat pumps can reduce heating and cooling demands by 60 to 90% over conventional construction.
- Dramatic efficiency gains can make it economically viable for buildings to convert to low-emission electricity to meet all remaining energy needs, resulting in substantial reduction of emissions in this sector.
- Low-emitting district energy systems powered through renewable energy and cogeneration can also reduce emissions.
- Governments can support emission reductions through building codes, energy efficiency standards, capacity development, and urban planning.

Emissions from residential, commercial, and institutional buildings (referred to collectively as the buildings sector) accounted for roughly 29% of energy use in Canada and almost a quarter of Canada's greenhouse gas emissions as of 2012 (including the indirect emissions from electricity generation) (NRCan, 2014h). The buildings sector relies mainly on electricity and natural gas to meet energy needs (see Figure 3.4). As a result, the emission profile of the sector varies depending on the carbon intensity of electricity in each region. Space heating accounts for most energy use (and emissions), but water heating is another significant source of demand, as are appliances, motors, and equipment (see Figure 3.4). The buildings sector is characterized by fairly stable energy use and greenhouse gas emission levels (NRCan, 2014h) and slow building stock turnover.

Changes to reduce emissions in this sector can be made at various scales, from urban form to the building envelope to individual appliances and devices (Ürge-Vorsatz *et al.*, 2012). The Panel's analysis starts from the premise of a low-emission electricity system and explores strategies to enable emission reductions via efficiency gains and fuel switching. The discussion focuses on energy used for heating, since space and water heating together represent 72% of carbon dioxide emissions from the sector, and in most parts of the country fossil fuel energy is used to power space and water heaters.

3.3.1 Improving Building Efficiency

Energy efficiency improvements, including higher-efficiency space- and water-heating systems, gains in appliance efficiency, and energy-saving lighting, have all contributed to major reductions in energy demand from buildings



Data Source: NRCan, 2014h

Figure 3.4

Building Energy Use by Source and Greenhouse Gas Emissions by End Use, 2012

The buildings sector relies on two main sources of energy: natural gas and electricity. The *oil* category includes heating oil, light fuel oil, kerosene, and heavy fuel oil. The *other* category includes coal and propane. Most greenhouse gas emissions from the buildings sector (including associated electricity emissions) are associated with space heating. Water heating and appliances, motors, and equipment are also important emission sources. Upstream emissions from the production of non-electricity fuel sources are reported as industrial emissions and are excluded. Greenhouse gas emissions include those associated with the consumption of electricity from fossil fuel-fired power plants as well as those from other energy sources.

(NRCan, 2013).[23] However, these gains are offset by many other factors that are increasing demand, including population growth, the increasing size of residential and commercial floor space, and reliance on personal electronics and other equipment (NRCan, 2013).

Improved building design is a key strategy for reducing emissions going forward. Buildings can now be designed that demand 60 to 90% less heating and cooling energy than conventional construction (Ürge-Vorsatz *et al.*, 2012). In addition, the energy savings from operation of these buildings can offset the added costs of construction. Energy-saving designs are not only applicable for new buildings, but can also be used to lower energy use by at least half in existing buildings (Ürge-Vorsatz *et al.*, 2012). The Panel concluded that energy-efficient buildings featuring passive solar design; enhanced use of insulation; and air-, water-, and ground-source heat pumps hold the most promise for significant reductions in emissions in the building sector.

- *Passive solar design:* Passive solar building design can yield large energy savings by maximizing solar heat during cold months and minimizing it during warm months. This is achieved through placement of windows and awnings, building orientation, and use of thermal mass (e.g., a stone wall) to absorb heat (DOE, 2013a). The *Passive House Standard* is a highly aggressive standard for building design that can reduce heating requirements to as little as 1/25 of those of existing buildings, thereby requiring very little energy beyond the sun to maintain comfortable indoor temperatures (Harvey, 2009). Buildings that conform to the Passive House Standard are estimated to cost only 5 to 16% more than traditional construction, while some commercial buildings may even save money in construction as they require smaller mechanical and electrical systems (Harvey, 2009; Ürge-Vorsatz *et al.*, 2012; Lucon *et al.*, 2014).
- *Enhanced insulation:* In cold climates, addressing air leaks, using insulation, and installing high-efficiency windows can together reduce heating energy needs to between one-quarter and one-tenth of the amount required when using standard practices (Ürge-Vorsatz *et al.*, 2012).
- *Heat pumps:* Ground, air, or water (e.g., from a lake or river) can be used as the source of latent heat for a heat pump that can provide space heating, water heating, and even cooling. These systems can replace more carbon-intensive heating forms including oil, natural gas, and electricity. Heat pumps are least carbon intensive when the electricity used to power the pump is from a non-emitting electricity source. Natural Resources Canada estimates energy cost savings of 65% from a ground-source heat pump relative to an

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[23] As in other end-use sectors, electric efficiency gains yield emission reductions in areas where electricity is generated from emitting sources like coal, but not where electricity is generated from renewables such as hydro.

electric furnace (NRCan, 2004). In well-insulated buildings, heat pumps can run during periods where intermittent power sources such as wind and solar are available, further reducing their emission profile (Harvey, 2009).

District energy systems that rely on the cogeneration of heat and power offer an alternative approach to reducing carbon dioxide emissions associated with heating in conventional buildings. Such systems often take advantage of cogeneration by using heat from electricity generation distributed in the form of steam or hot water through a communal heating grid. However, where buildings are already very efficient, the use of district energy systems may not be economical because of the infrastructure and maintenance costs (Lucon *et al.*, 2014). Cogeneration is particularly suited to the buildings sector due to the low temperature of the heat required for space- and water-heating needs (compared to industry needs). Ürge-Vorsatz *et al.* (2012) note that "[s]ystem efficiency is maximized if heat from the cogeneration of electricity is supplied at the lowest possible temperature, as this minimizes the reduction in electricity generation caused by withdrawing useful heat from a steam turbine, maximizes the fraction of waste heat used, and minimizes heat losses during distribution." Several cogeneration district heating systems have been established in Canada, mainly providing heat to commercial and institutional spaces. In Ontario, the London cogeneration facility and the Sudbury district energy hospital cogeneration plant both use natural gas as an energy source and provide electricity to the grid as well as steam for space heating and cooling in nearby buildings (IESO, n.d.-a, n.d.-b). However, there are limits to the emission reductions that can be achieved through cogeneration when natural gas or other fossil fuels are used.

3.3.2 Energy Substitution in Buildings

Space heating accounts for 55% of building carbon dioxide emissions (NRCan, 2014h). Reliance on low-emission electricity as a heat source could enable substantial decarbonization of the sector. In most parts of the country, buildings currently rely on natural gas (or heating oil) rather than electricity for economic reasons.[24] Any comparison of the costs of heating options will be highly context specific, depending on fuel prices, the heating technologies used (and their efficiencies), the level of demand, and other factors. In general, given the cost differentials and the large quantities of electricity that would be needed to supply heat using traditional technologies, electrification is likely only feasible when coupled with significant improvements to the building envelope that result in lower heating requirements, and also potentially

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[24] Quebec is an exception. Due to the low cost of hydropower, it is widely used as a heat source in homes (Hydro-Québec, n.d.-a, 2014; NRCan, 2014h).

increased reliance on heat pumps (Lucon *et al.*, 2014). In buildings that meet the Passive House Standard, much of the required heat comes from people, lighting, and appliances as well as passive solar, requiring little additional heat from heating systems (Harvey, 2009).

Other non-emitting energy options, including solar thermal and biomass, are available for some buildings. Solar thermal systems use the sun's energy to warm a fluid that can be circulated in the home for space and water heating. These systems can complement traditional heating systems and are particularly effective on well-positioned roofs in sunny locations. Biomass, primarily wood, is also widely used for home heating, particularly in rural areas. Biomass is typically regarded as a low-emission energy source and can be economical in some contexts. However, drawbacks to biomass as a heating source include its labour-intensiveness and local air quality impacts, although the latter can be addressed with modern low-emission heaters that are commercially available.

District energy systems can support energy substitution when they rely on low-emitting fuels or waste products. These systems are most viable in densely populated areas or areas where buildings are proximate to industry. In Vancouver, the Southeast False Creek Neighbourhood Energy Utility collocated its district energy system with a municipal sewage-pumping station and installed a heat pump that uses waste heat from sewage pipes to heat water, which is then circulated to local buildings for space and water heating (City of Vancouver, n.d.). The system is integrated with solar thermal systems on some rooftops that further heat the water. Natural gas boilers provide a supplemental heat source on very cold days (City of Vancouver, n.d.). This system creates enough "energy for heat and hot water for 3.5 million square feet of building space" (City of Vancouver, 2014). In Toronto, cold water from Lake Ontario is used to chill a closed-loop district cooling system used by many downtown commercial buildings in the summertime (Enwave, 2013).

3.3.3 Systemic Considerations for Buildings

A key barrier to addressing emissions from buildings is the high cost of electricity as a heat source relative to natural gas in many contexts. This problem can primarily be addressed through extensive efficiency improvements that substantially reduce energy demand, making the higher per-unit costs of electricity less burdensome. This trade-off highlights the importance of pairing efficiency and fuel-switching responses in the buildings sector.

The buildings sector involves many decision-makers who might not be experts in energy management, and it can be time-consuming, complex, and costly to determine the most beneficial strategies for reducing energy losses. In landlord-tenant arrangements where the party making energy choices is not the same as the party paying the costs, there may be limited incentives to make upfront investments (Gillingham & Palmer, 2014). Harvey (2009) emphasizes the importance of integrated design processes that bring together all people involved in building design, noting that "[t]he main obstacles to achieving…high energy savings in new buildings is a lack of knowledge and motivation within the design profession[s]." Governments can address these problems through building codes, community engagement strategies, capacity development, energy efficiency standards, and demonstration projects (see Chapter 4) (Harvey, 2009; Lucon *et al.*, 2014). Transitions in the building sector will not yield large emission reductions in the near term, but near-term action can avoid further lock-in to inefficient infrastructure and equipment and improve the long-term emission trajectory (Lucon *et al.*, 2014).

Governments make structural choices that constrain or enable emission reductions in the buildings sector. For instance, new suburban developments composed of low-density and/or energy-inefficient housing can lock in high-emission building stock. In contrast, urban densification can reduce energy use, since attached dwellings require less energy per occupant. As discussed in Section 3.2, densification can yield co-benefits by lowering personal transportation emissions, since people live closer to services, work, and public transportation. Research from Toronto found that per capita greenhouse gas emissions in suburban settings are more than twice as high as in the high-density urban core, reflecting both lifestyle (and particularly transportation) differences and amount of living space occupied (Norman *et al.*, 2006). High-density neighbourhoods can be made more appealing when they are of mixed use: proximate to work, services, and transit.

3.4 INDUSTRY

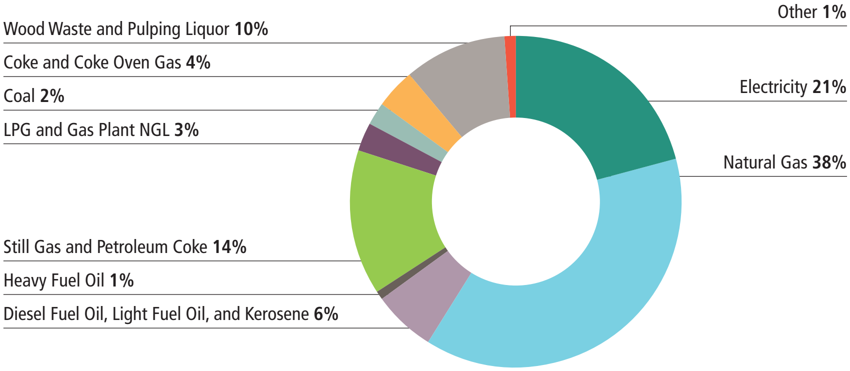
Key Findings

- Transitioning to a low-emission energy system will require substantial emission reductions in the oil and gas industry and across a range of other industrial activities. The key challenge is often identifying low-emitting and economical ways to produce high levels of heat, which account for 75% of industrial energy demand.
- Industry could enhance energy efficiency by improving equipment and maintenance, integrating processes to reduce demand, and reducing the use of energy in material processing.
- Greater reliance on low-emitting electricity can further drive emission reductions, and biomass could also be an important energy substitution option for some industries. CCS technologies are particularly relevant for industries that produce concentrated streams of carbon dioxide and are near potential geological storage sites. Monitoring and repairing leaks in natural gas production and distribution systems and reductions in venting and flaring could lower fugitive emissions in the oil and gas industry.
- The price responsiveness and heterogeneity of the industry sector point to the benefits of a uniform carbon-pricing policy. Governments can also encourage emission reductions by enhancing access to low-emission electricity, developing infrastructure to support low-emission energy technologies, promoting collaborative research, and sharing innovative practices and technologies.

In 2012, industry accounted for 38% of total energy use in Canada and 34% of greenhouse gas emissions (NRCan, 2014h). Coal mining and upstream oil and gas are together the largest industrial energy user, followed by pulp and paper, manufacturing (e.g., food, textile, automobile production), and petroleum refining. Industry uses energy in two key applications: to run motor systems and as a heat source. Motor systems generally power pumps, compressors, and other mechanical equipment using electricity as an energy source. However, in Canada, 75% of all industrial energy use is for process heating (NEB, 2010). Heat is widely used to convert raw materials into useable products (e.g., trees into paper), and fossil fuel energy sources are used heavily for these applications. As a result, the key challenge for reducing emissions from industry is to identify low-emitting and economical ways to produce high levels of heat.

The type of energy used by industry differs from Canada's overall energy mix. Industry relies heavily on natural gas and electricity, but also uses large quantities of still gas and petroleum coke, as well as wood waste and pulping liquor. Figure 3.5 shows this energy supply mix for industry, and Figure 3.6 shows the breakdown of greenhouse gas emissions across industries. Because different industries use different energy sources, the share of emissions for each industry does not match its share of overall energy use. For instance, extensive use of carbon dioxide-emitting natural gas, still gas, and petroleum coke in the coal mining and upstream oil and gas industries means this sector has a particularly high emission profile, while heavy reliance on biomass in the pulp and paper industry results in a low-emission profile.

Canada's oil and gas industry, and in particular the oil sands, is widely recognized to be an important economic driver for the nation but also a growing source of carbon dioxide emissions (although future growth of the industry is linked to the price of oil). Most industrial emissions have been stable or declining over recent decades, but the oil and gas industry is an important outlier. Emissions from oil and gas production in Canada grew 63% between 1990 and 2012 (Environment Canada, 2015c), primarily reflecting growing oil sands production. Based on 2014 production forecasts, the greenhouse gas emissions of the oil sands could be twice their 2013 level by 2025 (CCA, 2015b), though

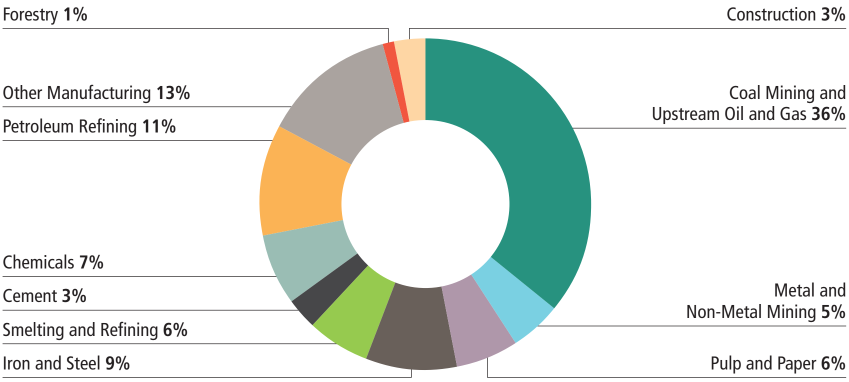


Data Source: NRCan, 2014h

Figure 3.5

Industrial Energy Demand by Energy Source, 2012

Natural gas is the largest single energy source for industry, followed by electricity, then still gas and petroleum coke. LPG is liquefied petroleum gas and NGL is natural gas liquids.



Data Source: NRCan, 2014h

Figure 3.6

Greenhouse Gas Emissions by Industry, 2012

Coal mining and upstream oil and gas account for 36% of industry emissions, followed by manufacturing and petroleum refining. Emissions include those associated with the consumption of electricity from fossil fuel-fired power plants. These data exclude industrial process emissions. Fugitive emissions, including venting and flaring of natural gas, are also excluded. Their inclusion would increase the share of emissions from upstream oil and gas. Canada's *National Inventory Report* (NIR) indicates fugitive emissions accounted for 39% of emissions from the upstream oil and gas industry in 2013 (Environment Canada, 2015c).

the pace of emission growth will depend in part on global oil prices and access to new markets. Emissions from the oil sands arise from surface mining, in situ extraction, and bitumen upgrading, and the technologies and process changes that could reduce emissions vary across these activities.

Since energy sources and uses vary across industries, there is no one solution, and emissions need to decline substantially in oil and gas and across a range of other industrial activities. The evidence points to some overarching options for reducing emissions through energy efficiency, CCS, and energy substitution. This section identifies these options and some related systemic considerations. To further illustrate these ideas, more in-depth focus on the findings of the Council's Expert Panel on the Potential for New and Emerging Technologies to Reduce the Environmental Impacts of Oil Sands Development (the Oil Sands Panel) is integrated throughout each subsection (Boxes 3.4 to 3.7). The discussion focuses mainly on in situ extraction processes, since this is the largest source of emissions and a growing one, but upgrading technology options are also explored.

3.4.1 Improving Industry Efficiency

Energy represents a large share of overall costs for industry, so many traditional energy efficiency opportunities have already been exploited in an effort to economize (UNIDO, 2010). If more stringent emission reduction policies were introduced, several overarching efficiency options could lead to further reductions (for further discussion see Brown *et al.* (2012), Banerjee *et al.* (2012), IEA (2009a)).

Improving Equipment and Maintenance

Potential efficiency gains are estimated at 20 to 25% for motor systems, and 10 to 15% for steam systems used in high-heat applications (IEA, 2007). For motor systems, efficiency gains can be achieved through many strategies, including better aligning the motor capacity to the system need, using adjustable speed drives to continuously adjust motor power in line with demand, and improving maintenance (IEA, 2007; Brown *et al.*, 2012). For steam systems, efficiencies can be gained through improving pipe insulation, matching supply and demand, and enhancing system maintenance (IEA, 2007).

Reducing the Use of Energy in Industrial Materials Processing

Globally, most industry emissions occur in the transformation of natural resources into production materials (e.g., conversion of iron ore into steel) (Fischedick *et al.*, 2014; IPCC, 2014b). In some cases, it may be possible to use entirely new production processes that achieve these transformations with little or no energy. For example, in the production of paper, chemical additives could reduce the substantial amount of heat used to dry paper (Laurijssen *et al.*, 2010). However, enhanced use of chemicals for material processing may raise other environmental concerns, particularly in terms of water pollution. Novel process changes could be an important source of energy savings in the chemicals and petrochemicals industries (IEA, 2009a). Enhanced use of catalysts to aid in chemical reactions can make current conversion processes more efficient or allow for the use of alternative, less energy-intensive processes. The use of membranes to separate chemical components is another promising technology (IEA, 2009a).

Integrating Processes to Reduce Demand

Cogeneration of heat and power is well-suited to facilities that have high demand for both heat and power, including pulp and paper, chemical and petrochemicals, and refining (NEB, 2010). Cogeneration typically relies on natural gas combustion but can use other energy sources, such as concentrated solar power (which uses mirrors to concentrate the sun's rays) or biomass. The emission reduction benefits of cogeneration depend on the efficiency of conventional technologies. In industrial contexts, boilers often have efficiencies of 80% or higher, which is difficult to improve upon (CIEEDAC, 2014). As a result, the emission benefits of cogeneration may be relatively modest.

The *Global Energy Assessment* concludes that "[t]he only way to cut energy use by industry more than marginally is to use much less of the products of industry and to sharply increase the rate of product reuse, renovation, remanufacturing, and recycling" (Banerjee *et al.*, 2012). Material efficiency in design and production and more intensive product use could reduce demand. For instance, 26% of liquid steel is wasted as process scrap, and elimination of this waste could reduce carbon dioxide emissions from the sector by 16% (Milford *et al.*, 2011). Similarly, using recycled aluminum rather than raw materials to produce new aluminum requires only 5 to 8% as much energy (IEA, 2009a). The replacement of an energy-intensive material with an alternative material that provides the same service while requiring less energy is also possible in some cases. For instance, greater reliance on wood in construction could reduce demand for steel and cement (Brown *et al.*, 2012). In some cases, integrated industrial areas can achieve greater system-level efficiencies than would individual firms, through cascading energy and use of one firm's waste products as inputs to another firm's production process (Ehrenfeld & Gertler, 1997). These integrated industrial areas use an industrial ecology approach to "[move] from linear throughput to closed-loop material and energy use" (Ehrenfeld & Gertler, 1997).

3.4.2 Carbon Capture and Storage in Industry

Continued use of fossil fuels to meet high-heat application needs can be compatible with significant carbon dioxide reductions when emissions are captured and stored (as described in Section 3.1.2). Some industrial processes are particularly well-suited to CCS, owing to their proximity to potential storage locations combined with highly concentrated carbon dioxide emission streams that arise at specific production points. Cement is one such example: "50% of CO_2 emissions arise from calcination of limestone. Capturing the CO_2 and sequestering it is the only option for avoiding these CO_2 emissions to the atmosphere" (Brown *et al.*, 2012). As of 2013, five large CCS facilities were in operation, sequestering emissions from industrial processes that have relatively

Box 3.4
Oil Sands In-Depth: Exploring Energy Efficiency

Research points to several potential efficiency gains for in situ extraction and upgrading of bitumen, including insulated tubing, cogeneration, and use of solvents.

In situ extraction processes traditionally use steam to separate bitumen from surrounding materials below the ground, and then use pumps to bring the bitumen to the surface. Vacuum-insulated tubes reduce heat loss as steam moves from the surface into the well. According to Canada's Oil Sands Innovation Alliance (COSIA), the use of this tubing can reduce the time required to pre-heat a well before bitumen starts to flow from three to four months to 75 days (COSIA, n.d.-b).

Cogeneration has also yielded significant energy efficiency gains for the oil sands industry (Moorhouse & Peachey, 2007). It is particularly advantageous when oil sands extraction and upgrading are collocated, creating demand for both heat and electricity. Cogeneration is also an option for facilities that require heat and where infrastructure exists to sell excess electricity to the grid. This can reduce the greenhouse gas emissions of Alberta's electricity system by allowing electricity from natural gas cogeneration facilities to meet demand that would otherwise have been met by coal-fired power plants (Moorhouse & Peachey, 2007).

Research is under way to develop in situ extraction processes that use solvents as a supplement to or in place of steam to release bitumen. Solvent-assisted extraction (a hybrid of steam and solvent extraction) could lower emissions by 15 to 35% and could be deployed in the near term. Solvent-based technologies that do not require the use of steam, which are at an early pilot stage, could cut emissions by up to 90% through the elimination of steam use and reduced need for post-extraction upgrading (since the use of solvents would potentially partially upgrade the bitumen in situ). Such a reduction could lower emissions by 2030 so they are close to that of average crude in the United States. The use of solvents for in situ extraction raises potential groundwater contamination concerns and could be a source of fugitive emissions, but it could also lower air pollution and water use in the oil sands (CCA, 2015b). The Oil Sands Panel concluded that solvent-based extraction is among the transformative technologies that hold the greatest potential to reduce emissions from the oil sands, though it is not likely to be deployed in the near term (CCA, 2015b).

pure (and therefore low-cost) carbon dioxide waste streams (Bruckner *et al.*, 2014). These five facilities have collectively stored over 30 megatonnes (Mt) of carbon dioxide (Bruckner *et al.*, 2014). An inventory of existing projects indicates that gas processing is the most common industrial application of CCS, but that CCS has also been applied in coal gasification, ethanol production, and hydrogen production (MIT, 2015). The captured carbon is either used for enhanced oil recovery or injected into saline reservoirs (MIT, 2015).

Box 3.5
Oil Sands In-Depth: Exploring CCS

The Oil Sands Panel found that CCS, with current technology, is most viable for bitumen upgrading, as opposed to bitumen extraction (CCA, 2015b), mainly because upgrading can produce a concentrated stream of carbon dioxide for capture. Alberta also has accessible carbon dioxide storage capacity in exploited gas reservoirs and saline aquifers. The Panel observed that "[p]ractical considerations in retrofitting upgraders for CCS likely limit carbon capture to 20 to 40% of the carbon stream." In the medium term, this technology offers the greatest promise to reduce emissions from upgrading (CCA, 2015b). The first commercial-scale application of CCS in the oil sands is the Quest CCS project, which will capture over one million tonnes of carbon dioxide a year from Shell's Scotford upgrader and inject it underground. The project could become operational in late 2015.

3.4.3 Energy Substitution in Industry

Several energy substitution options could lead to reduced emissions (see Banerjee *et al.* (2012), Brown *et al.* (2012), IPCC (2014b)); however, the viability of different energy sources varies based on characteristics specific to given industries and end-use needs. Options most pertinent for transformational change include enhanced use of electricity and biomass.

Electricity

Increased reliance on electricity can reduce emissions if the electricity comes from a low-emission source. Electricity is already widely used in industry to run motor systems (NEB, 2010), and as a heat source in some applications. For example, electric arc furnaces are used in the iron and steel industry to recycle scrap steel (IPCC, 2014b). Several steel electric arc furnace plants are operating in Canada; this production technique requires less than half the energy required to produce steel from iron ore (CIPEC & CSPA, 2007). The aluminum industry relies heavily on electricity; smelting uses an electric current to convert alumina into aluminum. Quebec's 10 aluminum smelters use the equivalent of 14% of Hydro-Québec's installed capacity, and the aluminum industry produces roughly half of the electricity it uses (AAC, 2012).

Biomass

Biomass is another low-emission energy source that can be used in high-heat applications. The pulp and paper industry already sources approximately 60% of its energy from waste biomass (NEB, 2010). Waste products can also be combusted as a fuel source in some applications. Brown *et al.* (2012) note that "[c]ement kilns are particularly suited to the incineration of waste; the high incineration temperature, alkaline environment, residence time and good mixing of gases and products ensure that the waste is safely disposed of with minimal environmental impact."

Box 3.6
Oil Sands In-Depth: Exploring Energy Substitution

Low-emission electricity sources could be used to displace other energy sources in several oil sands applications. Electricity from hydropower or geothermal resources, or biomass, rather than natural gas, could be used to generate steam for in situ extraction. Modular nuclear power plants could also be used to provide both heat for steam production and electricity. However, these alternatives face substantial barriers. Using electricity from hydropower in oil sands operations would require new transmission lines and potentially new hydropower generation facilities. Geothermal power for electricity generation in the oil sands is largely untested, though it is being explored in Saskatchewan in an area with geology similar to the Athabasca region. The main barriers for modular nuclear power relate to cost uncertainty and public concerns about safety, waste storage, and environmental impacts. None of these alternative energy sources is likely to be widely deployed in the oil sands without more stringent emission mitigation policy and additional support from industry and government.

3.4.4 Systemic Considerations for Industry

Industry is price sensitive and therefore responsive to policies that constrain or increase the price of emissions. Chapter 4 reviews the policy instruments that could be deployed to limit emissions from industry through binding regulation or price signals. The industry sector is highly heterogeneous, and the technologies used and energy choices made are highly variable, even within a given industry. This variability underscores the importance of introducing a uniform carbon price for industry or finding regulatory approaches that offer firms flexibility in choosing emission reduction strategies. Governments may also be able to support transitions in industry by ramping up low-emission electricity production and by supporting the development of carbon dioxide pipelines. While some industries, particularly oil and gas, may have access to on-site carbon dioxide storage reservoirs, other industries could incorporate CCS if pipeline infrastructure existed to move the captured carbon to off-site storage locations. Another major systemic challenge faced by the oil and gas industry is controlling fugitive emissions (see Box 3.8).

Box 3.7
Oil Sands In-Depth: Systemic Considerations

The Oil Sands Panel underscored the importance of carbon pricing for driving greenhouse gas reductions, noting that the current low prices of natural gas and carbon dioxide discourage the use of CCS, low-emitting electricity sources, and solvents. In addition, enhanced emphasis on scientific research and knowledge transfer could further support emission reductions. The Oil Sands Panel noted that collaborative research between industry, academia, and governments can be valuable in addressing complex challenges. COSIA is a group of 13 oil sands producers working to improve the environmental performance of the industry through innovation and collaboration. According to COSIA, “member companies have shared 777 distinct technologies and innovations that cost over $950 million to develop” since the group was established in 2012 (COSIA, n.d.-a). The Panel also noted that regulation can drive innovation when it sets out minimum environmental performance mandates. Finally, government support for the development of CCS infrastructure has enabled projects to move forward.

Box 3.8
Fugitive Emissions from Fuels

Canada’s *National Inventory Report* defines fugitive emissions from fossil fuels as “the intentional or unintentional releases of greenhouse gases from the production, processing, transmission, storage and delivery of fossil fuels” (Environment Canada, 2015c). Fugitive emissions originate from oil and gas activities, including the flaring of natural gases at oil and gas drilling, fracturing, production, and processing facilities, and leaks from compressors, valves, seals, pipelines, and natural gas processing facilities. To a much smaller extent, they also arise from methane release from coal mining and oil sands mining operations.

continued on next page

On a global basis, satellite data estimates show that more than 139 billion cubic metres of gas are flared annually (Elvidge *et al.*, 2009). This is equivalent to about 5% of world natural gas consumption, producing the equivalent of approximately 289 million tonnes of carbon dioxide annually (Johnson & Coderre, 2011). For natural gas production, recent analyses suggest that fugitive emissions are likely in the range of 2 to 3% of the total gas produced, with emissions generally between the levels found in conventional and shale gas production (Bruckner *et al.*, 2014). Estimates of fugitive emissions are uncertain, owing to the significant challenges associated with monitoring and estimating emissions from many disparate sources across the oil and gas industry (Picard, n.d.). It is reasonable to assume that actual fugitive emissions could be significantly larger than values being reported.

Fugitive emissions contributed to about 8% or 61 Mt of Canada's total greenhouse gas emissions for 2013 (Environment Canada, 2015c) — roughly equivalent to the greenhouse gas emissions from the oil sands. The potential for future increase in unconventional gas production and shale/tight oil production in Canada may result in increased fugitive emissions unless corrective actions are taken. Fugitive emissions can be reduced by monitoring and repairing leaks throughout gas production and distribution systems and by capturing gas during well completions instead of venting or flaring.

Governments at many levels are now taking steps to mitigate fugitive emissions. Provincially, the Government of Alberta regulates flaring and venting, setting out best practices for leak detection and repair. As a result, fugitive emission releases per unit of production fell by roughly one-quarter between 2000 and 2010 (Environment Canada, 2015c). The federal government has also announced plans to develop new regulations to manage fugitive emissions. Internationally, Canada is an active member of the Global Gas Flaring Reduction public-private partnership launched in 2002 as a World Bank initiative. This partnership brings together "representatives of governments of oil-producing countries, state-owned companies, major international oil companies, and donor countries to overcome the worldwide barriers of reducing associated gas flaring by sharing global best practices and implementing country-specific programs" (NEB *et al.*, 2008).

3.5 SUMMARY

Across all sectors, existing technologies and energy sources collectively could yield major reductions in Canada's energy-related emissions over the course of several decades. Previous modelling exercises have identified portfolios of actions consistent with those described throughout the chapter, which could reduce Canada's energy-related emissions by 60 to 90%:

- Modelling to find a least-cost approach to meeting the federal government's 2050 target of reducing emissions by 60 to 70% below 2006 levels identifies increased uptake of CCS, greater reliance on biofuels and hybrid vehicles, electrification, and energy efficiency improvements among the key technologies deployed to achieve the target (NRTEE, 2009).[25]
- A more recent modelling exercise considered the actions required to reduce domestic emissions almost 90% below 2010 levels by 2050. Key strategies include greater use of renewables and biomass, energy substitution toward low-emission electricity and biofuels, and enhanced energy efficiency (Bataille *et al.*, 2014).

The *Global Energy Assessment* conducted extensive modelling of pathways with a greater than 50% chance of limiting global average temperature change to 2°C (corresponding to a 30 to 70% reduction in emissions by 2050 from 2000 levels) and identified a similar set of strategies for achieving these results, including efficiency improvements, growth in renewable energy and bioenergy, decarbonization of the electricity sector, and greater reliance on electric vehicles.

In the Panel's view, no purely technological barriers prevent Canada from transitioning to low-emission energy systems. The greater costs associated with these technologies, however, along with other social and institutional barriers, will prevent them from being widely adopted and deployed without additional government policy. Emissions from the energy system can be reduced through three main avenues:

- reducing the energy intensity of the economy;
- capturing and storing carbon dioxide emissions; and
- reducing the emission intensity of the energy consumed.

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[25] The modelling exercise used a mid-point of a 65% reduction, and 10% of the emission reductions are achieved with the purchase of international credits.

The opportunities for reducing energy intensity through efficiency-enhancing technologies and operational changes are widespread across all sectors. In transportation systems, LDVs can be made 30 to 50% more efficient with known technologies. Shifting freight transport to rail also offers substantial efficiency gains. New buildings can achieve 60 to 90% reductions in energy demand for space heating and cooling by using energy-efficient building technologies such as passive solar; enhanced insulation use; and air-, ground-, and water-source heat pumps. In industry, improved equipment and maintenance, industrial integration, and reduced use of energy for material processing can all contribute to reductions in emissions. In electricity, industry, and buildings, greater use of cogeneration could also result in energy savings. These types of efficiency gains often offer early emission reductions and can result in substantial aggregate emission reductions when pursued over the long term.

Deeper emission reductions than these, however, will depend on either using CCS technologies or shifting to low-emission energy sources. Low-emission electricity is the foundation for economy-wide emission reductions in transportation, buildings, and industry. While Canada already benefits from relatively low-emission power generation, remaining high-emission generation facilities will need to be replaced, and all provinces will need to expand low-emission electricity generation capacity to meet growing demand and enable further reductions. Hydropower, nuclear, solar, wind, geothermal, biomass, and fossil fuels with CCS all are viable low-emission generation options for Canada. In the transportation sector, biodiesel is the most promising alternative fuel choice for freight-transportation emission reductions. In passenger LDVs, electric vehicles powered by low-emission electricity offer the possibility of large emission reductions, though alternative fuels and technologies could also play a role. Energy substitution in the buildings sector would likely be dominated by a transition to electricity as a fuel for space heating (which could be viable once major efficiency gains are achieved). In industry, electricity, biomass, and fossil fuels with CCS can all be used as energy sources, with the optimal fuel choice being dependent on the industrial context. Fugitive emissions from the oil and gas industry can be addressed in various ways, such as monitoring and repairing leaks in gas production and distribution systems and capturing gas during well completions instead of venting or flaring.

In many cases, transitions to low-emission energy systems are impeded by larger systemic constraints relating to long-lived capital. Adding new low-emission electricity generation can entail the need for expansion or modification of transmission and distribution systems and result in additional challenges for system management and load balancing. Expanding low-emission generation may also engender public opposition because of localized environmental impacts, and so requires a systemic approach to energy and land-use planning. Transportation systems depend on fuel production and distribution systems, and the prospects of energy substitution may hinge on the extent to which the required refuelling infrastructure is in place. Urban planning and investments in infrastructure can facilitate the development of low-emission buildings, industries, and communities.

4

Public Policies for Low-Emission Energy Systems

- The Need for Compulsory Policy
- Appraising Climate Change Policies
- Compulsory Policy Instruments
- Enabling Policies
- The Potential Economic Impacts of a Low-Emission Transition for Canada
- Summary

4 Public Policies for Low-Emission Energy Systems

Key Findings

- In Canada, select provincial and federal policies have initiated emission reductions, and businesses and consumers are taking independent actions to curtail their emissions. However, more stringent compulsory policy is needed to achieve significant emission reductions overall.
- The choice of policy instruments to drive emission reductions will depend on context and how decision-makers weigh different objectives. Regardless of the type of compulsory policies adopted, there are strategies that can improve their environmental effectiveness, cost effectiveness, distributional fairness, administrative feasibility, and political acceptability.
- Policies that impose a consistent price on carbon throughout the economy are most successful at limiting the costs of emission reductions. Especially in industry, there is a strong argument for policies that put a price on carbon — through either carbon taxes or cap-and-trade systems — because of the sector's heterogeneity and ongoing efforts to limit costs.
- In addition to enacting compulsory policy, other important government roles include adjusting subsidies, making direct investments, providing infrastructure, supporting innovation, and making regulatory processes for low-emitting technologies more efficient.
- Canada could implement climate policies with much greater weight and effect than those implemented to date without compromising its economic well-being.

Earlier chapters have established that Canada meets many of its energy needs through the use of high-emission energy sources, and this dependence will continue in the absence of some combination of major technological and policy change. This chapter explores how policies can motivate transformations to a low-emission energy system. Experience over recent decades illustrates the need for compulsory emission constraints or financial penalties; therefore, the following sections review a range of policies that include these features. Enabling policies that further foster emission reductions are also reviewed. In both cases, the chapter draws out lessons learned in designing and implementing policies for system change.

4.1 THE NEED FOR COMPULSORY POLICY

Some voluntary emission reduction activities are already under way among businesses and individuals. For some businesses, climate change represents an opportunity to bring new low-emission technologies to market, mobilize capital to support emerging technologies, reduce energy costs, and improve corporate reputations. Some businesses are also lobbying for collective action on climate change.[26] At the same time, many individuals are changing their behaviour to reduce emissions, such as by switching modes of transportation and improving home efficiency. Governments have also rolled out public information and education campaigns to encourage businesses and consumers to make these kinds of voluntary behavioural changes.

Head (2008) identifies several features that make reducing carbon dioxide emissions and mitigating climate change a particularly challenging public policy problem, including the variability of the time horizon, the scale of the impacts and expected costs, contested assignment of responsibility, equity concerns, and interrelationships between components of the climate change problem. Additionally, the costs of reducing emissions will be incurred in the near term, while the benefits will vary by region and will mostly be experienced many decades into the future (Victor, 2011). Furthermore, efforts to reduce fossil fuel use in some regions can drive down fossil fuel prices elsewhere and even encourage faster fossil fuel extraction in anticipation of more stringent future policies (Sinn, 2008). The incentive of each country to free ride on emission reductions in other jurisdictions further complicates action and points to the need for an international solution. The presentation of climate change as an environmental problem without acknowledging the risks and opportunities it creates for Canada's energy and financial systems and culture further undermines action. For these reasons, the various policy initiatives undertaken in Canada since the early 1990s — which have largely encouraged voluntary action — have not been enough to reduce emissions to the extent needed to meet federal targets. Rather, overall emissions have risen (see Chapter 2). So long as carbon dioxide can be freely released into the atmosphere, people and businesses will usually choose fossil fuels because they tend to be cheap, convenient, plentiful, widely distributed, easily transported, and energy dense compared to alternatives.

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[26] In the United States, several prominent industry and policy leaders have initiated the *Risky Business* project, which "focuses on quantifying and publicizing the economic risks from the impacts of a changing climate" (Risky Business, n.d.).

It is therefore clear that if widespread emission reductions are desired, new compulsory policy will be needed. Policy-makers can choose between several types of compulsory policies, including carbon taxes, traditional regulations, and market-based regulations like cap-and-trade schemes (see Section 4.3 for a discussion of these instruments). Each of these policies will work in its own way to encourage changes in business decision-making and to motivate consumer behavioural change by changing the price of doing business or imposing new constraints to which businesses and/or consumers will adjust. For example, with an economy-wide carbon tax, individual behaviour change could range from a discrete action like installing a more fuel-efficient furnace to improving home insulation or even moving to a smaller, more energy-efficient home. New policies may even open up the choices available to people. For instance, furnace manufacturers may produce more energy-efficient models if consumers are willing to pay a high enough premium.

Implementing new policies is easier when consumers, businesses, and other governments understand the reasons and the need for government action. The Panel also observed other socio-political conditions that support policy change, such as certain social norms and willingness to change behaviour, new opportunities for businesses, a recognition of the potential co-benefits and avoided costs of reducing emissions, and mechanisms that support interjurisdictional cooperation and harmonization. These conditions have generally been lacking in the Canadian policy landscape. However, recently there have been signs that stronger policy measures may be increasingly feasible: the technologies needed to support widespread emission reductions are more available and affordable, more businesses are pursuing clean technology market opportunities,[27] the public continues to identify the environment as an important public policy issue, and provinces are moving forward with new policies, including some that have demonstrated promise in reducing emissions in some regions and activities (see Section 4.3 for discussion). The provinces also recently agreed to a pan-Canadian energy strategy aimed at fostering collaboration on energy policy and emission reductions (Canada's Premiers, 2015). These developments point to the emergence of a window of opportunity that could allow for further developments in climate change policy.

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[27] According to consultancy Analytica Advisors (2015), in 2015, 50,000 Canadians were employed in clean technology. Clean technology companies use "proprietary technology to deliver products or services that reduce negative environmental impacts, while delivering competitive performance, and/or using fewer resources than conventional technologies" (Analytica Advisors, 2013).

4.2 APPRAISING CLIMATE CHANGE POLICIES

The best choice for climate change policy in a given jurisdiction will depend on the political context, the specific problem the policy seeks to overcome, the sector(s) targeted by the policy, and many other criteria. Environmental policies are often evaluated using some variation on the following criteria (Gupta *et al.*, 2007; Goulder & Parry, 2008):

- *Environmental effectiveness:* This refers to the ability of the policy to achieve its objective of reducing emissions without compromising other environmental objectives (e.g., clean water). All other things being equal, a policy will lead to a greater reduction in emissions when it covers more emission sources and types of greenhouse gases, and when it has more stringent reduction targets and stronger enforcement and penalty provisions (Gupta *et al.*, 2007). Performance reporting and program evaluation are both important tools for assessing the environmental effectiveness of a policy.
- *Cost effectiveness:* The most cost-effective policies are those that achieve their objectives at the lowest possible cost to society. The costs of policies arise from many sources, including economic impacts on people or firms covered by the policy, administrative costs for governments, and wider impacts across the economy (such as on employment or innovation) (Goulder & Parry, 2008). Policies can have free-rider effects, create windfall gains for some participants, or disadvantage new competitors, all of which can influence overall cost effectiveness. If the policy creates an incentive for encouraging technological change, this is also an important consideration in and of itself (Stavins, 1997), and ultimately affects the cost effectiveness of the policy.
- *Distributional fairness:* Climate change policies can have a range of distributional impacts, redistributing wealth across regions, income groups, and even generations. The perceived fairness of this redistribution will vary across segments of society, and inter-regional equity has been a key challenge in negotiating climate change agreements. Because of variations in natural resource availability and energy policy choices across Canadian provinces and territories, the economic burden of emission reduction policies will also vary across the country.
- *Administrative feasibility:* Some policies are straightforward to administer, while others require much more work in order to be successful. Administrative challenges include emission monitoring and verification, enforcement, institutional capacity, and the need to update and adapt policy over time as new information emerges (Gupta *et al.*, 2007; Goulder & Parry, 2008). An additional complication in the Canadian context is the shared responsibility for climate change management between provincial and federal governments (see Box 4.1).

- **Political acceptability:** Political acceptability speaks to the degree of policy-maker buy-in, which depends on public attitudes, special interest groups, structure of the economy, and the support and capacity of civil servants to implement the policy. Challenges in achieving political support could include a lack of familiarity with the proposed policy instrument, concerns about financial losses, or unpopular distributional impacts (Gupta *et al.*, 2007).

Box 4.1
Jurisdictional Context for Canadian Climate Change Policy

Provincial and federal governments have jurisdiction over different environmental matters in Canada, and also have different legal powers (Hsu & Elliot, 2008). Moreover, provincial governments can delegate powers to municipalities (some of which have introduced climate change policies) and the federal government can delegate powers to territorial governments. Schemes to address emissions have been introduced at federal and provincial levels, and the relevant authority exists at both levels. Both federal and provincial governments have the authority to collect taxes, and provinces can regulate industries within their jurisdiction. In addition, the federal government can make environmental laws that apply to provincial areas of responsibility using federal criminal law power (as is used to limit emissions of toxic substances under the *Canadian Environmental Protection Act* (CEPA)). Court decisions taken to date indicate that regulation of greenhouse gases under CEPA would likely be upheld as constitutional (Hogg, 2008). While some have suggested that the federal government could also use its responsibility for peace, order, and good government, or its powers over trade and commerce, as a basis for regulating emissions, criminal law powers may be the best fit (Lucas & Yearsley, 2011). With this range of authorities, no single entity has sole responsibility, and action can take place across both orders of government.

In this context, it is not surprising that policy consistency and alignment is challenging. For instance, an energy producer may be subject to a suite of environmental and industrial policies established by federal, provincial, and municipal governments. A provincial subsidy to the energy sector could dilute the impact of a federal carbon price (Hood, 2013). Or, federal delays in approving developments of interprovincial electricity transmission systems could limit the ability of provinces to collaborate on reducing emissions from electricity. Provincial governments have also argued that they should be provided with opportunities to meaningfully engage in international discussions and negotiations on energy and climate issues given their constitutional authority over natural resources (Canada’s Premiers, 2015).

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Finally, complex relationships exist between federal and provincial governments and Aboriginal peoples. In establishing climate change policies, the Panel noted the importance of respecting the detailed agreements, often defined by land titles and treaty rights, that exist between these parties. This jurisdictional consideration is particularly relevant in the case of building new energy infrastructure, as underscored by the Supreme Court of Canada's recent landmark ruling that granted the Tsilhqot'in First Nation title to over 1,700 square kilometres of land in British Columbia (SCC, 2014).

	Federal	Provincial
Areas of Jurisdiction	Environmental • Coastal waters • Shipping • Federal lands End-Use Sectors • Interprovincial transportation	Environmental • Provincial Crown lands (and the natural resources within them) • Municipal institutions • Resource exploration End-Use Sectors • Electricity generation • Intraprovincial transportation • Buildings • Industry
Powers	• Taxation • Regulation • Criminal law power • Peace, order, and good government • Trade and commerce	• Taxation • Regulation • Property rights • Civil rights

Policies — and the relative importance of the criteria used to judge them — will play out differently across the electricity, transportation, buildings, and industry sectors, and consideration of the nature and dynamics of the targeted sector(s) will inform policy choice. The nature of the problem that a policy seeks to address is also an important factor and shapes the appraisal of policy options. For example, compulsory greenhouse gas mitigation policies such as cap-and-trade schemes and carbon taxes seek to address the hidden costs of emissions, which are typically not considered in the decision-making of producers and consumers, by putting a price on carbon. Alternatively, enabling policies that encourage innovation (e.g., through tax benefits) can help to address the challenge of firms, individuals, or societies at large free-riding on the research and development (R&D) investments of others, since the resulting knowledge and technology eventually becomes a public good (CCA, 2013).

4.3 COMPULSORY POLICY INSTRUMENTS

Compulsory policies take place along a continuum of government intervention. At one end are flexible, market-oriented policies, such as carbon taxes that levy a charge on the harmful outcome (greenhouse gas emissions) and allow firms and households the option of paying the charge or changing their investment choices and behaviour in order to reduce emissions. At the other end are prescriptive command-and-control regulations that specify in detail the investment choices or behaviour of firms and households (e.g., all refrigerators of size X must achieve a minimum energy efficiency standard of Y). Market-oriented regulations (such as a cap-and-trade system) exist somewhere between the two. Each option has its own particular characteristics.

4.3.1 Carbon Taxes

A carbon tax requires individual emitters to pay a fee for every tonne of carbon dioxide released into the atmosphere.[28] Emission taxes create a uniform carbon price, so emitters that can make inexpensive reductions will do so (to avoid paying the tax), while emitters faced with expensive reduction options will pay a tax instead. This ensures that emission reductions are concentrated in the economic sectors or activities where they are least costly. The imposition of a price on all emissions also ensures a constant incentive for further emission reductions, which can create a dynamic incentive for technological innovation. British Columbia introduced a $10/tonne carbon tax in 2008, and by 2015 that tax had been gradually increased to $30/tonne. While energy economists have long known that energy demand falls when the price rises, it will take some time to assess the full effect of British Columbia's carbon tax on fossil fuel consumption and greenhouse gas emissions, particularly since the timing of this tax coincided with an economic recession. However, preliminary research has shown that between 2008 and 2012, British Columbia saw a 17% decline in fuel use per capita in contrast to a slight increase in use per capita in the rest of Canada (Elgie & McClay, 2013). Moreover, the tax seems to have provoked a stronger reduction in gasoline use than would have been prompted by equivalent market-driven increases in the price of gas (Rivers & Schaufele, 2012).

Carbon taxes can raise new income for governments, or they can be made revenue neutral if the new tax revenues are used to fund a reduction in other taxes or to fund lump-sum payments to the general population (the fee-and-dividend approach advocated by James Hansen (Hansen, 2009)). Such revenue-recycling measures can improve the distributional fairness of carbon

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[28] Emissions of other greenhouse gases besides carbon are converted into a carbon-equivalent measure (CO_2eq) based on their global warming potential.

taxes, as has been done with British Columbia's carbon tax. A portion of that tax's revenues supports a refundable tax credit for low-income groups and reduces the tax rates for the bottom two tax brackets (Government of British Columbia, n.d.-a). Revenue recycling could also be used to compensate for uneven regional impacts, address competitiveness concerns, or reduce the distortionary effects of other taxes (e.g., using carbon tax revenues to reduce income taxes, which impose inefficiencies and costs on the economy).

A key administrative benefit of a tax is that the existing taxation system can be used to administer the policy, rather than requiring a new bureaucracy. However, taxation systems do still pose administrative challenges. Policy-makers need to make a series of choices relating to strategies for monitoring or estimating emissions, which activities (if any) would be exempt from the tax, and where to impose the tax: either on upstream producers or downstream consumers. Each of these choices has the potential to simplify or complicate the administration of a tax. In British Columbia, taxes are applied based on the carbon content of each fuel; exemptions are offered for industrial processes, non-combustion emissions, and fuels for farm operations; and, just like the provincial sales tax, taxes are applied upstream, at the wholesale level for motor fuels and at the retail level for natural gas and propane (BCMF, 2013; Government of British Columbia, n.d.-a).

Carbon taxes are a politically divisive issue, as is any policy perceived as increasing energy costs for consumers. The divergence in public support for carbon taxes versus other climate change mitigation policies can be seen in British Columbia, where a public opinion survey found that support for regulatory approaches was at roughly 90%, while support for carbon taxes was at 56% (Rhodes *et al.*, 2014). In general, the public tends not to support policy measures that will impose clear costs on voters, especially when the benefits are delayed (Harrison, 2012). As taxes become increasingly stringent and have a greater financial impact on consumers, public support can decline. Recent survey research from the United States found limited support for carbon taxes when the use of revenues is unspecified. However, a small majority of respondents support revenue-neutral carbon taxes when the revenues are returned to the public, and a slightly larger majority supports carbon taxes when revenues are used to fund renewable energy R&D (Amdur *et al.*, 2014).

4.3.2 Market-Oriented Regulations

Cap-and-Trade Systems

In contrast to a carbon tax, in which the government sets a price on emissions, in cap-and-trade schemes the government sets a limit on the total amount of emissions. Permits are then issued with a total amount equal to the overall cap, and firms must submit enough permits to cover their emissions at the end of each compliance period. Firms can trade or sell permits among each other in order to obtain the permits they need, with the resulting market setting uniform prices for carbon dioxide emissions based on the supply and demand for permits. The market value of the permits encourages emission reductions even beyond a company's cap, enabling the policy's ability to motivate sustained emission reductions over time.

Two carbon trading schemes have been established in Canada. Alberta's Specified Gas Emitters Regulation applies to facilities that emit more than 100,000 tonnes of CO_2eq emissions per year and offers compliance flexibility through emission trading (among other measures) (AEP, 2015). The policy limits the emissions per unit of output (so it is an emission intensity-based trading system rather than a cap-and-trade system), and the lack of stringency of this cap has allowed total emissions to increase substantially since the policy was implemented. In contrast, the province of Quebec recently introduced a cap-and-trade scheme that applies to large emitters and fuel distributors, defined as those emitting the equivalent of at least 25,000 tonnes of carbon dioxide per year (Government of Quebec, 2014). Ontario recently announced plans to join Quebec's scheme. A brief summary of Alberta's and Quebec's programs is provided in Table 4.1.

The distributional impacts of a cap-and-trade system depend on how permits are initially allocated. Distributing permits for free creates value for existing firms (or anyone else) that receive the permits, but can disadvantage new entrants to the system (Stavins, 1997, 1998). An emission trading system can be administratively complex, requiring new administrative systems and processes, careful design of monitoring and enforcement plans, and a series of choices about flexible compliance options. For instance, can permits be banked and used the following year? Should there be a floor or ceiling on permit prices? Should the system be designed with a firm cap, or should the rate of emissions be limited through an intensity-based system? All of these decisions create winners and losers and thus can be contentious.

Table 4.1

Comparison of Alberta's and Quebec's Trading Schemes

Province	Type of Market Instrument	Target and Coverage	Key Features
Alberta	Intensity-based trading system	• 12% reduction in emission intensity by facilities that emit more than 100,000 tonnes of CO_2eq per year • Target increasing to 20% in 2017	• Imposes limits per unit of production rather than in absolute terms • Offset system incorporates Alberta-based emission reduction projects outside of regulated facilities • For those emissions that exceed the 12% intensity reduction target, compliance can be achieved through a payment of a ceiling price of $15/tonne to the Climate Change and Emissions Management Fund (CCEMF) (increasing to $30/tonne in 2017), or other flexible compliance mechanisms • When factoring in total emissions rather than just the emissions that exceed the intensity target, the 2015 effective price ceiling for the system could be up to $1.80/tonne • The scheme resulted in reductions of 61 Mt CO_2eq during the first eight years relative to business as usual and contributions of $578 million to the CCEMF • CCEMF revenues are used primarily to support GHG reduction projects within the province
Quebec	Cap-and-trade system	• Part of province-wide target of reducing emissions 20% below 1990 levels by 2020 • Cap increases in stringency over time • Applies to businesses that emit or distribute a quantity of fossil fuels whose combustion emits at least 25,000 tonnes CO_2eq per year (covering 85% of provincial emissions)	• Linked to California's emission trading system • Permits distributed freely or by auction, with free allocations used to address competitiveness concerns • Offset system credits can cover up to 8% of a firm's compliance obligation • Credit for early action issued for verified reductions between 2008 and 2012 • Minimum auction price increases over time, and ceiling price mechanism can be activated if necessary • Auction proceeds finance other sustainable development initiatives

Sources: AEP (2015), Leach (2012), Government of Quebec (2014), Environment Canada (2015a, 2015b)

Alberta and Quebec have both implemented emission trading systems. The variability in coverage, stringency, and flexibility of mechanisms highlights the many important choices that are part of policy design.

Trading systems impose administrative costs on participants as they gather information about the permit market and buy and sell permits; these costs are referred to as *transaction costs*. For this reason, trading schemes typically apply upstream to producers or to fuel distributors rather than to end-use consumers. Alberta's Specified Gas Emitters Regulation and the European Union's Emissions Trading Scheme were both designed to address emissions from large industry. Other schemes, including the linked programs established in California and Quebec under the Western Climate Initiative, are also implemented upstream, but include fuel distributors as a way of addressing emissions from consumers (particularly associated with road transportation). This approach demonstrates how trading can cover a large part of overall emissions while still limiting the number of participants. The lower visibility of consumer costs tends to make trading more politically acceptable than a carbon tax (Harrison, 2013).

Obligation and Certificate Trading

Whereas cap-and-trade systems impose a limit (cap) on an undesirable product (in this case greenhouse gas emissions), obligation and certificate-trading systems do the opposite, by first requiring a minimum level of a desirable product, such as low-emitting vehicles or renewable electricity production, and then issuing certificates for each unit of the desirable product that is produced. Like cap-and-trade systems, these market-based regulations also allow trading and offer compliance flexibility in many different ways. By allowing for the trade in obligations within and across regulated entities, these policies create an incentive for firms to produce more of the desired product than is required by regulation. They therefore provide an indirect incentive to further reduce emissions.

California's vehicle emission standard uses this policy instrument to motivate the development of new low- and non-emitting vehicles, requiring that these vehicles represent a specified (and growing) share of overall vehicle purchases, but allowing for trading of permits among manufacturers (Jaccard, 2006b). A vehicle emission standard "accelerates the process of developing, commercializing and disseminating low-emission vehicles, while letting industry pick technologies to meet the emissions criteria that are in accord with customer preferences" (Jaccard & Rivers, 2008). The Government of Canada instituted performance-based regulations for passenger vehicles, requiring gradual reductions in emissions from the tailpipes of cars and light trucks in alignment with the regulations in place in the United States (Government of Canada, 2014a). These regulations include flexibility mechanisms designed to reduce the overall burden of the requirements (Government of Canada, 2014a):

- The requirements apply across each company's vehicle fleet rather than to each specific vehicle.

- Companies can earn credits in years where they exceed the requirement and use these credits in years where they do not meet the requirement, or they can sell the credits to other companies for use in any of the following five years (Government of Canada, 2014a).

Renewable portfolio standards (RPSs) are another common type of obligation and certificate-trading system (widely used in the United States). They set out minimum shares of overall electricity generation that must come from renewable sources, and they can offer compliance flexibility through strategies that can include trading of renewable energy credits across producers, price ceilings on credits, differentiated targets for different types of renewables, and the ability to average out performance across multiple years (Berry & Jaccard, 2001). RPSs tend to ratchet up renewables requirements over time (Rabe, 2007).

RPSs can have several strengths: energy producers have an incentive to meet the standard at the lowest possible cost rather than favouring one renewable source over another; governments play a limited role; and producers will favour renewables that produce more electricity during periods of high demand, since electricity prices are higher at those times[29] (Rabe, 2007; Linn & Richardson, 2013). However, Linn and Richardson (2013) observe that "a renewable portfolio standard is a relatively blunt instrument — it taxes coal and gas, but does so indiscriminately; [g]as gets no credit for being cleaner." Widening an RPS to a clean energy standard that includes natural gas and nuclear power and awards credits based on actual emission rates rather than technology choice could improve the effectiveness of this type of policy (Linn & Richardson, 2013). To date, most RPSs have excluded large-scale hydropower projects, which has been a source of concern for many Canadian provinces that see potential market opportunities for Canada's extensive hydropower resources (Rowlands, 2014).

Similar to an RPS, British Columbia has established a Clean Electricity Standard, which provides further flexibility in electricity generation options. This was originally implemented as a government mandate to BC Hydro in January 2007 and was later enshrined in legislation with the *Clean Energy Act* in 2010. The standard requires 93% of new electricity generation to be non-emitting and allows a wide range of energy sources to meet the standard (Government of British Columbia, 2010, n.d.-b). As a result, fossil fuel-based electricity generation could still be permitted if CCS were used to eliminate the carbon dioxide emissions (Government of British Columbia, n.d.-b). While the Clean

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[29] This incentive is lost when subsidies offer a fixed rate for renewable energy irrespective of the time of day or the season.

Electricity Standard does not involve tradable permits, it does use market mechanisms, as private electricity providers submit bids and BC Hydro selects the most inexpensive bids that meet the standard.

4.3.3 Command-and-Control Regulations

Like a cap-and-trade system, command-and-control regulations (often referred to as standards in the United States) can directly or indirectly set a limit on the amount of emissions that are allowed. Regulations can either establish a performance standard or prescribe (or prohibit) a particular technology.

Appliance efficiency standards are one common form of traditional command-and-control regulation. Beginning in 1995, the Government of Canada established regulations mandating minimum energy efficiency levels for appliances, heating and cooling systems, lighting, and electronics sold in Canada (NRCan, 2014a). The regulations set out a performance standard for each type of device — in this case an energy efficiency standard — and are tightened over time and adjusted to provide greater harmonization or incorporate new product types (NRCan, 2012b). These regulations have a wide scope. For instance, "[i]n the residential sector, efficiency standards have been prescribed for more than 30 energy-using product categories, which represent almost three quarters (74%) of total residential energy use in Canada" (NRCan, 2012b). The regulations are estimated to have resulted in a reduction of 26 Mt of CO_2eq emissions in 2010, with a projected annual reduction of 45 Mt by 2020 (NRCan, 2012b).

Conventional regulatory approaches tend not to be particularly cost-effective. Due to a lack of flexibility, firms may be required to make specific types of emission reductions even when less expensive strategies could have equal benefits, and firms may be reluctant to innovate new low-emission technologies and processes out of a fear that this could lead regulators to make the rules more stringent in the future (Stavins, 1997; Gupta *et al.*, 2007). Recent modelling by Canada's Ecofiscal Commission compares the economic impacts of hypothetical provincial-level climate policies that use an inflexible command-and-control regulatory approach (requiring an equal extent of emission reductions from each sector) with policies that offer flexibility to allow more reductions to occur in sectors where they can be made more cheaply (as could be established through a trading system or a carefully designed flexible regulatory approach). The model found that GDP could be 2.5% higher in 2020 using a flexible approach rather than a prescriptive approach (Canada's Ecofiscal Commission, 2015).[30]

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[30] This same modelling exercise found that the economic benefits of providing flexibility in how and where emission reductions are achieved in a given province are much greater than the additional economic benefits gained from revenue recycling or establishing links between provincial schemes. The modelling is based on each province's emission targets for 2020 but uses stylized emission reduction policies rather than modelling current policies.

Performance standards at least allow firms to choose the processes or technologies they use to achieve the standards, which can help to enhance cost effectiveness and encourage innovation (Stavins, 1997; Gupta *et al.*, 2007). Flexibility can also be provided through longer compliance periods that allow firms more control over the timing of emission reductions, and through providing long lead times that send clear signals to firms so they can prepare for future regulatory changes. Recent federal regulations limiting carbon dioxide emissions from coal-fired power plants establish a performance standard rather than an outright ban and provide facilities with extensive lead time, only requiring changes to existing plants once they reach the end of their useful life (Environment Canada, 2013a). This kind of flexibility is increasingly common, making the term *command and control* misleading in describing many regulatory approaches.

As in the case of market-oriented regulations, the distributional consequences of command-and-control regulations can be difficult to assess. Costs incurred by regulated parties generally will be passed to consumers, but consumers do not see which part of the price of a good or service is due to the regulation.

Stavins (1997) identifies several political reasons that command-and-control regulations tend to be the preferred choice for managing environmental issues: environmental groups like the certainty of regulations, legislators are more familiar with them, and firms may fare better financially under regulatory schemes. Command-and-control regulatory approaches can create benefits for existing firms when they receive preferential treatment relative to new entrants (Keohane *et al.*, 1998). In addition, regulatory measures can target specific activities or sectors that have political support.

4.3.4 Comparing Policy Options

Policy instruments can be compared across the criteria of environmental effectiveness, cost effectiveness, distributional fairness, administrative feasibility, and political acceptability. However, each of these considerations is qualitatively different, and there is no objective way to develop a relative ranking of the policy instruments. Each has its own strengths and weaknesses, and any real-life comparative policy appraisal would be context specific, factoring in many details of the policy design. However, Jaccard and Rivers (2008) note that “it is important to choose policies that do not fare badly against any single evaluation criterion.” Table 4.2 provides a summary of many of the key features of the policies reviewed above.

Table 4.2

Strengths and Weaknesses of Compulsory Policy Instruments

Policy Type	Key Variants	Strengths	Weaknesses	Keys for Success	Examples of Existing Schemes
Carbon Tax: A program that imposes a fee on GHG emissions through the tax system		• Businesses and consumers have certainty about the costs of compliance • Cost-effective way to reduce emissions • Revenues can be used to reduce other taxes or to alter distributional consequences of the tax • Can be administered through existing institutions	• Governments face uncertainty about the emission reductions that will occur in response to the tax • Politically divisive	• Stringent target • Wide coverage • Revenue recycling • Connect with existing tax administration • Simple process to adjust tax • Ramp up tax over time • Effective monitoring and enforcement	• British Columbia Carbon Tax
Market-Oriented Regulations	**Cap-and-Trade:** A program that caps emissions by firms and enables the development of a market for emission permits	• Governments have certainty about the emission reductions that will occur • Cost-effective way to reduce emissions • Revenues can be used to reduce business or consumer taxes, to support the innovation ecosystem, or to alter distributional consequences of the program	• Businesses and consumers face uncertainty about the costs of compliance • Requires new administrative processes • Transaction costs for participants in the carbon market • Vulnerable to pressure to allocate permits in ways that advantage some groups over others	• Stringent target • Wide coverage • Compliance flexibility • Effective monitoring and enforcement • Use of a permit auction system to the extent feasible	• Quebec Carbon Market • European Union Emissions Trading Scheme
	Obligation and Certificate Trading: A program that establishes a minimum level of a desirable product and issues tradable certificates for each unit of the desirable product that is produced	• Governments have certainty about the emission reductions that will occur • Cost-effective way to reduce emissions	• Businesses and consumers face uncertainty about the costs of compliance • Coverage likely limited to one sector of the economy • Requires new administrative processes • Transaction costs for participants buying and selling certificates • No additional revenues are raised by governments	• Stringent target • Compliance flexibility • Effective monitoring and enforcement	• Greenhouse Gas Regulations for Passenger Vehicles • British Columbia Clean Electricity Standard

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Policy Type Key Variants	Strengths	Weaknesses	Keys for Success	Examples of Existing Schemes
Command-and-Control Regulations: A mandated performance standard or prescribed/prohibited technology	• Environmentally effective • Political/public support	• Costs of compliance vary across participants, increasing the overall cost of achieving emission reductions • May discourage technological innovation • Requires governments to have a lot of information	• Ramp up stringency over time • Harmonize across jurisdictions and establish linkages where feasible • Apply at firm level rather than facility level to provide flexibility • Incorporate market elements that enhance flexibility without jeopardizing environmental integrity • Synchronize with capital stock turnover • Combine with other policy instruments to cover larger portions of the economy	• Energy Efficiency Standards • Coal-Fired Generation Regulation

In reviewing the evidence on these different types of compulsory policy instruments, the Panel drew several conclusions.

Policies that impose a consistent price on carbon throughout the economy are most successful at limiting the costs of emission reductions. Especially in industry, there is a strong argument for a carbon price — through carbon taxes or emission trading — because of the sector's heterogeneity and ongoing efforts to limit costs.

A key advantage of carbon-pricing policies (including carbon taxes and cap-and-trade systems) is the ability to apply a uniform carbon price across heterogeneous sectors. This uniformity makes these policies cost-effective, since they encourage the lowest-cost emission reductions to occur first. Carbon pricing is particularly effective for industry, since businesses are highly price-responsive, and the diversity of industry makes it challenging to design a flexible low-cost regulatory approach.

When there are impediments to the adoption of specific policy instruments, alternative instruments can often accomplish similar goals. Regardless of the general type of instrument adopted, there are options to tailor policies to improve their performance.

Climate policy discussions in Canada focus too much on policy type at the expense of important design considerations. At first glance, each policy instrument appears to have distinct advantages and disadvantages. For example, carbon taxes appear the most administratively simple; cap-and-trade, if there is an absolute cap, offers the best guarantee of achieving a certain level of emission reductions; and command-and-control regulations appear to be the most costly. However, in practice, the lines between these policies are increasingly blurred. The administration of carbon taxes becomes complicated by political pressures for various exemptions (as witnessed in British Columbia), cap-and-trade systems often have price ceilings that make the overall reductions uncertain,[31] and regulations can incorporate various flexible provisions to become more cost-effective.

Various policy instruments can be used to motivate widespread emission reductions across the economy, and could, with careful assessment and flexible design, be made to impose similar marginal costs across sectors. While carbon-pricing policies are the most cost-effective, even command-and-control regulations

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[31] This occurs when price ceilings are designed in a way that allows firms to pay a fee rather than remitting permits. However, if a price ceiling is created using an allowance reserve that provides a finite number of additional allowances at a set price, then overall reduction levels are maintained.

that focus on a particular sector can yield large overall reductions and still be implemented in a relatively cost-effective manner. Irrespective of the choice of policy instrument, successful policies will:

- be directly linked to binding and increasingly stringent emission limitations or binding and increasingly high carbon prices;
- include appropriate monitoring and penalty provisions;
- incorporate compliance flexibility that encourages low-cost reductions to occur prior to high-cost reductions;
- use a permit auction system, ideally from the outset, or as quickly as possible after a transition, to avoid benefiting existing firms relative to new entrants;
- use additional revenues (e.g., from permit auctions) to compensate consumers and businesses that are disproportionately affected during transition and adjustment periods; and
- have wide coverage across sectors and jurisdictions, achieved through a single policy or in combination with other compulsory policies (Box 4.2 provides additional details on the importance of wide coverage).

Political and public support for climate change policies is a key ingredient for success.

Where political controversy or lack of support for some policy instruments are major barriers to progress, it can be valuable to consider alternative policy instruments that have greater political support and that can be designed to achieve many of the same objectives. In addition, political support for some policy instruments may allow for a more stringent target than would be possible for less popular measures. For instance, a stringent low-carbon fuel standard may be more successful in encouraging transformation in the transportation sector than would a less stringent economy-wide carbon price.

Trade-offs exist between the environmental, economic, and social performance of each type of policy instrument.

The five criteria of environmental effectiveness, cost effectiveness, distributional fairness, administrative feasibility, and political acceptability can compete with one another. Goulder and Parry (2008) observe that “assuring a reasonable degree of fairness in the distribution of impacts, or ensuring political acceptability often will require a sacrifice of cost-effectiveness.” The choice of policies for a jurisdiction will be based on a context-specific evaluation of what matters most there.

Box 4.2
Policy Coverage and Emission Leakage

When greenhouse gas mitigation policies apply to one jurisdiction but not another, there is a risk of leakage, which can arise in two scenarios. In the first, a carbon policy reduces demand in one jurisdiction for carbon-intensive fuels, but that reduced demand causes the price of those fuels to fall, which then drives up demand in jurisdictions that have fewer or no greenhouse gas constraints. In the second, emission-intensive activities move to the jurisdiction where the cost of emitting is lower (Stavins, 1997). Modelling conducted for the Kyoto Protocol estimated leakage rates between 5 and 28%, assuming no trading occurred (Viguier, 2000). Leakage is a greater challenge in emission-intensive, trade-exposed industries like oil extraction, iron and steel, chemicals, and coal mining (Bataille *et al.*, 2009). Newell *et al.* (2013) note that in practice, leakage does not appear to have been a major issue to date, but the Panel noted that this could be explained by the fact that climate policies have nowhere been stringent enough to significantly affect production costs in a given jurisdiction. The price of carbon is one factor among many that influence a firm's location choice; empirical evidence indicates that in practice, environmental regulations have not deterred investment (Jaffe *et al.*, 1995; Levinson, 1996; Adams, 1997; as cited in Viguier, 2000). However, the threat of leakage remains a major concern for governments considering more stringent policies.

Rather than delaying action, mechanisms can be employed to address leakage concerns and connect domestic climate policy to global solutions. Establishing links between domestic cap-and-trade systems and systems abroad can strengthen consistency in policies across regions. Under the Western Climate Initiative, California and Quebec worked within two legal systems and languages to develop a linked system. Imposition of a border carbon adjustment has been proposed as a mechanism to level the playing field by levying duties on imports from jurisdictions that do not impose comparable limits on emissions (Cockfield, 2011).

Policies need to balance adaptability and certainty.
Uncertainty is an unavoidable element of climate change policy. Robust polices can "incorporate unexpected technologies…adapt to shifting targets, and… anticipate and mesh with international policy instruments" (Jaccard & Rivers, 2008). Some policies are inherently more adaptable than others. Traders participating in emission permit markets can respond immediately to new climate policy-related information, increasing or reducing permit prices as they anticipate future changes in government policy or market conditions, whereas tax policies require more discrete government interventions to make adjustments to

prices (Goulder & Parry, 2008). Policies that prescribe the use of a particular technology are least adaptable, since they lock in one approach. At the same time, businesses and consumers need a degree of certainty in order to make investment choices (Newell *et al.*, 2013). Current policy uncertainty may lead businesses and consumers to pursue short-term emission reduction measures, like investments in energy efficiency, rather than longer-term technological changes (Newell *et al.*, 2013). Box 4.3 profiles approaches that can contribute to policy certainty. A compromise between adaptability and certainty usually involves providing businesses and consumers with warning before changes to policies are instituted.

Box 4.3
Legal Instruments for Enhancing Policy Certainty

Some policies are designed to be resilient to political shifts and therefore create more certainty for businesses and individuals, while other policies could quickly be eliminated and are therefore less likely to motivate long-term investment changes. For instance, the United Kingdom passed the *Climate Change Act* in 2008, committing to reducing emissions to 80% below 1990 levels by 2050 (CCC, n.d.). This act of Parliament requires the government to develop five-year carbon budgets that will gradually rise up to the 2050 target (CCC, n.d.), thereby enhancing certainty in terms of the stringency of the target and the likelihood of such policies persisting over time. California's 2006 *Global Warming Solutions Act* also sets out emission targets in law, mandating that the California Air Resources Board develop regulations to motivate emission reductions (CARB, 2014). A recent court ruling in the Netherlands determined the state must intervene to ensure that a specified level of emission reductions is achieved by a set date, based on the state's duty to protect its citizens (Schiermeier, 2015). Such court rulings could underpin further policy actions in other jurisdictions in the future and could serve to enhance or undermine policy certainty (Schiermeier, 2015).

4.4 ENABLING POLICIES

The compulsory policy instruments described above have the potential to motivate wide-scale emission reductions across the economy. However, governments can pursue many important enabling policies alongside compulsory policy to facilitate emission reductions in specific sectors and for particular activities. Governments can support the transition to a low-emission Canada through policies that re-evaluate subsidies, directly invest in enabling infrastructure, engage communities, improve regulatory processes, and support the innovation ecosystem.

4.4.1 Rethinking Subsidies

Subsidies for low-emission energy sources can encourage emission reductions, as can elimination of fossil fuel subsidies. The environmental effectiveness of this policy instrument can vary. Broad-based investment subsidies reward all investments equally, irrespective of their environmental outcomes (Linn & Richardson, 2013). Also, some of the businesses or individuals that qualify for funding may have chosen to undertake the action that is being funded even without a subsidy or incentive. Subsidies have been widely used to encourage greater renewable electricity generation. Feed-in-tariff (FIT) programs encourage development of renewable electricity generation by guaranteeing a set electricity price over an extended period, typically higher than the price for carbon dioxide-emitting natural gas and coal-generated power. Unlike traditional electricity generation procurement programs, this type of program is accessible to many small-scale actors; even households can participate by installing solar panels and selling their electricity to the grid. This can help improve the political feasibility and distributional fairness of this policy relative to single large-scale electricity projects.

However, recent Canadian experiences with subsidies highlight the potentially high costs of relying on this type of policy:

- An evaluation of energy-efficiency incentives offered by Natural Resources Canada under the ecoENERGY retrofit program reported roughly one-quarter of residential projects and three-quarters of small business projects would have gone ahead without the program (NRCan, 2010).
- High-price offerings for some types of solar electricity projects in Ontario's FIT program greatly exceeded the cost of alternatives like coal and natural gas (even when the costs of environmental, health, and climate change impacts were factored in) as well as other renewable energy options (Dewees, 2012). In addition, the introduction of the FIT program coincided with major reductions in the cost of solar photovoltaics, but the government delayed making rate price adjustments in favour of maintaining investor confidence (AGO, 2011). The high solar price offerings will result in a large wealth transfer from electricity ratepayers to FIT participants (Pirnia *et al.*, 2011).

Phasing out subsidies for more carbon dioxide-emitting energy sources may help support a transition to low-emission energy. Estimates of the extent of fossil fuel subsidies in Canada are highly variable, owing to differing definitions of *subsidy*, and also to challenges in accessing relevant data, but the magnitude of these subsidies is clearly declining (CESD-OAG, 2012). Research estimates that the Government of Canada provided $508 million of direct support between 2007–08 and 2011–12, but over 95% of this support was for R&D — over half of which was focused on improving the environmental performance of fossil fuels. It also shows two large tax expenditures: the accelerated capital cost allowance for oil sands projects, estimated to be worth $1.5 billion from 2006–07 to 2010–11 (and which has since been eliminated), and flow-through share deductions[32] estimated at $1.9 billion from 2006–07 to 2010–11 (including not only oil and gas, but also mining and clean energy) (CESD-OAG, 2012). Additional subsidies exist at the provincial level.

4.4.2 Direct Government Investments and Enabling Infrastructure

Federal, provincial, and municipal governments hold large volumes of buildings, equipment, infrastructure, and employees. They can implement policies that influence the emissions associated with each of these resources and enable emission reductions in other sectors. Governments can directly reduce greenhouse gas emissions in many cases by ensuring such reductions are an accepted objective incorporated into public procurement decision-making processes. The Government of Canada's *Policy on Green Procurement* favours procurement options that produce fewer emissions across their life-cycle (PWGSC, 2014). Green procurement could be relevant for the acquisition of a range of goods, from paper through to a vehicle fleet, and also for services and construction activities. The Panel noted that these types of policies are most effective when they demonstrate leadership while building capacity and supporting improvements, which can then be implemented in other parts of the economy.

Provincial and municipal governments have opportunities to effect emission reductions through municipal planning and development decisions that affect urban form and design. Jaccard *et al.* (2012) underscore the potential for governments "…to influence the evolution of urban form through land-use zoning, development permitting, siting requirements, building codes, and infrastructure investment in public transportation, district energy, and even urban liquid and solid waste collection and disposal systems." The City of Vancouver has updated building rules to require new homes to emit only half the greenhouse gases relative to the provincial code and to require energy-efficiency improvements in renovation projects (City of Vancouver, 2014). The *Global Energy Assessment* identified "stringent, continuously updated, and well-enforced building and appliance standards, codes, and labeling" among the policy tools that are most effective in yielding energy savings from the buildings sector (Ürge-Vorsatz *et al.*, 2012).

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[32] Flow-through shares are issued to finance exploration and development activities. Investors benefit from tax deductions and credits (CRA, 2008).

Community energy management (CEM), which integrates urban planning with energy system planning, could also contribute to emission reductions. CEM recognizes that "urban form is a public policy choice…and densification and integrated community energy use can only occur if long-term municipal, provincial and federal public policy are aligned with these goals" (MKJA *et al.*, 2010). CEM uses a range of policy tools, including development permitting, building codes, subsidies, and taxes, to encourage urban densification around transit hubs, mixed use neighbourhoods, and district heating. Unlike taxes and cap-and-trade policies, CEM policies typically take effect gradually, because they apply to long-lived infrastructure. These policies can be economically attractive when they are implemented at the time that an asset requires replacement, even sometimes coming in at a negative cost (MKJA *et al.*, 2010). Canadian modelling undertaken for the non-profit organization QUEST (Quality Urban Energy Systems of Tomorrow) found the deployment of an aggressive set of CEM policies, including land-use, transportation, and district energy policies, would result in a 12% reduction in emissions from the buildings and personal transportation sectors by 2050 (MKJA *et al.*, 2010).

All levels of government can support development of enabling infrastructure on a local to national scale. Many of the emission-reducing technologies identified in Chapter 3 require new public or quasi-public infrastructure, including new or modified energy infrastructure for new vehicles, enhanced electricity grid capacity, and carbon dioxide transport pipelines. The Panel noted that the path dependence of the innovation system, which favours existing energy systems and technologies (Grubler *et al.*, 2012a), paired with the public good nature of this new infrastructure, points to a potential government role. In particular, government could play a key temporary role in supporting the development of alternative energy infrastructure for new vehicle types. Once this infrastructure is established and use of alternative vehicles becomes common, governments could cease involvement, and the infrastructure could be managed by the private sector (as is the case with current gasoline refuelling infrastructure).

4.4.3 Engaging Communities and Regulating Energy Utilities

In some instances, community opposition and regulatory processes may discourage implementation of low-emission technologies. This is an emerging area of research, and renewable energy projects offer a good example of the potential dimensions. The permitting processes for these projects can be onerous, and local opposition can cause delays and increase costs. Regulations may need to be revisited to better support enhanced deployment of renewables while protecting communities and the local environment (Mitchell *et al.*, 2011). The IPCC notes the "need for systems that are pro-active, positive and place- and scale-sensitive" (Mitchell *et al.*, 2011). Jaccard *et al.* (2011) note renewable energy policies should provide for local participation in planning processes and find ways to balance local and global concerns. Locational siting concerns may also be a significant obstacle for grid expansion and enhancements, as they can be for pipeline construction. Community ownership of renewable energy resources and provisions for compensating those that are adversely affected can also boost public support (Mendonca *et al.*, 2009). Public support for wind development declined in Denmark as wind turbine ownership moved away from community ownership toward distant or single owners (Mendonca *et al.*, 2009).

Regulated utilities play key roles in the existing energy system, and the ways in which these utilities are regulated can enable change or create barriers for transitioning to a low-emission future. There may be several disincentives for regulated utilities to promote energy efficiency: utilities may not be able to recover the costs of energy efficiency programs through rate adjustments; efficiency gains can drive down demand for energy services; and in the case of private utilities, shareholders may not be able to reap rewards from energy efficiency investments (in contrast to energy supply investments) (Carter, 2001; NAPEE, 2007). Various approaches can be used to ensure regulated utilities are rewarded not only for building new supply, but also for eliminating the need for new supply at all. Vermont's Green Mountain Power illustrates that utilities can also be leaders. This utility has established a home-retrofit program that partners with contractors to identify and implement a range of energy-saving measures and offers heat pump rental services rather than requiring home owners to cover all the costs upfront (GMP, 2015; McKibben, 2015). Such strategies can help overcome barriers to individual action, and technologies that reduce peak demand can save money for utilities.

The Panel observed that energy regulators can be valuable contributors to transformation of the energy system through their focus on long time horizons, their ability to incorporate external costs into energy rates and address equity concerns, and the arms-length nature of quasi-judicial regulatory processes. These considerations point to the role of energy regulators as a potentially promising area of focus in the future.

4.4.4 Supporting the Innovation Ecosystem

Technological progress can support the full-scale deployment of existing technologies and also lead to deployment of new technologies that bring down the costs of mitigation. Compulsory policies, particularly pricing policies, often encourage innovation by increasing the reward for successful R&D. Additional government policies, financial or otherwise, can go further by supporting various components of the innovation ecosystem (which spans from early R&D to demonstration, deployment, and company growth), both encouraging research and enhancing the commercialization prospects for new technologies. These additional policies pay off only occasionally, but this is to be expected, since all innovation is inherently risky. One breakthrough can more than compensate for many unsuccessful projects. However, this uncertainty underscores the importance of pairing innovation support policies with compulsory policies to ensure emission reductions are achieved.

Several innovation-specific challenges point to a role for government policy, including spending and other supports. As noted earlier, innovation faces an important market failure: the inability of firms to capture all the economic benefits of innovation leads to a suboptimal level of investment. Businesses encounter widespread challenges in accessing finance between the initial R&D phase of product development and ultimate commercialization, often referred to as the "valley of death" (CCA, 2009). Accessing finance can be particularly challenging for developers of low-emission technologies where the market depends on government mitigation policies, and investors may have less familiarity with these product types and therefore consider them to be overly risky investments (Justice, 2009).

Additional barriers include the capital intensity of energy technologies and the long lag between conception and commercialization (SEF Alliance, 2008). Finally, some researchers argue that many of the technologies (e.g., CCS, BEVs) required to achieve the deep emission reductions required to limit global warming to 2°C are not ready to be deployed at full scale (Hoffert *et al.*, 2002; Grubler *et al.*, 2012a; Sachs *et al.*, 2014; Loftus *et al.*, 2015). This has led some scholars to conclude that technology policy should play the central role in responding to climate change, with carbon tax revenues and/or auction revenues from a cap-and-trade system used to support global efforts to establish viable technology solutions (Galiana & Green, 2010).

To the extent that new technologies reduce the cost of achieving emission reductions, technology can also enable increasingly stringent compulsory policies (Victor, 2011). A group of United Kingdom scholars recently initiated the Global Apollo Programme, a project aimed at finding ways of producing non-carbon dioxide-emitting energy more cheaply than fossil fuels (King *et al.*, 2015). Bill Gates recently announced plans to invest $2 billion in renewable energy technology over the next five years in an effort to find low-cost renewable energy options (Adams & Thornhill, 2015). However, the costs of fossil fuels may also fall over time due to technological progress or climate change policy, potentially undermining this strategy (Sinn, 2008).

Government policies can encourage innovation by addressing the regulatory environment, the macroeconomic context, access to finance, protection of intellectual property rights, trade policies, and access to skilled workers. Successful innovation policies take a holistic approach by providing support throughout the innovation ecosystem (Grubler *et al.*, 2012a). Gallagher *et al.* (2012) note the importance of relying on a package of energy innovation policies that "support knowledge development, feedback processes, and learning for the entire innovation system" and also target social innovation, which refers to "changes in the adoption, use, and adaptation of technologies in a social and institutional context." Governments can also foster industry collaborations that bring people together to work toward shared goals. For instance, the Government of Canada's Network of Centres of Excellence program has funded initiatives like Auto 21, which fosters automotive research in various areas, and BioFuelNet, which focuses on improving the biofuel production chain (NCE, 2015).

Canadian innovation policies generally take the form of a subsidy or tax incentive or directly participating in government laboratory-led development. In Alberta's Specified Gas Emitters Regulation, innovation support is a component of the emissions-intensity-based trading system: firms can contribute $15/tonne of emissions that exceed the target to Alberta's Climate Change and Emissions Management Fund. This fund distributes monies to projects that support emission reductions, including in the priority areas of energy efficiency, CCS, and greening energy production (CCEMC, 2013). By 2013, over $200 million had been distributed to projects across the innovation spectrum, with the large majority of funds focused on projects at the market demonstration and commercialization phases (CCEMC, 2013). The fund is expected to generate emission reductions of 10.2 Mt by 2020 (CCEMC, 2013). Public financing can play an important role in complementing traditional private financing by providing investments over longer periods, accepting a higher degree of technology risk, and funding smaller, earlier-stage companies that may be too risky for private investors. For instance, Sustainable Development Technology Canada (SDTC)'s $915 million SD Tech Fund awards funding to pre-commercialization projects that complete an intensive SDTC investment screening process (SDTC, 2015b). According to SDTC, "66 technologies completed by the end of 2014 reported actual GHG emissions reductions of approximately 4.5 million tonnes of CO_2 equivalent that year" (SDTC, 2015a). Revenues generated by SDTC companies were estimated at $1.1 billion in 2014, estimated to correspond to 500 direct and indirect jobs created in that year (SDTC, 2015c). SDTC projects have leveraged significant private sector support; the OECD identified SDTC's approach to project development as an example of an effective strategy to promote public-private partnerships and eco-innovation (OECD, 2011).

4.4.5 Choosing Enabling Policies

Enabling policies can be important supplements to the compulsory policies described in Section 4.3. A systems approach can be used to explore the interaction and complementarity of different carbon policy combinations. For instance, if an energy efficiency regulation helps to overcome barriers to progress, such as a mismatch between those who pay for energy efficiency improvements and those who benefit, it could reduce the economy-wide costs of reducing emissions. Similarly, public investments in improving electrical grid capacity may be required to accommodate renewable electricity generation in some locations. Adding a carbon price alongside enabling policies helps to level the playing field among energy sources and can accelerate emission reductions. At the same time, policies can interact with one another in negative ways, and the cost of administering them can be considerable, so deploying an extensive portfolio of policies aimed at reducing emissions could be counterproductive. Governments must be strategic in planning what combination of policies will be most advantageous for their particular context.

4.5 THE POTENTIAL ECONOMIC IMPACTS OF A LOW-EMISSION TRANSITION FOR CANADA

Emission reductions are not costless on any scale — for firms, industries, individual countries, or globally. However, with careful design, Canada could implement climate policies of much greater weight and effect than those implemented to date without compromising the country's economic well-being. The best evidence available suggests policies can be adopted that will lead to substantial decline in our greenhouse gas emissions over the next decade and position us for more significant declines in the decades to follow, without imposing unmanageable costs on most consumers and businesses or jeopardizing long-term economic growth. When specific regions, sectors, or individuals are disproportionately affected, there are ways to compensate these groups during periods of transition.

Impacts on Consumers and Businesses

Stringent climate change policy is likely to increase the costs of electricity in many parts of the country. However, as noted in Section 3.1.3, low-emission electricity is currently available across Canada for a premium of 2.5¢/kWh, and the increased cost of electricity from low-emission energy sources would not put Canada out of line with other industrialized countries.[33]

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[33] Electricity costs vary across the country, however, with particularly low rates in Montréal and Winnipeg and far higher rates in Halifax, Toronto, and some other cities (Hydro-Québec, 2014).

Transportation costs would also increase. Plug-in hybrid electric vehicles currently cost around US$7,000 more to manufacture than gasoline-powered vehicles (NRC, 2013). These costs can be partially recovered, since the operating costs for vehicles operating on electricity in North America are likely to be much lower than those for vehicles operating on gasoline (NRC, 2013; DOE, 2015a). Depending on how much a vehicle is driven, these savings already can exceed the additional vehicle costs.[34] In British Columbia, imposition of a $30/tonne carbon tax translated to a 7¢/litre increase in the cost of gasoline (Government of British Columbia, n.d.-c). Under this approach, a $100/tonne carbon tax would increase gasoline prices by 23¢/litre. These kinds of price changes are not out of line with the kinds of gasoline market price swings experienced within a given year (Statistics Canada, 2015). For example, recent price fluctuations have been particularly large; in Toronto in 2014 the monthly average retail price for regular unleaded gasoline ranged between $1.04 and $1.40 per litre.

Climate policies, like all policies, can create both winners and losers. Emerging clean technology industries could see growth in the markets for their products and services. The IEA estimates global growth in renewable electricity generation of 50% between 2013 and 2020 (IEA, 2014c). In the OECD, renewable sources are expected to account for nearly 80% of new electricity generation capacity over this period (IEA, 2014c). On the other hand, regions that rely more heavily on energy-intensive industry, and those regions with more carbon-intensive electricity systems, will face higher-than-average costs when transitioning to low-emission energy sources. If Canada were to implement a more stringent climate policy than its trading partners, the competitiveness of energy-intensive, trade-exposed industries like oil and gas, iron and steel, cement, aluminum, pulp and paper, and some chemical manufacturing industries could be adversely affected (NRTEE, 2011). However, policies can be designed to partly address these distributional concerns.

Economy-Wide Impacts

British Columbia's experience indicates that economy-wide impacts of its carbon tax have been manageable. Provincial government analysis found the tax has had a small negative impact on GDP (BCMF, 2013). However, an analysis of provincial growth rates of GDP per capita found that between 2008 and 2011, British Columbia slightly outperformed the country as a whole, indicating the tax has not prevented the province from keeping pace with the rest of the Canadian economy (Elgie & McClay, 2013).

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[34] An online tool provided by the U.S. Department of Energy allows comparisons of the cumulative ownership costs of current alternative and conventional vehicles, based on factors such as vehicle costs, fuel costs, other operating costs, and vehicle use. See www.afdc.energy.gov/calc.

Reductions in fossil fuel consumption can also have significant co-benefits. Ontario's decision to eliminate coal-fired electricity likely resulted in significant savings in terms of the health costs of air pollution. A report commissioned by the Ontario Ministry of Energy estimated that eliminating coal-fired electricity generation in the province and replacing it with a combination of nuclear power and natural gas plants would avoid approximately 660 premature deaths, 920 hospital admissions, and 1,090 emergency room visits per year (DSS & RWDI, 2005). These impacts impose costs relating to health care, lost productivity, pain and suffering, and the risk of premature mortality, the sum of which was estimated at over $3 billion. In contrast, if all coal-fired electricity generation were to switch to natural gas, estimated damages would fall by almost 90%, to $388 million (DSS & RWDI, 2005).

Economic modelling provides additional evidence on the potential impacts of a more stringent carbon constraint. Modelling of a deep decarbonization pathway for Canada shows that by 2050, the country could reduce emissions by 90% from 2010 levels while maintaining strong economic growth (Bataille *et al.*, 2014). A 2009 analysis by the National Round Table on the Environment and the Economy estimated that emissions could be reduced 65% below 2006 levels by 2050 with only a small reduction in the growth of the Canadian economy in 2050 (NRTEE, 2009). This is broadly consistent with international modelling for scenarios where there is cost-effective global action (Nordhaus, 2013; IPCC, 2014e). Evidence also shows that policies that allow change slowly over time, replacing capital stock as it reaches the end of its useful life, can be less expensive than policies that come into effect quickly and require premature capital stock replacement (NRTEE, 2011).

Globally, the IEA reported a decoupling of economic growth and carbon dioxide emissions in 2014 (IEA, 2015b). The IEA noted that "the global economy grew by around 3% in 2014 but energy-related carbon dioxide (CO_2) emissions stayed flat, the first time in at least 40 years that such an outcome has occurred outside economic crisis," but that additional years of data would be required to confirm this was not an anomaly. Almost half of new electricity generation capacity added in 2014 came from renewable sources, as the prices of renewable sources fell relative to fossil fuel sources (IEA, 2015b).

Strategies for Reducing Negative Economic Impacts

The Panel noted several factors that could minimize negative economic impacts of climate change policy, including:

- anticipating adverse impacts and designing measures to soften or eliminate them;

- providing flexibility so that least-cost emission reduction strategies can be used before more expensive strategies;
- emphasizing emission reduction strategies that create co-benefits (such as air quality improvements from reduced urban fossil fuel combustion) and avoid negative side-effects (such as reduced resilience in the electricity grid from overreliance on intermittent sources); and
- designing policies that encourage major investments to coincide with natural capital stock turnover.

4.6 SUMMARY

Policies in place in Canada are currently not stringent enough, or broad enough in their coverage, to motivate a transition to a low-emission economy. New compulsory policies are required to drive significant emission reductions in Canada. However, this work has begun. In 2015, one-third of Canadians already live in provinces that have a carbon price on all fossil fuel-related emissions. If Ontario proceeds in implementing a trading system comparable to that in Quebec, three-quarters of Canadians would be covered by such a carbon price.

Either economy-wide carbon-pricing policies (carbon taxes or cap-and-trade systems) or a series of more narrowly applied flexible regulations could create the conditions needed for change. The advantages of carbon pricing are well-established and include cost effectiveness and the potential for low administrative burden. However, political controversy and concerns about distributional impacts have been barriers to establishing stringent carbon-pricing schemes. Flexible regulations may be more readily accepted and can be designed to offer many of the same benefits as pricing schemes, but they may come at a higher cost to the economy. Regardless of the compulsory policies adopted, governments can further support emission reductions by deploying the right enabling policies. Government purchase decisions; emission-conscious urban planning; support for innovation; provision of enabling infrastructure; and adjustments to subsidies, energy planning, and regulatory processes can all further encourage emission reduction in different parts of the economy. While reductions in Canada's greenhouse gas emissions will come at a cost to the economy, evidence suggests that well-designed policies can bring about major emission reductions without jeopardizing economic growth.

5

Conclusions

- The Canadian Context for Reducing Carbon Dioxide Emissions from Energy Use
- Technological Opportunities for Developing a Low-Emission Energy System in Canada
- Policies to Motivate a Transition to a Low-Emission Energy System
- Final Thoughts

5 Conclusions

The extraction of energy from fossil fuels was critical to the technological and economic progress of the 19th and 20th centuries. These fuels contributed to great advances in living standards across industrialized countries and continue to help alleviate the burdens of poverty in low-income countries. However, the combustion of fossil fuels is increasing carbon dioxide concentrations in the atmosphere and causing pervasive changes in the Earth's climate. The risks such changes pose to natural systems and human communities are increasingly evident. Mitigating these risks requires a sustained reduction in absolute greenhouse gas emissions from human activity, including an eventual complete transition to low-emission energy sources and technologies. The Panel was tasked with synthesizing recent evidence on the energy sources, technologies, and public policies that would advance such a transition in Canada. This chapter summarizes the Panel's principal observations and conclusions.

5.1 THE CANADIAN CONTEXT FOR REDUCING CARBON DIOXIDE EMISSIONS FROM ENERGY USE

Canada, like many countries, currently depends on fossil fuels for most of its energy needs. Coal, oil, and natural gas make up 72% of Canada's total primary energy supply (domestic production plus imports, minus exports) (IEA, 2014b). These fuels provide nearly all the energy used in Canada's transportation systems (including road, air, and marine transport) and much of the energy for space heating in buildings and for industrial processes, as well as most electricity generated in Alberta, Saskatchewan, Nova Scotia, and New Brunswick. Large amounts of carbon dioxide are emitted during the combustion of these fuels. Canada ranked 12th in the world in total carbon dioxide emissions in 2013, accounting for 1.4% of the world's total (Boden *et al.*, 2013). Canada also has the fourth-highest level of carbon dioxide emissions per capita among OECD countries (The World Bank, 2015).

Despite a succession of national emission reduction targets, Canada's greenhouse gas emissions have increased significantly relative to 1990 levels, driven primarily by carbon dioxide emissions from energy extraction and use. Federal and provincial governments have adopted a range of climate policies to address this challenge, including sector-specific regulatory measures at the federal level and market-based carbon-pricing policies, including taxes and trading systems, in several provinces. However, these policies are still only moderately stringent, with small cost implications for emitting carbon dioxide, and thus emissions have not fallen significantly at the national level. Comparatively high levels of energy consumption in Canada are driven by high per capita incomes, low energy prices arising from abundant domestic energy resources, and Canada's variable climate and large land mass.

Electricity, transportation, buildings, and industry are all major emission sources, but the trends in these four sectors are different. Emissions from electricity have declined in recent years because of deliberate policy choices in provinces such as Ontario, which closed its last coal-fired power plant in 2014, while emissions from buildings have been stable for some time. In contrast, transportation and industry are both major sources of emission growth. Transportation emissions are growing because of an increase in total kilometres travelled and expansion of freight transportation. Industrial emission trends are dominated by increasing oil sands development, an issue unique to Canada. Exports of oil from the oil sands have become increasingly important to the Canadian economy, and as production has increased, so have emissions, accounting for 42% of the total change in Canada's emissions between 1990 and 2013 (Environment Canada, 2015c). Future oil sands production and its associated emissions will be affected by Canadian policy and by evolving conditions in the global oil market, as well as technological innovation and global policy developments.

Canada has natural resource endowments, energy-related assets, and technological expertise that can help facilitate a transition to low-emission energy sources and technologies. Relatively low-emission electricity systems in many provinces, coupled with extensive opportunities for renewable and nuclear energy development and the eventual application of CCS technologies, can help decarbonize electricity generation throughout Canada. Large-scale energy transitions typically require many decades, because of the long-lived nature of the capital stocks involved. However, experience from Canada and other countries shows that narrower or more targeted energy transitions can, with government support, occur more rapidly and achieve deep emission reductions over relatively short time spans. In the Panel's view, no technological obstacles preclude the possibility of a low-emission energy future for Canada over the course of several decades *if* current policies are made more stringent in concert with additional effective policies.

5.2 TECHNOLOGICAL OPPORTUNITIES FOR DEVELOPING A LOW-EMISSION ENERGY SYSTEM IN CANADA

Canada can realize a low-emission energy future by taking advantage of a number of critical opportunities for emission reductions, such as those identified in Table 5.1. The opportunities highlighted here illustrate a portfolio of promising emission reduction strategies and energy and technology choices for Canada that rely largely on existing commercial technologies. While these opportunities will affect the many ways energy is produced and consumed, they do not require wholesale redesign of energy systems, despite the current dominance of fossil fuels. The strategies and technologies highlighted here illustrate the Panel's judgment as to what are significant opportunities for reducing energy system emissions. New technological or socio-economic developments could alter these judgments and favour other choices; however, given the range of alternative energy sources and technologies available, the potential for achieving large emission reductions in Canada and in other countries is resilient across multiple technological scenarios. The results of previous modelling exercises indicate that portfolios of opportunities similar to those described in Table 5.1 could reduce Canada's energy-related carbon dioxide emissions by 60 to 90% by mid-century (see, for example, NRTEE, 2009; Riahi *et al.*, 2012; Bataille *et al.*, 2014), in line with federal targets and the recently announced G7 goal of decarbonizing the global economy by the end of the century (G7, 2015).

Table 5.1

Opportunities for Energy-Related Emission Reductions in Canada

Electricity	• Replacement of coal-fired electricity plants in Alberta, Saskatchewan, New Brunswick, and Nova Scotia with low-emission alternatives. • Expansion of low-emission generation capacity in all provinces. • Investment in electricity transmission and distribution systems and energy storage to facilitate greater integration of low-emission power.
Transportation	• Efficiency gains across all modes of transportation. • Increased reliance on electric vehicles for passenger light-duty vehicle transportation. • Expansion of biofuel use in freight transportation, and of biofuel production and distribution capacity. • Urban planning, land-use planning, and infrastructure investments consistent with efficient, low-emission transportation systems.
Buildings	• Efficiency gains in new buildings and coinciding with building renovations. • Transitioning to electricity for space heating in highly energy-efficient buildings. • Selective adoption of low-emitting district heating systems powered through renewable energy and cogeneration.
Industry	• Efficiency gains across industries. • Reduction of fugitive methane emissions from the oil and gas industry. • Application of carbon capture and storage in suitable industrial processes. • Electrification and use of biomass in applicable industrial applications.

Low-emission electricity is the foundation for a low-emission energy system. Canada already benefits from large amounts of low-emission electricity from hydropower and nuclear power, and installed generating capacity from wind and solar power is growing rapidly. Canada is also accumulating experience with CCS technologies, with the world's first large-scale application of CCS at the Boundary Dam coal-fired power plant in Saskatchewan. Achieving low-emission electricity systems across Canada requires transitioning away from emission intensive sources in those provinces still dependent on them. It also requires expanding generation from low-emission sources in all provinces to facilitate increased use of low-emission electricity as an energy carrier in all end-use sectors. Emissions from Canada's electricity sector are declining due to a gradual phase-out of coal-fired generation; however, this transition could be accelerated, taking advantage of a variety of low-emitting energy sources. The costs of low-emission electricity generation technologies, while still generally higher than those for fossil fuel-fired power plants, have been falling rapidly. Maximizing emission reductions from electricity systems will eventually require limiting the role of natural gas to mostly providing power in periods of peak demand (or adopting CCS where feasible). New investments in electricity transmission and distribution systems (e.g., new transmission lines, interconnections, smart grid technologies) and energy storage can accelerate reliance on low-emission electricity and the overall expansion of the electricity system, while expanded reliance on distributed energy could reduce transmission costs and losses.

Current transportation systems are dependent on petroleum-based fuels, which have advantages in terms of their portability, energy density, and compatibility with existing infrastructure. After assessing the evidence, the Panel concluded that efficiency improvements, increased use of electricity for passenger transportation in light-duty vehicles (likely PHEVs) and biodiesel in freight transportation, and judicious urban planning and infrastructure investments represent the most promising medium- to long-term opportunities for emission reductions in this sector. Reductions are possible through continuing efficiency improvements in conventional gasoline and diesel engines, increased use of hybrid vehicles, and a shift to lower-emission forms of transportation. Using electricity as an energy source in passenger vehicles takes advantage of existing infrastructure in the form of electricity grids and Canada's supply of low-emission electricity. Expanding biofuel production (and use) is consistent with Canada's large potential to develop biomass energy and the limited applicability of other fuel choices for long-haul freight transport. Natural gas vehicles also have the potential to achieve modest reductions in carbon dioxide emissions from freight relative to conventional oil. Over the longer term, urban planning and investments in public transportation systems and new refuelling infrastructure can play a supporting role by encouraging shifts to less emission intensive modes of transportation.

In the buildings sector, a combination of substantial efficiency gains and electrification — particularly for space heating — are critical. Space heating accounts for most greenhouse gas emissions in Canadian buildings, and a switch to electric heating systems is the most promising technology for reducing those emissions. However, substituting electricity may be prohibitively expensive without large efficiency gains stemming from building shell improvements (particularly more extensive use of insulation and passive solar features) and the use of heat pumps in place of traditional furnaces. Efficiency gains and emission reductions can also be achieved by the adoption of cogeneration plants and district heating systems powered through renewable energy, waste products, or sources such as deep lake water where appropriate.

Reducing energy-related emissions in industry is complicated by the diversity of industrial applications, processes, and technologies. Often the key challenge for industry is finding low-emitting and economical ways to produce high levels of heat. Reduced use of energy for material processing, for instance through increased use of solvents in place of heat, could contribute to efficiency gains in industry (particularly in the oil sands). In addition, monitoring and repairing gas leaks and reduced venting and flaring of fugitive emissions could contribute to emission reductions in the oil and gas industry. Electrification and CCS technologies also have potential as strategies. Electricity can be used as an energy source for many industrial processes, with the main barrier typically being the added cost over natural gas. CCS has already been used in industries that produce relatively pure streams of carbon dioxide as a waste product, and in the future could be used to reduce emissions from various Canadian industries, taking advantage of sequestration opportunities in nearby depleted oil and gas reservoirs or saline formations. Biomass is already important in some industries, like pulp and paper, but could be used in others as well.

Emission reductions can be initiated immediately in all sectors, though the timing of reductions will vary depending on the technologies and capital stocks involved. Capital stock turnover defines the lowest-cost emission reduction pathways. For longer-lived capital such as buildings or power plants, achieving a transition at the lowest possible cost requires beginning emission mitigation immediately and replacing capital at the end of its economic life. Some opportunities are complementary. For example, reduced emissions in transportation, buildings, and industry partly depend on the availability of low-emission electricity; however, even where electricity generation is only partly decarbonized, investments in electrification in these sectors can enhance the potential for future emission reductions. Efficiency gains can also provide a foundation for energy substitution, for example, with high-efficiency buildings being much more affordable to heat with electricity. Individual actions to reduce emissions may also hinge on governments addressing systemic barriers to more widespread adoption of low-emission energy technologies.

The opportunities identified throughout this section largely depend on commercially available technologies, many of which have been widely deployed in existing energy systems in recent years. Though innovation may still be required to deploy these technologies to new contexts, major technological barriers do not prevent Canada or many other jurisdictions from immediately reducing emissions. Additional R&D and technological development could reduce the costs of low-emission energy technologies over time and foster new technologies for improving energy efficiency. However, businesses and individuals will not choose low- and zero-emission technologies to a significant degree without public policies that make these options more cost-competitive, either by pricing carbon or restricting carbon dioxide emissions.

For the time being, the economic barriers to implementing these technologies are significant. Coupled with systemic constraints relating to existing energy infrastructure, the increased cost of low-emission sources over conventional fossil fuels will prevent most of the opportunities identified above from being realized unless more stringent emission mitigation policies are implemented.

5.3 POLICIES TO MOTIVATE A TRANSITION TO A LOW-EMISSION ENERGY SYSTEM

Canada will need broad, compulsory, and increasingly stringent policies if it is to establish a low-emission energy system. Compulsory policies designed to reflect the negative impacts of carbon dioxide emissions can influence business and individual decision-making and encourage movement away from emission intensive activities. For instance, an economy-wide carbon tax can increase the costs of gasoline for consumers, encouraging the development and purchase of more efficient and alternative energy vehicles, reducing the amount of driving, and increasing demand for public transportation. Similarly, a cap-and-trade system applied to industry could encourage greater use of biomass and low-emission electricity rather than fossil fuels as a heat source. With flexible economy-wide policies in place, government does not need to choose winning technologies. Instead, individual and business decision-makers can choose the technology responses that are right for their context and change these choices over time to adapt to further scientific progress, emission trends, and technological developments.

Current policies are a mix of federal and provincial initiatives that vary in their design, coverage, and stringency. Although many may bring about emission reductions, collectively they are not enough to drive a low-emission transition. Federal market-oriented energy efficiency regulations on passenger vehicles and heavy-duty trucks will motivate ongoing efficiency gains in road transportation and could motivate greater use of electric vehicles. The average greenhouse gas emissions from passenger vehicle models in 2025 will be roughly 50% of those from 2008 models (Government of Canada, 2014b). British Columbia's Clean Electricity Standard, another market-oriented regulation, requires 93% of new electricity generation to be virtually non-emitting, but offers electricity providers choice in the form of energy they use to meet this standard, so as to encourage a least-cost approach. British Columbia's $30/tonne carbon tax also provides a consistent price signal for almost all sources of fossil fuel emissions across large parts of the economy. Alberta's trading system limits the emission intensity of large industry, allowing firms a variety of compliance options, including contributing $15 to a technology fund for each tonne of emissions that exceed the target. The emerging emission trading platforms in Quebec and Ontario could also be the basis for substantial emission reductions. These policies could be made increasingly stringent and could be combined with new policies that cover other sectors and regions.

Policy impacts will vary across the electricity and end-use sectors. For instance, the price-responsiveness and technological diversity of the industry sector point to the benefits of a uniform carbon-pricing policy — through either carbon taxes or cap-and-trade. In the buildings sector, informational and institutional barriers may limit the effectiveness of carbon pricing, but command-and-control regulations like enhanced energy efficiency standards and changes to building codes could ensure that new buildings are highly energy efficient. In transportation, carbon pricing could encourage consumers to purchase less-emitting vehicles, while regulatory policies could enhance the use of particular technologies or fuel types and encourage ongoing efficiency gains. Carbon pricing and clean electricity standards could both be promising approaches for the electricity sector; however, this sector's sensitivity to price signals depends on the way in which electric utilities are regulated, including the extent of competition and the financial incentives to shareholders to reduce emissions.

A broad-reaching carbon price, achieved through either carbon taxes or a cap-and-trade system, ensures that the lowest-cost emission reduction opportunities are adopted first, minimizing the overall economic costs of climate change policy. Command-and-control regulatory approaches, however, can enable the pursuit of emission mitigation strategies with highly divergent abatement costs simultaneously. The choice of policy instrument will depend on context and the relative importance of different policy objectives. When there are barriers to implementing a particular policy instrument, alternative instruments can often be used instead to accomplish similar goals.

Table 5.2 summarizes strategies to tailor compulsory policies to improve their performance on key objectives such as cost, environmental effectiveness, fairness, administrative feasibility, and political acceptability regardless of the type of instrument adopted.

Table 5.2

Designing Compulsory Policies to Satisfy Key Evaluative Criteria

Criteria	Design Features
Environmental Effectiveness	• Implement binding policies • Ramp up emission reduction requirements over time • Include as much of the economy as possible (using one or multiple policies) • Commit to long-term policies that give households and businesses the confidence to invest in making changes
Cost Effectiveness	• Provide choice in the technologies and energy forms used to meet required emission reductions • Maximize the ability to concentrate emission reductions in the sectors of the economy where those reductions will cost the least • Ramp up emission reduction requirements over time to reduce adjustment costs • Commit to long-term policies that give households and businesses the confidence to invest in making changes
Distributional Fairness	• Identify those most likely to be adversely affected • Design policies to offset initial impacts and costs for highly impacted groups, regions, and sectors • Use fiscal levers to offset regressive policy impacts associated with increasing costs for consumers • Use mechanisms such as border tax adjustments across countries and policy harmonization between provinces to minimize the displacement of emissions from one location to another
Administrative Feasibility	• Use existing administrative and bureaucratic structures where possible • Consider monitoring and enforcement requirements in policy design • Design policies that can be adapted over time as new information on costs, technologies, and consumer preferences becomes available • Minimize exemptions and exceptions to the extent possible
Political Acceptability	• Involve the public in policy decision-making • Ramp up emission reduction requirements over time to avoid rapid changes in consumer prices and industry costs • Take advantage of opportunities for policy co-benefits • Be realistic about the importance of political acceptability as a criterion when comparing policies

In summary, compulsory policies are more likely to be successful if they:

- are directly linked to binding and increasingly stringent emission limitations or binding and increasingly high carbon prices;
- include appropriate monitoring and penalty provisions;
- provide extensive compliance flexibility;
- treat new and existing firms fairly;
- compensate groups that are adversely impacted by policies (at least on a transitional basis); and
- involve the public in decision-making.

The success of policies or policy portfolios is also enhanced through wide coverage across sectors and jurisdictions, which can be achieved through harmonization across regions of Canada and establishing linkages internationally. Concerns about competitiveness impacts arising from less stringent policies among Canada's trading partners can be addressed through appropriate tariffs where necessary.

Support by all levels of government for the innovation ecosystem is an important policy tool that can encourage deployment of existing technologies and the development and future deployment of new technologies. Financial support by means of a technology fund, tax policies, or otherwise, along with other means of support across the innovation continuum from R&D to demonstration, deployment, and company growth, can all foster emergence of new and improved technologies. This support could address domestic and export market risks, trade, intellectual property rights, and investment ecosystems. A mix of other policies, such as public infrastructure investments, community engagement, and regulatory reform can further support the emission reductions and energy system transformation encouraged by compulsory policies. For instance, energy utility regulators could be well-suited to support a transformation, owing to their long-term approach to planning, their ability to use prices to reflect a range of costs and address distributional concerns, and the arms-length nature of quasi-judicial regulatory processes.

A transition to a low-emission energy system requires an iterative policy process, and the sequence of emission reductions will depend, in part, on the policies adopted. Businesses and consumers will begin to make changes in response to policy immediately, but the effects of policies will take place in the short, medium, and long term as capital and building stock needs replacement. In addition, new and improved technologies may become available. As policy-makers assess the system as a whole, gathering information about the extent of emission reductions taking place, technological progress, policies established in other jurisdictions, and economic impacts, new policies can be introduced, or the stringency of existing policies can be adapted as needed (balancing the need for adaptability with the benefits of policy continuity). While the transition is not costless, with appropriately stringent and flexible policies in place, large-scale emission reductions from Canada's energy system are achievable over the course of several decades and are unlikely to jeopardize Canada's long-term economic growth and competitiveness.

5.4 FINAL THOUGHTS

In the course of its deliberations, the Panel observed that many important changes in assumptions and knowledge of climate change policy and technology responses have come about in recent decades. In the early 1990s, some of the technologies needed to transition to a low-emission economy were not commercially available, and it was hard to imagine a concrete pathway to achieving emission reductions on the scale needed. The prevailing focus was often on energy efficiency gains rather than energy substitution, and discussions emphasized pursuing emission reduction opportunities sequentially. Opinion was divided on how long a transition to low-emission energy technologies would take, and political messaging often suggested that greenhouse gas emissions could be reduced largely through voluntary actions by corporations and individuals if only they had the right information. Debates frequently centered on identifying the *right* technologies and policies to address climate change.

Today, our understanding of these and related issues has evolved. The technologies needed to transition to a low-emission economy are now commercially available, and their prices are dropping. It is possible to envision several pathways to achieving emission reductions of 60 to 90% by mid-century. We also know that carbon dioxide emissions have continued to grow in absolute terms since 1990 despite widespread energy efficiency gains, hence the need for a quicker shift to zero-emission energy sources. And given the challenge and timescales involved, rather than sequencing emission reduction initiatives, a wide range of emission reduction actions must be pursued concurrently. A growing body of evidence on the dynamics of energy system transitions demonstrates that transitions tend to unfold slowly, over multiple decades, but that they can be accelerated with the right government support. Finally, today we know compulsory policies are necessary for change, and that policies using price signals to change decisions can be particularly effective in achieving emission reductions at a manageable cost. While debate continues about which technologies and policies are most effective in addressing climate change, there is increasing recognition that there is no one right way to do things and that flexibility is key.

The energy system and the Earth's climate are dynamic, complex systems, linked by carbon dioxide emissions from the combustion of fossil fuels. Climate change is a formidable institutional challenge, combining the need for widespread action to protect a common resource — the Earth's atmosphere — with the need for society to willingly accept costs now for benefits that largely accrue to future generations. However, the complexity of climate change as a technological and policy problem can be overstated. Both the problem of climate change and its potential solutions have been extensively studied and are now well understood, and the technologies and policies needed to mitigate carbon dioxide emissions from energy use are increasingly being deployed in countries around the world. A transition to a low-emission energy system will not be without costs, but with the right combination of stringent and flexible policies in place, ideally in conjunction with technological innovation, Canada can eventually complete such a transition over the course of the coming decades.

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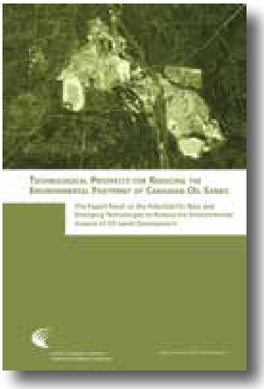

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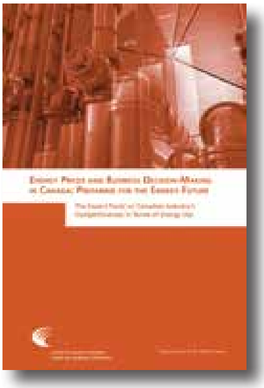

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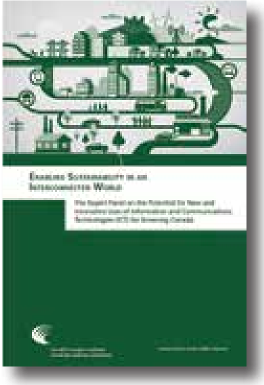

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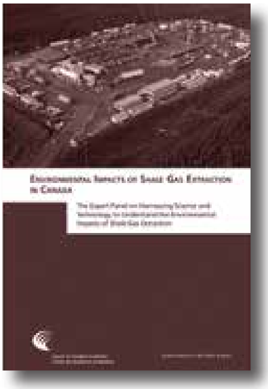

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