3 Energy Systems

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KEY FINDINGS

1. In 2013, primary energy use in North America exceeded 125 exajoules,[1] of which Canada was responsible for 11.9%, Mexico 6.5%, and the United States 81.6%. Of total primary energy sources, approximately 81% was from fossil fuels, which contributed to carbon dioxide equivalent (CO_2e)[2] emissions levels, exceeding 1.76 petagrams of carbon, or about 20% of the global total for energy-related activities. Of these emissions, coal accounted for 28%, oil 44%, and natural gas 28% (*very high confidence, likely*).

2. North American energy-related CO_2e emissions have declined at an average rate of about 1% per year, or about 19.4 teragrams CO_2e, from 2003 to 2014 (*very high confidence*).

3. The shifts in North American energy use and CO_2e emissions have been driven by factors such as 1) lower energy use, initially as a response to the global financial crisis of 2007 to 2008 (*high confidence, very likely*); but increasingly due to 2) greater energy efficiency, which has reduced the regional energy intensity of economic production by about 1.5% annually from 2004 to 2013, enabling economic growth while lowering energy CO_2e emissions. Energy intensity has fallen annually by 1.6% in the United States and 1.5% in Canada (*very high confidence, very likely*). Further factors driving lower carbon intensities include 3) increased renewable energy production (up 220 petajoules annually from 2004 to 2013, translating to an 11% annual average increase in renewables) (*high confidence, very likely*); 4) a shift to natural gas from coal sources for industrial and electricity production (*high confidence, likely*); and 5) a wide range of new technologies, including, for example, alternative fuel vehicles (*high confidence, likely*).

4. A wide range of plausible futures exists for the North American energy system in regard to carbon emissions. Forecasts to 2040, based on current policies and technologies, suggest a range of carbon emissions levels from an increase of over 10% to a decrease of over 14% (from 2015 carbon emissions levels). Exploratory and backcasting approaches suggest that the North American energy system emissions will not decrease by more than 13% (compared with 2015 levels) without both technological advances and changes in policy. For the United States, however, decreases in emissions could plausibly meet a national contribution to a global pathway consistent with a target of warming to 2°C at a cumulative cost of $1 trillion to $4 trillion (US$ 2005).

Note: Confidence levels are provided as appropriate for quantitative, but not qualitative, Key Findings and statements.

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[1] One exajoule is equal to one quintillion (10^{18}) joules, a derived unit of energy in the International System of Units.

[2] Carbon dioxide equivalent (CO_2e): Amount of CO_2 that would produce the same effect on the radiative balance of Earth's climate system as another greenhouse gas, such as methane (CH_4) or nitrous oxide (N_2O), on a 100-year timescale. For comparison to units of carbon, each kg CO_2e is equivalent to 0.273 kg C (0.273 = 1/3.67). See Box P.2, p. 12, in the Preface for more details.

3.1 Introduction

This chapter assesses the contribution of the North American energy system to the global carbon cycle, including the identification of pathways to greater energy efficiency with lower emissions. The system—defined by energy-related activities in Canada, Mexico, and the United States—includes primary energy sources; the infrastructure to extract, transport, convert, transmit, distribute, and use these resources; and the socioeconomic and political structures and dynamics associated with these processes (Romero-Lankao et al., 2014). This definition is larger and more inclusive of socioeconomic and political components than that offered by the Intergovernmental Panel on Climate Change (IPCC; Bruckner et al., 2014). The assessment presented in this chapter includes quantitative indicators of energy use and carbon dioxide equivalent (CO_2e)

emissions from different energy system components since 2003, as well as quantitative and qualitative analysis of the changes in system dynamics, technologies, and costs for an average global warming of less than 2°C. Coverage includes 2004 to 2013, although in some cases updates to 2017 are also provided. (For a more extensive description of CO_2e, see Box P.2, p. 12, in the Preface).[3]

An important source of CO_2e emissions for the continent and the world, the North American energy system in 2013 was responsible for approximately 1.76 petagrams of carbon (Pg C), or 20% of global energy-related emissions (EIA 2016c).[4] From 2004 to 2013, the system experienced significant changes that have affected the North American contribution to CO_2e emissions. These changes include alterations to the fossil fuel mix, increases in renewable energy sources, advances in production efficiencies, an economic shock from the global financial crisis (GFC) of 2007 to 2008, changing fuel prices, and changing carbon management policies. These trends and drivers of change may continue to influence energy-related carbon emissions in the coming decades.

The historical context for North American energy use and CO_2e emissions is described in Section 3.2, this page, emphasizing dynamics associated with previous large fluctuations in carbon emissions. Section 3.3, p. 113, details the state of the energy system as of 2013, including 1) an overview of energy infrastructure; 2) overall energy resources and uses; 3) technologies to increase efficiency and reduce emissions such as total CO_2e emissions, by economy; and 4) end use (e.g., buildings, industry, and transportation) and secondary energy use (electricity). Section 3.4, p. 126, discusses five important patterns and dynamics of the North American energy system that have emerged since the *First State of the Carbon Cycle Report* (SOCCR1; CCSP 2007). Section 3.5, p. 140, places the North American energy system in a global context, in terms of both energy use and CO_2e, while Section 3.6, p. 140, presents an examination of drivers, based on the Kaya Identity.[5] Governmental policy drivers, including carbon management decisions, are the focus of Section 3.7, p. 149, followed by a comparison in Section 3.8, p. 154, of selected recent scenario results to 2040 and 2050 of energy use and CO_2e emissions for the Canadian, U.S., and Mexican economies including projections as well as exploratory and backcasting approaches. The final section (Section 3.9, p. 167) synthesizes the information, identifies knowledge gaps, and summarizes key challenges.

3.2 Historical Context

Given the recent trends in the region's energy use and CO_2e emissions, examining past emissions fluctuations and their relationship to social and economic trajectories is useful for understanding the current situation as well as the range of plausible energy and CO_2e emissions futures.[6] Historically, North American energy use and carbon emissions fall for short periods of time after major societal shocks. For example, energy use and emissions levels peaked in North America around 1929, subsequently fell during the Great Depression, and did not exceed the 1929 peak until around 1941. From the late 1950s to the early 1970s, emissions from fossil fuel burning grew as energy demand rapidly increased. From 1960 to 1973, total final energy

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[3] In addition to the definition of CO_2e in the Preface, natural gas values in this chapter do not include methane emissions during production from coal mines, oil or gas wells, or abandoned mines and wells.

[4] Consistent with formatting in the *Second State of the Carbon Cycle Report* (SOCCR2), this chapter presents emissions data in grams (g) and the International System of Units for multiples of grams—teragram (Tg): a unit of mass equal to 10^{12} grams = 1 million metric tons (Mt); petagram (Pg): a unit of mass equal to 10^{15} grams = 1 billion metric tons. Petagrams of carbon (Pg C) = gigaton of carbon (Gt C); teragrams of carbon (Tg C) = million metric tons of carbon = megaton of carbon (Mt C); Tg C = 10^{12} grams = 10^6 ton.

[5] The Kaya Identity is an accounting technique that includes factors, sometimes called "immediate drivers," that connect with or represent a larger number of underlying drivers, such as processes, mechanisms, system characteristics, policies, and measures (Blanco et al., 2014).

[6] For a broader historical examination of the North American energy system and its relationship to the carbon emissions, see Pacala et al. (2007) and Marland et al. (2007).

use[7] for North America increased from 36 exajoules (EJ) to more than 62 EJ, or by 70% (IEA 2016d).[8] During this period, CO_2e emissions from energy increased from 859 teragrams of carbon (Tg C) to 1.45 Pg C, or by more than 68%. This was an exceptional period, in terms of both absolute increases and the energy–economic output relationship. Then, because of "oil shocks," restructuring of the global economy, and other factors including an economic recession, total North American final energy use fluctuated, slowly increasing to reach a new high of about 66.3 EJ in 1979 before falling again in 1980. Thereafter, total final energy use remained below the 1979 record-high, increasing throughout the 1980s. Energy use and emissions increased over this period, falling again in the early 1990s during a short economic recession. Rebounding almost 14 years after the large fall in 1980, North American final energy use reached a new record-high in 1993. After that time, North American energy use started to increase monotonically again. From 1994 to 2007, both total final energy use and CO_2e emissions followed an increasing trend. By 2007, total North American energy use had reached 128 EJ, and CO_2e emissions approached 1.86 Pg C. The 2007 to 2008 GFC marked the beginning of another decreasing trend, as North American CO_2e emissions, primary energy use, and total final energy use dropped below the 2007 peak and remained below it through 2015 (Boden et al., 2016; EIA 2016c; IEA 2016d).

The historical trajectories of energy use, CO_2e emissions, and economic fluctuations seem to move together, and, if previous average trends portend system response, North American energy use can be expected to rebound from its current trend and exceed the previous peak energy use and emissions levels by around 2020. Recent detailed examinations of the U.S. historical trends, however, suggest that since 1949, there appears to be a shift from a path that closely maps gross domestic product (GDP) with energy use and CO_2e emissions to a divergence of these trends, and this divergence became particularly evident after 1972 (see Figure 3.1, p. 114). Further research suggests that structural changes in the energy and economic systems are reducing the growth of emissions, such that emissions are contracting during recessions faster than they increase during economic expansions. Thus, the rate of increase of CO_2e emissions during the expansion phase continues to be substantially reduced, and this has been particularly noticeable since the early 1990s contraction (Burke et al., 2015b; Shahiduzzaman and Layton 2015). The dynamics underpinning the most recent trends are examined in this chapter and may signal shifts in the energy–economic growth relationship, implying the potential for future new energy and emissions patterns.

3.3 North American Energy System

This section presents a description of the state of the North American energy system by first identifying the size of the system in terms of population and economy, energy resources, and primary energy supply. End-use sectors of buildings, industry, and transportation, along with electricity generation, are then discussed and their regional contributions to the carbon cycle evaluated. Technologies for increasing efficiencies and lowering emissions levels are briefly described for each sector. The last subsection describes promising technologies for increasing carbon sinks.

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[7] Energy end use includes all energy supplied to the consumer for services, such as motive power, cooking, illumination, comfortable indoor climate, and refrigeration. Energy end use typically is disaggregated into end-use sectors: industry, transport, buildings (residential and commercial), and agriculture. It is differentiated from energy supply, which consists of all energy used in a sequence of processes for extracting energy resources, converting them into more desirable and suitable forms of secondary energy (i.e., electricity and heat), and delivering energy to places where demand exists. Primary energy is the energy embodied in resources as they exist in nature, and final energy is the energy transported and distributed to the point of users (e.g., firms, individuals or organizations) (Grubler et al., 2012).

[8] Energy is measured with different units such as joules (J), British thermal units (BTUs), tons oil equivalents (toe), gigawatt hours (GWh), barrels of oil (BBL), and billion cubic feet (ft^3) of natural gas (BCF). This chapter refers to energy use in joules (J) and the International System of Units for multiples of joules: kilojoule (kJ) = 10^3 J, megajoule (MJ) = 10^6 J, gigajoule (GJ) = 10^9 J, terajoule (TJ) = 10^{12} J, petajoule (PJ) = 10^{15} J, exajoule (EJ) = 10^{18} J, and zettajoule (ZJ) = 10^{21} J.

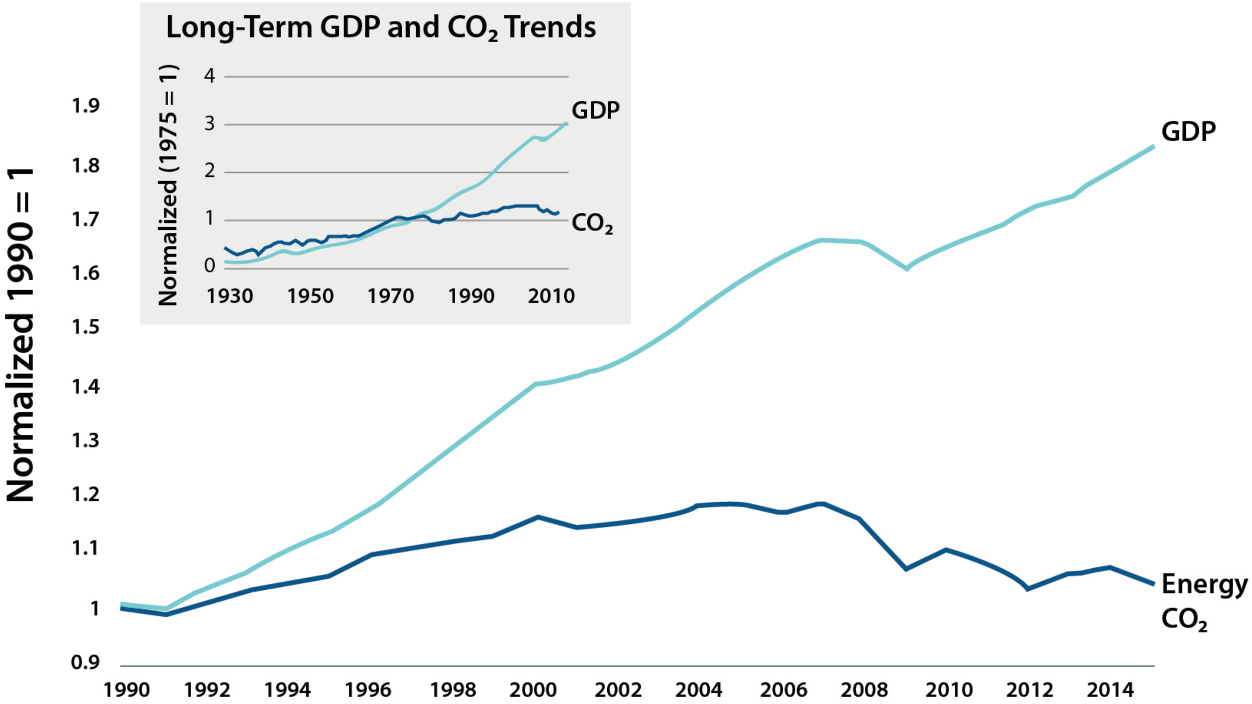

Figure 3.1. U.S. Energy Carbon Dioxide (CO_2) Emissions and Gross Domestic Product (GDP).

The data compiled for this assessment come from a variety of sources, which have different methods of estimating and reporting energy use and emissions levels. For example, the International Energy Agency (IEA) of the Organisation for Economic Cooperation and Development (OECD) reports energy consumption on a net calorific value (or low heat value), while the U.S. Department of Energy's (U.S. DOE) Energy Information Administration (EIA) and Canada report on a gross calorific value (or high heat value; IEA 2016c). (For a discussion of the different inventories and their sectoral scope and methodologies, see Appendix E: Fossil Fuel Emissions Estimates for North America, p. 839.) This section presents data as consistently as possible, using ranges when there is significant disagreement between numbers. When possible, sources are combined using national data to present absolute values for energy and emissions from end-use sectors, and international sources are used in presenting shares of regional totals.

3.3.1 Size of the North American Energy System

By 2013, the North American energy system was serving around 491 million people, or about 6.7% of the global population (UN 2015). Of North America's population, Canada contributed 7%, Mexico 26%, and the United States 67% (UN 2015). According to the World Bank (2016a), North America in 2013 had a combined GDP of more than $19.7 trillion (constant US$ 2010), almost 26% of world GDP. Within North America, the approximate 2013 GDP per capita was $49,200 for Canada, $49,900 for the United States, and $9,300 for Mexico (constant US$ 2010).

The World Energy Council (2016a) and BP (2017b) have identified massive fossil fuel energy reserves in North America (see Table 3.1, p. 115). "Proven" or "proved" coal reserves exceed 7.2 zetajoules (ZJ), accounting for more than 27% of the world share in 2015 (for definitions of reserves and resources, see

Table 3.1. North American Proven Energy Reserves (2015)[a]

Country or Region	Coal Recoverable Reserves	Oil Recoverable Reserves	Gas Recoverable Reserves
Canada	193.0 EJ[b]	1,163.9 EJ	74.9 EJ
Mexico	35.9 EJ	62.8 EJ	12.2 EJ
United States	6,950.1 EJ	276.7 EJ	393.6 EJ
North America	7,201.3 EJ	1,503.1 EJ	481.5 EJ
North America Share of Global	27.5%	14.0%	6.8%
R/P[b] (Years)	276.0	33.1	13.0

Notes

a) Sources: BP (2016); World Energy Council (2016a).

b) EJ, exajoule; R/P, reserve-to-production ratio.

Box 3.1, Energy Resources and Reserves, p. 116). Most North American coal is high quality: 46% is bituminous, 40.7% subbituminous, and only 13.2% lignite, which has the lowest heat content of the three types of coal (World Energy Council 2013). The majority of these coal reserves, almost 6.95 ZJ, are in the United States, which produced 23.8 EJ of coal in 2015. This production represents a 10.4% decline from 2014, as coal consumption has decreased by 20% from 2011 levels (Houser et al., 2017). Canada's coal deposits, most of which are in the western provinces, are significant as well, reaching 193 EJ. Mexico's coal reserves are small by comparison, totaling 37 EJ. At current production rates, North America has more than 270 years of proven coal reserves.

The continent's proven oil reserves amounted to 1.5 ZJ in 2011, or more than 12% of the global total in 2015. Canada's oil reserves, the largest in North America, are the third largest in the world after Saudi Arabia and Venezuela. Particularly significant to the carbon cycle are Alberta's oil sands, which underlie 142,000 km^2 of land in the Athabasca, Cold Lake, and Peace River areas in the northern part of the province. Mining and processing this unconventional source of oil currently account for approximately 8.5% of Canada's total CO$_2$e emissions (Government of Alberta [Canada] 2016). Oil sands also now represent about 98% of Canada's growing oil reserves and about half the country's production in 2011. Despite this large reserve, in 2015 the United States produced 23.7 EJ, more than twice as much as Canada's production of 9.04 EJ. The United States also has developed unconventional technologies for extracting oil, including from shales. Proven oil reserves in the United States increased by 57% from 2005 to 2015 (EIA 2016k), and by 2012 shale oil accounted for about 22% of those reserves (EIA 2014a). Mexico's oil reserves have decreased over the past decades. Although the country's Cantarell oil field is one of the largest in the world, production has declined since 2003. In 2011, Mexico's oil reserves were 62.8 EJ. According to BP (2016), oil reserves within the country have fallen from 285 EJ in 1995. Mexican oil production has been relatively stagnant since 2009 (World Energy Council 2016a). Overall, the North American share of total global proven oil reserves was 14% in 2016, with a projected use of more than 32 years of reserves under current conditions (BP 2017b).

In 2015, North America's proven natural gas reserves reached 482 EJ. The United States has about 82% of the total proven natural gas reserves in North America, and the continent has approximately 6.8% of world reserves. As with oil, unconventional extraction techniques have expanded the region's reserves dramatically. Over the last 10 years, shale gas reserves in the United States have increased

Box 3.1 Energy Resources and Reserves

Fossil fuels are abundant in many regions of the world including North America. To provide an understanding of their quantity and quality for various purposes, energy analysts classify them according to availability. Classification systems typically divide *resources* from *reserves*. This distinction reflects the likelihood that the fossil fuels will be brought to the market. Energy resources include volumes that have yet to be fully characterized, present technical difficulties, or are costly to extract. For example, there are existing resource volumes for which technologies have yet to be developed that permit their extraction in an environmentally sound and cost-effective manner. Reserves include volumes whose production can be achieved economically using today's technology. Often associated with ongoing production projects, energy reserves are further classified as "proven" (proved) and "unproven" (unproved). Proven reserves are those with a reasonable certainty (a minimum 90% confidence) of being recoverable under existing economic, technological, and political conditions. Unproven reserves include sources that have a lower probability of being produced (IEA 2013).

To provide information on future availability of nonrenewable energy reserves, analysts typically use reserve-to-production ratios (RPR or R/P), which are expressed in years. The denominator is the production rate of the reserve during the latest years. The reserve typically includes proven amounts. In the United States, however, resource categories are expressed as "proved," "economically recoverable resources," and "technically recoverable resources" (see Figure 3.2, this page). Using this extended definition increases the years of calculated use of the fuel. That is, the length of time that a resource is available often

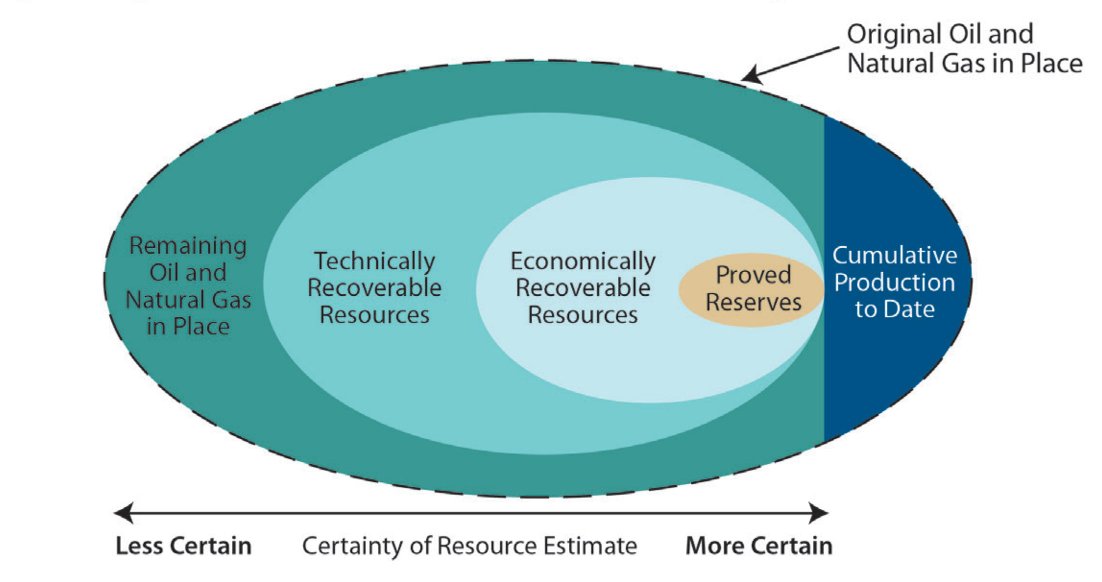

Figure 3.2. Stylized Representation of Oil and Natural Gas Resource Categories. Figure is not to scale. [Figure source: Redrawn from EIA 2014b.]

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is expressed in terms of a ratio of the proved reserve to the amount consumed annually. This U.S. ratio includes the technically recoverable resource to the amount consumed annually (EIA 2014b). Technically recoverable resources, consisting of both proved and unproved reserves, include all the oil and gas that can be produced based on current technology, industry practice, and geological knowledge. As technology develops, industry practices improve. As understanding of the geology increases, the estimated volumes of technically recoverable resources also expand. Each year, the U.S. Department of Energy's Energy Information Administration (EIA) reports proved U.S. oil and natural gas reserves and its estimates of unproved technically recoverable resources for shale gas, tight gas, and tight oil resources. These reserve and resource estimates are used in developing EIA's *Annual Energy Outlook* projections for oil and natural gas production. In 2015, for example, estimates for oil in the United States suggest approximately 244 exajoules (EJ) of proved reserves of oil and 1.4 zettajoules (ZJ) of unproved resources, for a total of 1.7 ZJ of technically recoverable resources. For natural gas, the United States has about 369 EJ of proved reserves and 2.1 ZJ of unproved reserves, for a total of 2.5 ZJ of technically recoverable resources (EIA 2017k). Economically recoverable resources are the amounts of technically recoverable resources that can be profitably produced. The volume of economically recoverable resources is determined by both oil and natural gas prices and by the capital and operating costs that would be incurred during production.

For consistency across economies, this chapter uses proven reserves and expresses availability in R/P ratios. However, the differences are noted when these figures conflict with numbers provided by individual nations.

ninefold. As of 2015, the United States produces 22% of the world's natural gas and Canada produces almost 5%. Mexico also has increased gas production over the past decade, producing as of 2015 about 1.5% of the world's natural gas (BP 2016). North American proven gas reserves are projected to last another 13 years under current production conditions. However, the United States estimates its national gas reserves will last another 86 years. These estimates disagree because of different definitions of reserves (see Box 3.1, p. 116). While international analysis typically uses proven reserves to estimate how long an energy reserve will last, the United States uses both proven and unproven technically recoverable resources (EIA 2017e).

The concept of proven reserves is mainly for stock accounting that energy entities maintain to ensure adequate production in the near future. At a global scale, for example, proven oil reserves relative to current production have changed very little over decades. Resources have various definitions, but as a very broad generalization, technological advances have consistently overcome depletion of fossil fuel reserves. This outcome is likely to continue over the short to medium term. Using regional proven reserves, however, holds tremendous potential for increasing the atmosphere's carbon concentration.

In 2013, the three economies of North America had a combined total energy use that exceeded 125.6 EJ (EIA 2016c), or approximately 22% of global primary energy use. Of the total, Canada was responsible for approximately 11.9% (14.9 EJ), Mexico 6.5% (8.2 EJ), and the United States 81.6% (102.6 EJ). The per capita energy-use levels are relatively similar between the United States and Canada but different for Mexico. For example, according to the World Bank (2016a), in 2015, energy use per capita in Canada and the United States was 318 gigajoules (GJ) and 284 GJ, respectively, while Mexico's was about 62 GJ.

Table 3.2 North American Nonfossil Fuel Electricity Capacity (2015)[a]

Area	Hydro-Installed Capacity (GW)[b]	Solar-Installed Capacity (GW)[b]	Geothermal-Installed Capacity (GW)[b]	Wind-Installed Capacity (GW)[b]	Nuclear-Installed Capacity (GW)[b]
Canada	79.2	2.2	1.5	11.2	13.5
Mexico	12.4	0.2	1.1	3.1	1.4
United States	102.0	27.3	3.6	72.6	99.2
North America	193.0	29.8	23.7	86.9	114.1

Notes

a) Sources: BP (2016); World Energy Council (2016a).

b) GW, gigawatts.

Although about 81% of North America's total energy use is from fossil fuels, the continent also has significant renewable and low-carbon inputs to the electricity system (see Table 3.2, this page). These include 1) the world's leading installed hydropower capacity; 2) 13% of the world's solar capacity; 3) 28% of the global geothermal capacity; 4) approximately 86.9 gigawatts (GW) of wind capacity, which is rapidly increasing (e.g., 8.6 GW of wind power installed by the United States in 2015, a 77% increase from 2016); 4) significant nuclear capacity at approximately 114 GW (i.e., 29% of global nuclear capacity and 36% of global nuclear generation in 2016; Nuclear Energy Institute 2017; IAEA 2017); and 5) uranium resources estimated at 0.82 Tg (World Energy Council 2016a). Changes in the regional renewable energy generation capacity, via increases in renewable resources, are having significant effects on the regional energy system's contribution to the carbon cycle (for a discussion of the renewable resources in the region, see Section 3.4.3, p. 131, and Section 3.6.4, p. 147).

Fossil fuel combustion contributes considerably to the global carbon cycle. In 2013, North American CO_2e emissions from fossil fuel combustion exceeded 6.45 Pg CO_2e (1.76 Pg C). These emissions, down approximately 11% from 2007 levels, represent about 20% of the global total for energy-related activities (see Section 3.4.1, p. 127, for details). Among North American CO_2e emissions from fossil fuels, coal accounted for 28%, petroleum 44%, and natural gas 28%. Energy-related CO_2e emissions exceeded 5.4 Pg (1.47 Pg C) for the United States and 0.56 Pg (153 Tg C) for Canada and were about 0.45 Pg (123 Tg C) for Mexico (EIA 2016f). For 2013, the World Bank (2016b) estimated that CO_2e emissions per capita from energy use were 18.8 Mg (5.1 Mg C) for the United States; 15.3 Mg (4.17 Mg C) for Canada; and 6.5 Mg (1.77 Mg C) for Mexico, well below the averages for the two other countries.

3.3.2 North American Subsystem Contributions to Carbon Emissions

The North American subsystems include residential and commercial buildings, industry, and transportation end-use sectors along with the electricity-generation sector. Each subsystem is described in this section by identifying its major components, followed by a description of primary energy source contributions, the total energy use within the sector in 2013, and related carbon emissions during that year. Each energy sector description includes sector characteristics of each of the three nations defined as the "region," concluding with a brief overview of new and emerging technologies that increase efficiencies and lower carbon emissions. The final part attempts to synthesize much of this information through the presentation

and discussion of energy and CO_2e emissions flow diagrams specific to the U.S. energy system.

Electricity

The North American electric power system is integrated through more than 35 transmission interconnections between Canada and the United States and about nine between Mexico and the United States (CEA 2014). The U.S. electrical system is the largest within North America, including more than 7,700 power plants, 1.1 million km of high-voltage transmission lines, 10.5 million km of distribution lines, and almost 56,000 substations (U.S. DOE 2017d) with over 1 billion kilowatts (kW) of installed generating capacity (CIA 2018). The Canadian electrical system has more than 1,700 power plants (CGD 2016), over 160,000 km of transmission lines (IEA 2010), and about 148 million kW in installed generating capacity (CIA 2018). Mexico's energy system is also large, expanding and integrating with the U.S. system and containing about 400 thermal power plants (CGD 2012) with over 65 million kW in installed generating capacity (CIA 2018). Mexico's national transmission grid includes approximately 50,000 km of mostly high- and medium-voltage lines, and the country is constructing dozens of new natural gas–fired power plants to meet increasing electricity demand (EIA 2016j).

In 2013, North America generated 17.9 EJ of electricity, 18% of which was from nuclear power, 14% from hydropower, 6% from nonhydroelectric renewables, and 62% from fossil fuels, with about 7% of this total lost in transmission and distribution. Within North America, Mexico was responsible for 5.6% of the continent's total electricity generation, Canada 12.8%, and the United States 81.5%. Together, the total electricity generated by these countries in 2013 was approximately 22.5% of the global total (EIA 2016c).

The U.S. electricity sector contributed about 34% of total national CO_2e emissions, or 556 Tg C, in 2013 (U.S. EPA 2016). In Canada, electricity generation accounted for approximately 12% of national CO_2e emissions, or 85 Tg CO_2e (23 Tg C; ECCC 2016b). Canada's lower share of national emissions from electricity generation is due to the high share of hydropower in electricity generation as well as the high-carbon intensity (see Section 3.6.3, p. 144) of the country's other sectors. According to SEMARNAT-INECC (2016), the Mexican electricity sector emitted approximately 127 Tg CO_2e (34.6 Tg C) in 2013, or about 26% of net national CO_2e emissions. Recently, however, the Mexican government ended its state-owned electricity monopoly and subsequently held the first power auction in 2016, awarding more than 1.7 GW to solar and wind generation (Meyers 2016), suggesting changes in the future.

Emerging trends have been stressing the North American electricity sector. This system was not designed for the distributed and often nondispatchable generation (electrical energy that cannot be turned on or off to meet demand fluctuations) that is dominating electricity supply growth, the electrification of the transportation and low-temperature heat markets, and the effects of climate change itself. Although challenging, this changing landscape provides opportunities for increased efficiencies and lower emissions levels achievable through a number of energy-sector advances. These improvements include 1) grid modernization, 2) applications of intelligent technologies and next-generation components with "built-in" cybersecurity protections, 3) advanced grid modeling and applications, 4) distribution generation and innovative control system architectures, and 5) improved storage capacity (U.S. DOE 2017d). New energy storage technologies, including batteries to overcome solar and wind intermittency challenges, can help make these technologies directly competitive with fossil-based electricity options (Kittner et al., 2017). Advances in nuclear power such as small- and medium-sized and modular technologies offer opportunities to increase the already large fleet of plants, although the future of this technology remains unclear (see Box 3.2, Potential for Nuclear Power in North America, p. 120, and Section 3.4.4, p. 134).

Box 3.2 Potential for Nuclear Power in North America

Nuclear energy, generated from around 450 power reactors in 31 countries, has provided around 10% to 11% of the world's power generation over the past several years; nearly half the current global nuclear generation is from the United States and France, and another 20% is from China, Russia, and South Korea (Schneider et al., 2017). Except for China—which increased its nuclear generation by 23% from 2015 to 2016—the world is closing plants at a similar rate to building new ones (World Nuclear Association 2018). This is due partly to relatively expensive capital and operational costs and public fears of safety, but also to slow construction times with frequent delays. For example, average plant construction is around 7 years, and two new plants, one in Argentina and the other in the United States, took over 30 years each to complete (Schneider et al., 2017; The Economist 2017).

In North America, Canada currently has 19 nuclear reactors in operation supplying 344.5 petajoules (PJ) of electricity. Mexico has two reactors supplying 37.1 PJ of electricity, and the United States has around 99 reactors in 30 states supplying 2.9 exajoules of electricity (IAEA 2017). The current nuclear energy generated accounts for about 18% of electricity for the region. Within the region, the United States is the only economy with plans to expand its nuclear reactor fleet, partly in an effort to overcome decommissioning trends. For example, since 2013, five U.S. nuclear reactors have shut down and nine others supplied closure announcements, while five new nuclear reactors are scheduled to come online by around 2019 (White House 2016). Two nuclear reactors are actively under construction: Vogtle Units 3 and 4 in Georgia. They were the first new reactors to receive construction approval in more than 30 years, and their construction has been buffeted by delays and cost overruns.

Nuclear is often considered a key component of a high-energy, low-carbon future (e.g., Bruckner et al., 2014; NEA 2012). In the United States, for example, nuclear energy currently provides about 60% of national carbon-free electricity (White House 2016). New designs, such as small- and medium-scale and modular systems are innovations that address reductions in greenhouse gas emissions and extend nuclear power into other applications, such as heat for industrial processes and use in desalination plants (IAEA 2017; Rosner and Goldberg 2011). Current trends in small and modular systems, however, suggest that global interest in these technologies has faded (Schneider et al., 2017).

For nuclear power to be viable, reactors need to be fundamentally transformed, overcoming several challenges: 1) costs need to come down and be competitive with other energy sources; 2) development of plants needs to be quicker; 3) safety concerns need to be addressed; 4) opportunities for nuclear in areas with no preexistent nuclear power need to be explored; and 5) issues related to waste and national security need to be resolved (CATF 2018). Related to these challenges, the expansion of this industry requires changes in regulatory structures including licensing, design certifications, and control procedures and requirements. Moreover, there also are environmental justice issues surrounding uranium mines in the region. For example, about 75% of the 15,000 U.S. uranium mine locations are on federal and tribal lands, where mining activities have created significant health issues for Native Americans (Moore-Nall 2015) and extremely long-term ecological degradation (see Ch. 7: Tribal Lands, p. 303, for a discussion of the specific tribal land location of regional energy reserve shares and their impacts).

To address some of these issues, industry leaders and start-up companies have developed

Continued on next page

(Continued)

advanced designs and features for future nuclear reactors intended to address these barriers (CATF 2018). Advanced reactors employ different fuels and technologies that 1) reduce waste (e.g., via more efficient fuel use); 2) reduce costs (e.g., via coolants that require less materials for containment); 3) are faster to build (via smaller, segmented reactors built offsite and shipped to destination); 4) decrease the risk of weapons proliferation (via less desirable fuels and waste streams); and 5) improve safety (via nonwater coolants and stations on floating platforms at sea). While innovative reactor technologies are currently available, they will not be commercially scalable for rapid nuclear expansion across North America and the rest of the world without further research and development (CATF 2018; U.S. DOE 2017c).

Residential and Commercial Buildings

North America's building stock varies in quantity and quality. In 2013, Canada had 14.8 million residential households occupying over 2 billion m^2, plus 480,000 commercial buildings with 739 million m^2 of floor space (Natural Resources Canada 2015; Natural Resources Canada 2018a). Mexico had an estimated 28 million residential households and 25.5 million m^2 of commercial floor space (UNEP 2009). The U.S. had 114 million residential households occupying almost 18 billion m^2 (EIA 2015b) and more than 5.5 million commercial buildings with a total floor space of over 8 billion m^2 (EIA 2012c).

In 2013, the North American commercial sector used about 9.7 EJ of energy, mostly from electricity (58%), natural gas (37%), and oil products (7%). Residential buildings used about 13.3 EJ in 2013, supplied mostly by electricity (43%), natural gas (41%), heating oil (8.7%), and biofuels and waste (6.4%) (IEA 2016d). Given the large building stock in the region, the residential and commercial buildings sector accounts for a large share of energy use. In Canada, Mexico, and the United States, commercial and residential building operations account for about 20%, 30%, and 40%, respectively, of each country's primary energy consumption.

Much of the energy use in buildings is from electricity and natural gas. In 2013, U.S. buildings consumed 73% of the country's electricity and 52% of direct natural gas (60% of which was for electricity generation; EIA 2015b). In the residential sector, a significant fraction of overall energy consumption is for space heating and air conditioning, although in the United States the share of heating and cooling has dropped from 58% in 1993 to 48% in 2009 (EIA 2013a). The main U.S. sources of heating during the winter months are natural gas or electric furnaces and electric heat pumps, but the range of equipment and fuels varies across climate regions (EIA 2017h). Energy consumption for appliances and electronics continues to rise, signaling the importance of nonweather-related energy use in homes (EIA 2013a). In Canada, approximately 63% of residential energy use is for space heating, with another 24% for water heating (Natural Resources Canada 2016c; Natural Resources Canada 2018b).

Alternatively, removing electricity-related emissions from the buildings sector makes the sector's share of CO_2e emissions across the region the lowest among end-use sectors. For example, in 2013, the U.S. commercial and residential sectors together accounted for 10% of total national CO_2e emissions (U.S. EPA 2016; see Figure 3.3, p. 125). The U.S. commercial sector emitted approximately 59 Tg C, and the residential sector was responsible for about 89.5 Tg C. The Canadian buildings sector emitted 74 Tg CO_2e (20.2 Tg C), or 10% of total national emissions (ECCC 2016b). In Mexico, the buildings sector emitted about 25.6 Tg CO_2e (7.0 Tg C) in 2013, representing about 5% of total net national emissions for that year (SEMARNAT-INECC 2016).

Technological opportunities for improved energy efficiency and reduced carbon emissions from the building sector are extensive. By 2030, building energy use could be cut more than 20% using known cost-effective technologies. The United States identified potential technological improvements for the residential and commercial sectors, including high-efficiency heat pumps, thin insulating materials, windows and building surfaces with tunable optical properties, high-efficiency lighting devices, and low-cost energy-harvesting sensors and controls (U.S. DOE 2015a). Many of these technologies address thermal properties of buildings and technologies for space heating and cooling energy services, thus effectively reducing electricity and natural gas usage.

Industry

The extremely diverse North American industrial sector consists of mining, manufacturing, and construction. Mining enterprises extract raw materials from Earth's crust that are used as inputs for manufacturing and construction. Construction enterprises create North America's built environment, including buildings, industrial facilities, and infrastructure such as roads and the electric power grid. Manufacturing consists of a wide variety of small, medium, large, and very large facilities with subsectors including iron and steel, chemicals and petrochemicals, nonferrous metals, nonmetallic minerals, transport equipment, machinery, food and tobacco, paper, pulp and printing, wood and wood products, textile and leather, and nonspecified industry.

Manufacturing, in particular, represents a complex and diverse sector that both contributes to CO_2e emissions and offers the potential for reductions over the lifetime of manufactured products and materials. Manufacturing involves global supply chains of raw materials, processed materials, components, and final products that are sourced and traded globally. Manufacturing's complex supply and trade networks are exemplified in a case study by the Clean Energy Manufacturing Analysis Center (CEMAC) describing a typical solar crystalline silicon photovoltaic (PV) panel, a clean energy technology that reduces emissions from power production. This solar end product includes polysilicon made in the United States and exported to many other countries (US$1.8 billion in total exports in 2014). These countries then make PV cells and modules that are re-imported back to North America (US$3.9 billion; CEMAC 2017). Another example is the manufacture of turbine components (e.g., nacelles and blades) in the United States from steel and other materials from multiple sources; the parts are then installed in the United States and also exported (US$0.4 billion) to Canada, Brazil, and Mexico. Because these complex supply and trade networks are not comprehensively understood, further study could play an important role in supporting efforts to reduce emissions from industrial end uses.

In 2013, the total energy use for the North American industrial sector was about 14.7 EJ. The major energy sources for industry included natural gas (40%), electricity (29%), biomass and wastes (11%), oil and oil products (10%), coal (8%), and heat (2%; IEA 2016d). Additionally, about 6.11 EJ were consumed as industrial nonenergy use, or feedstock, major sources of which included oil and oil products (88%) and natural gas (12%; EIA 2016i). For the North American agriculture and forestry sectors, total energy use was approximately 1.3 EJ, supplied mostly by oil and oil products (76%), electricity (15%), natural gas (6%), and biomass and wastes (3%; EIA 2016i). The United States consumed 17.2 EJ, representing 78% of this sector's total energy and feedstock consumption in North America in 2013.

In 2014, IEA reports that the total North American industrial sector emitted 1.65 Pg CO_2e (450 Tg C), of which the United States contributed 1.24 Pg CO_2e, or 338 Tg C (IEA 2016d). Based on a comparison of U.S. DOE datasets for U.S. industrial sector emissions and the World Resources Institute's CAIT database for CO_2e emissions, the industrial sectors in Canada, Mexico, and the United States in 2012 emitted approximately 0.19 Pg CO_2e (51.8 Tg C), 0.17 Pg CO_2e

(46.4 Tg C), and 1.63 Pg CO_2e (445 Tg C), respectively. These estimates represent 27%, 24%, and 26%, respectively, of each country's total energy sector CO_2 emissions in 2012. By comparison, U.S. DOE reported 1.5 Pg CO_2e (410 Tg C) for the United States, Natural Resources Canada reported 0.179 Pg CO_2e (48.8 Tg C) for Canada, and the National Institute of Ecology and Climate Change (INECC) reported 0.115 Pg CO_2e (6.4 Tg C) for Mexico in 2013. If electricity-related emissions are excluded from the industrial sector, U.S. industrial emissions were approximately 264 Tg C and Canada's industrial emissions were about 41 Tg C in 2013. Both sets of values have remained at these respective levels through 2015 (EIA 2018e; Natural Resources Canada 2018c). In Mexico, INECC separates electricity emissions from other sectors (SEMARNAT-INECC 2016).

State-of-the-art technologies available today could provide energy savings for the manufacturing sector, although many have not yet penetrated the market. Clean energy manufacturing includes the minimization of energy and environmental impacts from the production, use, and disposal of manufactured goods. These technologies exist for a broad range of services, such as operations to convert raw materials to finished products, effective management of the use and flows of energy and materials at manufacturing facilities, and innovative new materials and new manufacturing technologies for products that affect supply chains (U.S. DOE 2015b).

Transportation

North America has a vast, extensive transportation infrastructure. The U.S. interstate highway system is about 77,000 km long (second in length only to China's), and the country's road system covers more than 6.5 million km and includes over 600,000 bridges. This infrastructure provides the nation's nearly 11 million trucks and over 250 million passenger vehicles (WardsAuto 2015) with direct access to ports, rail terminals, and urban areas. In addition to its more than 600 smaller harbors, the United States has over 300 commercial harbors that support more than 46.4 million twenty-foot equivalent units (TEUs) of annual port container traffic (World Bank 2016c).[9] There are 3,330 existing public-use airports in the United States composing the National Plan of Integrated Airport Systems, which supports more than 9.5 million registered annual carrier departures worldwide (World Bank 2016c). Finally, the U.S. rail network includes approximately 260,000 km of track, 76,000 rail bridges, and 800 tunnels that help move both passengers and freight around the country (ASCE 2013).

Canada's transportation infrastructure includes more than 1.3 million km of public roads, 38,000 km of which are in the National Highway System used by about 1 million trucks and 20.1 million passenger vehicles (WardsAuto 2015). The country has more than 560 port facilities supporting over 5.5 million TEUs of annual port container traffic (World Bank 2016c), 900 fishing harbors, and 202 recreational harbors. Canada's 26 major airports are part of the National Airport System, which supports more than 1.2 million registered carrier departures worldwide every year (World Bank 2016c). In addition, there are 71 regional and local airports; 31 small and satellite airports; and 13 remote airports, including 11 in the Arctic. The Canadian rail system includes 45,700 km of track (Transport Canada 2015).

Mexico has a road network of more than 365,000 km used by 8.8 million registered trucks and more than 22.9 million passenger cars (WardsAuto 2015). The country also has approximately 110 major airports that carry out more than 470,000 registered carrier departures worldwide yearly, and its 76 seaports and 10 river ports support over 5.2 million TEUs of port container traffic annually (World Bank 2016c). Railroads in Mexico's estimated 26,700-km railroad network generally operate within cities, such as Mexico City and Guadalajara. A proposed high-speed rail link would connect these two cities with other locations across the country.

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[9] TEUs are standardized measures of a ship's cargo-carrying capacity. The dimensions of one TEU are equal to that of a standard 20-foot shipping container (i.e., 20 feet long by 8 feet tall). Usually nine to 11 pallets fit in one TEU.

According to IEA (2017a), total North American energy use for transportation exceeded 30 EJ in 2013. The U.S. transportation sector consumed around 28.5 EJ of this energy, 91.6% of which was from petroleum, 3.3% from natural gas, and 5.0% from biofuels (EIA 2017b; IEA 2016d). Canada's transportation sector consumed approximately 2.6 EJ (IEA 2017a), and about 94% of transportation fuels were petroleum products and 5.3% natural gas (CESAR 2018). Mexico's transportation sector consumed about 2.1 EJ in 2013, equal to 48% of total national energy consumption, with almost all of it from motor vehicles (Secretaría de Energía de México 2016).

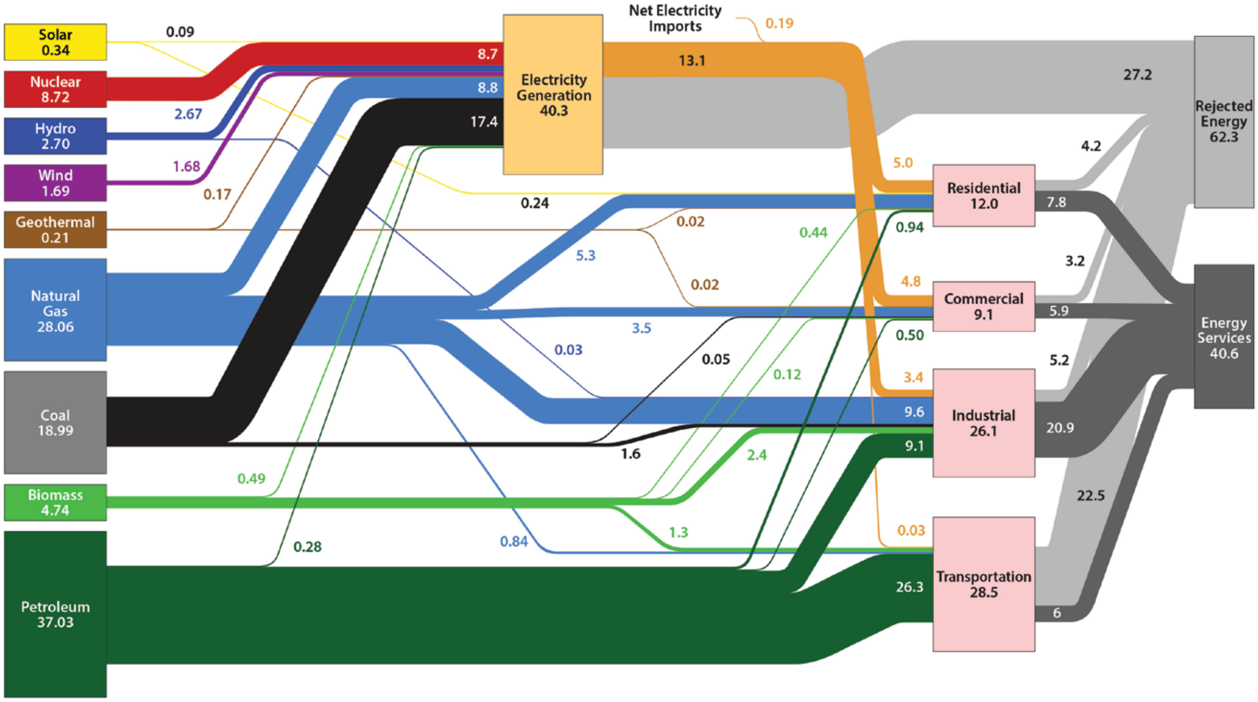
In 2013, North American transportation CO_2e emissions exceeded 2.15 Pg CO_2e (585 Tg C). The U.S. transportation sector alone contributed approximately 1.80 Pg CO_2e (499 Tg C) in 2013, or more than 28% of the nation's total greenhouse gas (GHG) emissions (U.S. EPA 2016). During the same year, Canadian emissions exceeded 0.2 Pg CO_2e (54 Tg C), accounting for about 24% of the country's total emissions (ECCC 2017b). In Mexico, emissions from road vehicles in 2013 dominated transportation emissions, with vehicles emitting 0.153 Pg CO_2e (41.7 Tg C), equal to 31% of the net national total. Total Mexican transportation-sector emissions were 0.174 Pg CO_2e (47.5 Tg C), equal to 34% of net national emissions for that year (SEMARNAT-INECC 2016). Mexican transportation energy use and emissions are expected to rise dramatically over the coming decades (IEA 2015b).

The North American transportation system is clearly large, complex, and highly integrated with regional economic and social development. Because of transportation's importance as an energy sector and its significant effects—including economic costs, risks of dependence on oil, environmental impacts on air quality and health, and carbon emissions—advancing clean (i.e., low-emission) and efficient vehicle systems and technologies could have extensive impacts across societies. A range of technologies at various stages of research and development offer the potential to increase energy efficiency and mitigate impacts, including reducing contributions to the carbon cycle. Key technologies for light- and heavy-duty vehicles include 1) low-temperature combustion engines; 2) alternative fuels and lubricants; 3) advanced light-weight, high-strength materials for vehicle body systems; 4) improved batteries and electric drives; 5) lower-cost and more durable fuel cells; and 6) more efficient onboard hydrogen storage. Beyond vehicle improvements, a variety of existing or developing technologies can be leveraged to meet projected increases in North American air, water, off-highway, and rail transportation. Improved technologies could reduce the energy intensity of the entire transportation system, resulting in significant reductions in carbon emissions (U.S. DOE 2015b).

Summary

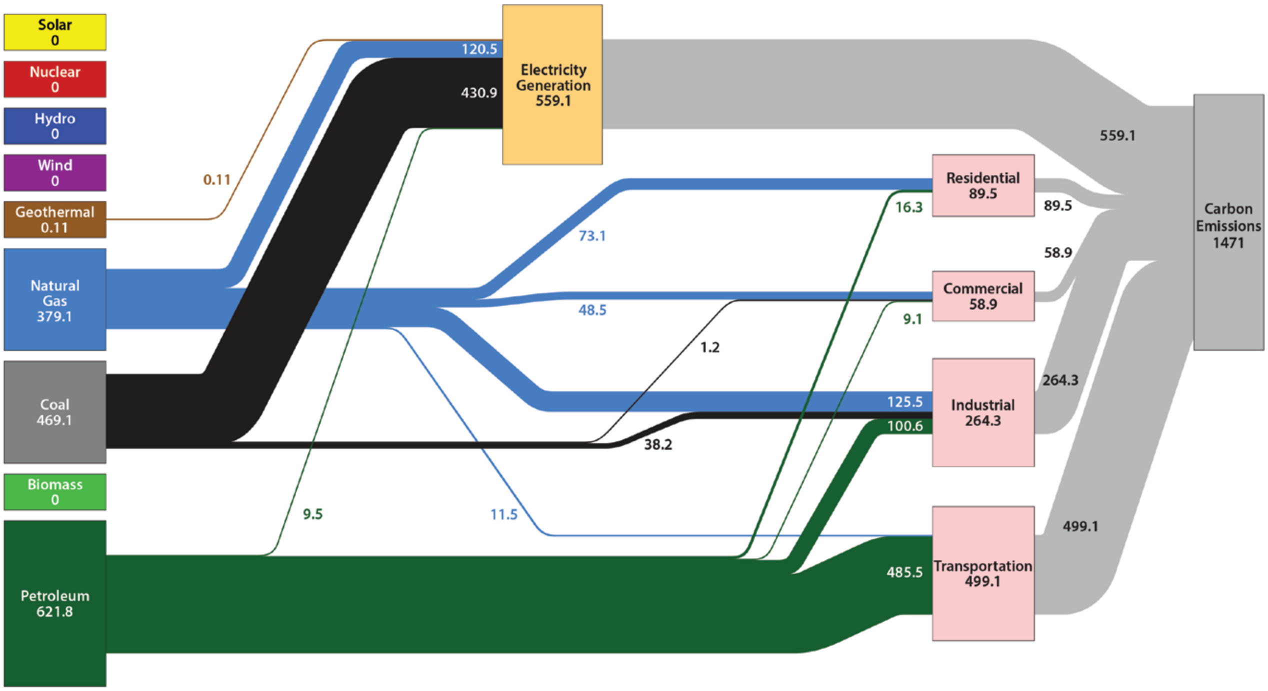
Given the complexity of the energy system, comprehending the size of relative energy flows from primary supply to end use is difficult. Sankey diagrams, developed by Matthew Henry Sankey in 1898, demonstrate flows to and from individual system components via the width of the bands, which, in this case, are directly proportional to energy production, usage, and losses. This visual account helps to summarize not only how the system works, but where efforts to change operations may be most effective. Figure 3.3, p. 125, presents Sankey diagrams for U.S. energy use and CO_2e emissions in 2013. On the left side of the diagrams are the primary energy supply sources, and on the right side are the energy end uses with electricity generation in the middle. A few immediately notable points are reviewed in this chapter: 1) renewables make up a small share of energy flows (although that share is growing); 2) most coal fuel is used for electricity generation (although the band width is decreasing); 3) natural gas fuel is split largely between electricity generation and residential, commercial, and industrial energy uses (all of which are increasing); 4) most petroleum fuel is used for transportation with some for industry; 5) values for rejected or unused energy are larger than those for energy services (suggesting a potential for enhanced efficiency); and 6) the electricity generation and transportation sectors are the largest sources of CO_2e emissions, followed by industry.

Estimated U.S. Energy Use in 2013: ~102.9 Exajoules



Values may not sum to totals due to rounding.

Estimated U.S. Carbon Emissions in 2013: ~1,471 Tg C



Values may not sum to totals due to rounding.

Figure 3.3. Flows of U.S. Energy Use and Carbon Emissions, 2013. Key: Tg C, teragrams of carbon. [Figure source: Adapted from Lawrence Livermore National Laboratory (2018), flowcharts.llnl.gov/commodities/energy.]

3.3.3 Carbon Sink Technologies

Carbon sequestration, the process of capturing and storing atmospheric carbon, has been proposed as a way to slow the atmospheric and marine accumulation of GHGs that are released by burning fossil fuels. One set of increasingly popular sequestration technologies comprises carbon capture and storage (CCS) and carbon dioxide utilization (CDU). CCS captures CO_2 emissions produced from the use of fossil fuels in electricity generation and industrial processes, thus preventing them from entering the atmosphere after their subsequent storage in deep geological formations. The CCS process also can be used to take carbon directly out of the atmosphere, typically including CO_2 capture, transport, and storage in depleted oil and gas fields or saline aquifer formations.

North American CCS achieved an important milestone in 2014, with Canada's Boundary Dam Unit 3, with a net capacity of 120 megawatts (MW) becoming the first commercial power plant to come online with CO_2 capture. The 38 large-scale CCS projects either in operation or under construction have a collective CO_2 capture capacity of about 60 Tg per year, while the 21 in operation now capture 40 Tg CO_2 per year (Global CCS Institute 2016). The present pace of progress in CCS deployment, however, falls short of that needed to achieve average global warming of 2°C (IEA 2015a). Constraints include financial and technological challenges to overcome low efficiency and energy losses, as well as a lack of public acceptance (Haszeldine 2009; Smit et al., 2014). Regardless, CCS technologies often are included in scenarios as an increasingly effective way to remove CO_2 from the atmosphere (see Section 3.8, p. 154). One particularly important application is bioenergy with carbon capture and storage (BECCS), which has been indicated as a key technology for reaching low-CO_2e atmospheric targets (Fischer et al., 2007).

Carbon dioxide usage includes direct and indirect aspects. The most successful direct use has been in enhanced oil recovery (EOR) and enhanced coalbed methane (ECBM; CH_4) recovery, in which CO_2 is injected into oil or natural gas fields to enhance the resource recovery rate (NETL 2010, 2017). Indirect CDU technologies involve the reuse of CO_2 emissions from power plants or industrial processes to produce value-added products. Indirect CDU includes using chemical, biochemical, and biotechnological means to create energy fuel, polymers, and carbonates from the CO_2. Overcoming technical, economic, and strategic challenges remains an issue before this option becomes viable (Al-Mamoori et al., 2017; Song 2006).

3.4 Indicators, Trends, and Feedbacks

This section identifies the major trends over the past 10 years that have shaped North American energy system dynamics and current understanding of the relationship between the energy system and the carbon cycle (see Table 3.3, p. 127). Importantly, the North American energy system is undergoing a transformation. How the system ultimately will emerge is unclear, but the outlines of change are already evident.

At least five major trends and a number of associated indicators demonstrate a shift from patterns described in SOCCR1. These new trends are 1) a decrease in energy use (e.g., reduced oil use and stable or reduced electricity demand) and total CO_2e emissions since 2007, 2) an energy transition based on increased shares of natural gas in North America's primary fuel mix and in electricity generation, 3) increased renewable energy inputs into the electrical system, 4) increased concern about aging energy-related infrastructure, and 5) new understanding that has altered thinking on the role of biofuels and natural gas in the carbon cycle. Each of these dynamics is described herein, first for the region and then for each economy within the region. The descriptions include historical and nationally comparable data from 2004 to 2013, with more recent information for some energy subsectors in individual nations. The section ends with a discussion of feedbacks related to energy use and energy-related CO_2e emissions that are immediately important or may become important for regional energy systems in the near future.

Table 3.3. Five Major Trends, Indicators, Drivers, and Impacts on the Carbon Cycle

Trends	Indicators	Drivers	Impacts on Carbon Cycle
Decline in energy use and carbon dioxide equivalent (CO_2e)[a] emissions	Decrease in total energy use with declines in demand for oil products and a slowed rate of increase in electricity demand	Economic recession, lower carbon intensities of fuels due to switching to natural gas and increases in renewables, lower energy intensities due to efficient new technologies, governmental policies, and ongoing structural changes leading to lower energy intensity	Lower emissions
Natural gas transition	Larger primary energy contribution from natural gas, increase in natural gas reserves, expansion of fracking, fuel switching in electricity generation and industry	New technologies, policies, and market forces (prices)	Lower emissions (potentially) offset by methane leakage
Increased renewable energy	Larger number and capacity of wind and solar power–generation plants, resulting in larger contributions of these sources to electricity generation	New technologies, governmental policies, and market forces (prices)	Lower emissions
Aging infrastructure	Age of infrastructure, higher costs of replacement, and increasing examples of infrastructure failure	Lack of public financing and political action	Potentially higher emissions
New understanding of biofuels and fugitive (e.g., leaked) natural gas emissions	Increasing number of studies demonstrating land-use emissions from biofuel production and potentially large unaccounted-for emissions levels from natural gas extraction, transmission, and distribution	Better understanding of 1) fuel life cycle and 2) indirect impacts of fuel production, transmission, and distribution	Revised estimates of emissions (impact may be positive or negative)

Notes

a) Carbon dioxide equivalent (CO_2e): Amount of CO_2 that would produce the same effect on the radiative balance of Earth's climate system as another greenhouse gas, such as methane (CH_4) or nitrous oxide (N_2O), on a 100-year timescale. For comparison to units of carbon, each kg CO_2e is equivalent to 0.273 kg C (0.273 = 1/3.67). See Box P.2, p. 12, in the Preface for details.

3.4.1 Decline in Energy Use and CO_2e Emissions

North American energy demand has decreased from 2004 to 2013 at about 1% annually. The greatest decreases occurred from 2007 to 2009 (see Figure 3.4, p. 128). In 2004, North American total primary energy demand was about 127 EJ, rising to 128 EJ in 2007. After that, energy consumption decreased to a low of 120 EJ in 2009. Over the past 4 years, average annual consumption has equaled about 124 EJ. The largest decreases in energy were experienced by the United States, which fell from a high of 107 EJ in 2007 to 103 EJ in 2013. However, energy consumption in both Canada and Mexico slightly increased. For example, Canada's primary energy use was 13.6 EJ in 2007 and 14.9 EJ in 2013. Mexico's energy use was 7.1 EJ in 2007 and 7.7 EJ in 2013 (EIA 2016c).

An important indicator of this trend has been reductions in oil consumption, particularly refined

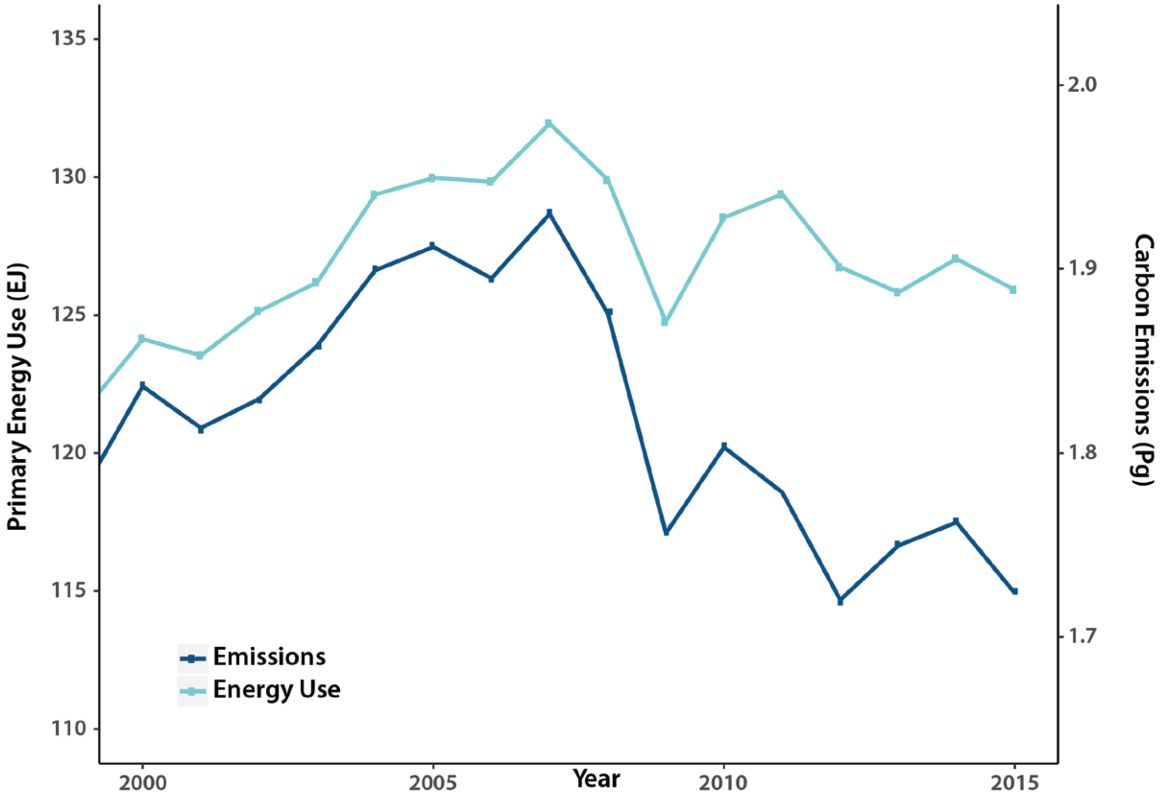


Figure 3.4. North American Primary Energy Consumption and Carbon Emissions, 2000 to 2015. Energy use in exajoules (EJ); carbon emissions in petagrams (Pg). [Data source: EIA 2017i.]

products. North American use of petroleum declined from 51.4 EJ in 2004 to 46.2 EJ in 2013. The trend was not monotonic, however. Between 2004 and 2007 consumption was stable before declining thereafter. The year with lowest consumption (45.6 EJ) was 2012. Similar to the trend in overall energy use among North American countries are decreases in oil consumption, which were experienced largely in the United States, while consumption in Canada increased from 4.6 EJ to 5.0 EJ and remained about the same in Mexico at 4.3 EJ to 4.2 EJ from 2004 to 2013 (EIA 2016c).

Total petroleum consumption per capita in the United States recently shifted as well. From 1990 to 2006, consumption was in the range of 142 GJ per capita. Since that time, petroleum consumption has dropped, reaching a low in 2012 of 116 GJ per capita. In 2013, consumption was 117 GJ per capita (EIA 2016b; Hobbs and Stoops 2002; U.S. Census 2016). Motor gasoline consumption per capita in the United States followed a similar trend. In 2006, gasoline consumption per capita was 63.2 GJ, but it fell thereafter, reaching a low of 56.1 GJ in 2012. Consumption levels were 56.5 GJ per capita in 2013 (EIA 2016b).

Another important indicator is the slow growth in U.S. grid–based electricity demand, which is now growing at its lowest level in decades. Since 2006, increases in electricity generation have slowed or stabilized (EIA 2016c, 2016f). Prior to 2007, electricity demand was on an increasing trend. For example, electricity generation was about 8.2 EJ in 1980; by 2007, it had reached 15 EJ. Electricity generation has since remained below 14.9 EJ and was 14.6 EJ in 2013 (including net imports). The trend has been similar in Canada where total electricity

demand has hovered just below 1.8 EJ for the past 10 years. There are variations across states and provinces within the United States and Canada, but the overall trend in these large markets has resulted in flat or slightly declining demand for electricity. The U.S. and Canadian slowdown in electricity demand is characteristic of a trend observed in other mature, industrial economies where structural change, energy end-use market saturation, and technological efficiency improvements are offsetting upward pressure from growth in population, economic output, and energy service demand. In Mexico, because the factors pushing electricity demand growth have continued to prevail over efficiency gains and other moderating influences, total electricity generation has continued to grow, from 0.79 EJ in 2004 to more than 1.01 EJ in 2013, a 27% increase.

North American total energy-related carbon emissions from 2007 to 2013 have declined at a rate of just under 2% per year, translating into an annual reduction of about 0.11 Pg CO_2e (30.6 Tg C). According to the U.S. Environmental Protection Agency (U.S. EPA; U.S. EPA 2016), U.S. energy-related fossil fuel emissions peaked in 2007 at 5.8 Pg CO_2e (1.58 Pg C) and subsequently dropped to 5.16 Pg CO_2e (1.47 Pg C) in 2013. Total emissions in Canada declined over the past few years. Between 2005 and 2013, its total GHG emissions decreased by 3.1%, falling from about 0.74 to 0.72 Pg CO_2e (201 to 197 Tg C; ECCC 2017b). Mexico, however, experienced an increase in emissions, from 0.4 Pg CO_2e (109 Tg C) in 2007 to 0.45 Pg CO_2e (122.73 Tg C) in 2013 (IEA 2016d). Given the relatively small increases in Mexico compared with the declines in the United States and Canada, overall emissions in North America declined.

3.4.2 North American Natural Gas Energy Transition

A natural gas boom is driving a transition in the North American energy system (EIA 2016d). This boom increased North American dry gas production from 28.5 EJ in 2004 to approximately 33.9 EJ in 2014, a 2% average annual increase over this period. Natural gas production from shale gas now makes up about half the U.S. total dry natural gas production. Canada's dry natural gas production decreased by more than 21% during this period. In Mexico, during the same period, dry gas production increased by 24% to 1.8 EJ (EIA 2016b). For North America, the natural gas share of total primary energy and electricity generation has climbed dramatically since 2005 from 24% and 14%, respectively, to about 30% for each in 2015 (see Figure 3.5, p. 130).

Resources in low-permeability rock formations have supplemented U.S. natural gas reserves. For natural gas, formations include the Barnett, Fayetteville, Haynesville, Woodford, Bakken, Eagle Ford, and Marcellus shales. Recent access through horizontal drilling and hydraulic fracturing (i.e., "fracking") has boosted both natural gas and oil production dramatically. In 2016, hydraulic fracturing accounted for about 48% of current U.S. crude oil production (EIA 2017d, 2017l) and 60% of total natural gas production.

Globally, unconventional gas production has the longest history in the United States. Commercial production of coalbed CH_4 began in the 1980s, expanded in the 1990s, and leveled off in recent years. Shale gas production has occurred for several decades but started to expand rapidly only in the mid-2000s, growing at more than 45% per year from 2005 to 2010. The United States, Canada, China, and Argentina are the only four countries currently producing commercial shale gas, with U.S. and Canadian production accounting for virtually all of the global supply. North American success in shale gas production holds the prospect of a large-scale unconventional gas industry emerging in other parts of the world where sizeable resources are known to exist. Mexico and Algeria expect to develop operations after 2030.

In the United States, natural gas demand for electric power generation has increased dramatically in recent years. In 2002, the electric power industry used 16.8 petajoules (PJ) of natural gas a day, or 6.07 EJ a year, accounting for approximately

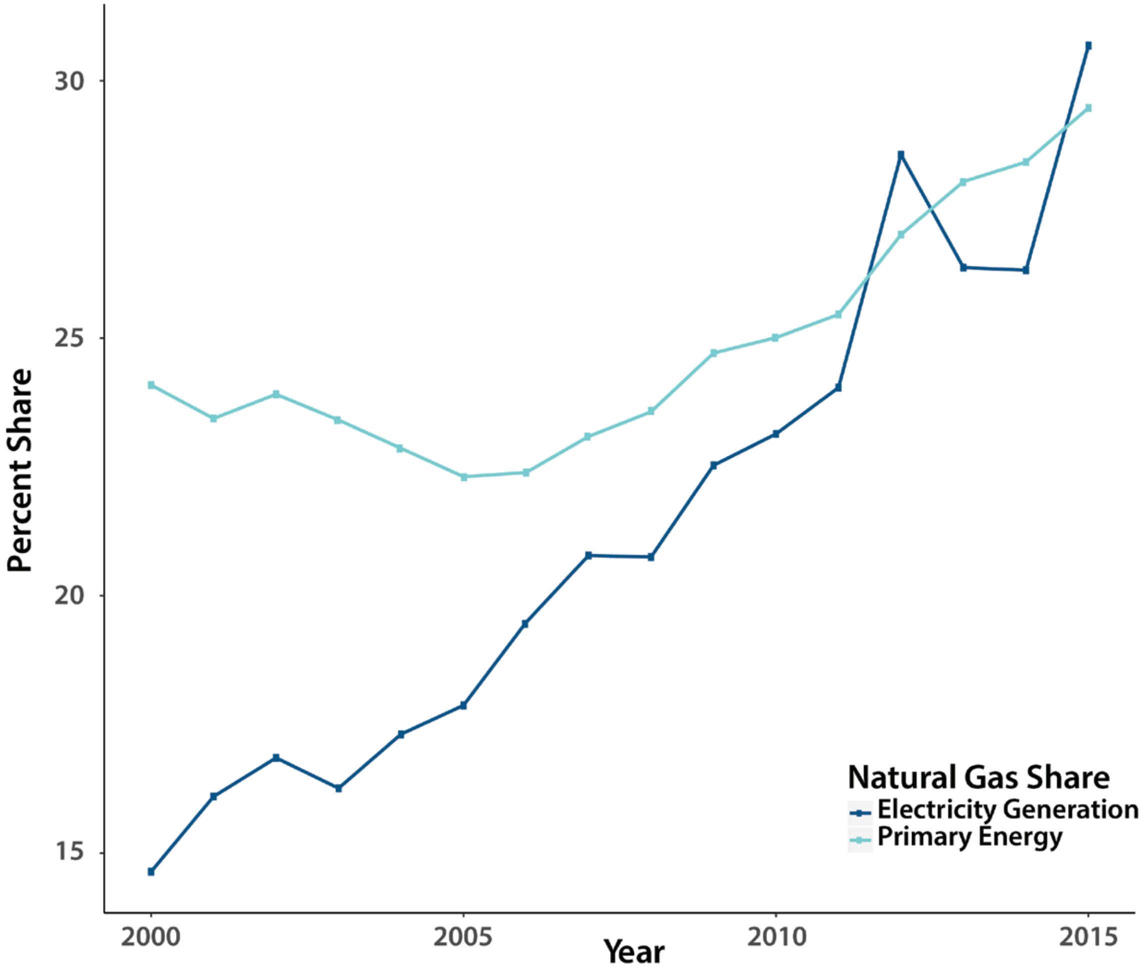


Figure 3.5. North American Natural Gas Share of Primary Energy and Electricity Generation, 2000 to 2015. [Data sources: EIA 2017i and IEA 2017b]

24.6% of all U.S. natural gas usage. Electric power industry demand for natural gas grew to 19.7 PJ a day in 2008 and then rapidly increased thereafter. By 2013, the electric power industry was using more than 24.3 PJ of natural gas a day; by 2015, levels had reached 28.6 PJ a day (EIA 2016e). Prior to 2016, natural gas had long been the second-most-prevalent fuel for electricity generation behind coal. However, in that year, natural gas–fired power plants accounted for about 34% of U.S. electricity generation, followed by coal (30%), nuclear (19%), and renewables (15%) (EIA 2016c). The electric power industry's use of natural gas now exceeds that of the industrial sector (EIA 2012b).

In 2003, Canadian natural gas production made up only 6% of total net electricity generation, using approximately 1.08 PJ of natural gas per day. By 2014, 8.5% of the country's electricity supply was generated from natural gas at a rate of about 1.3 PJ per day (Natural Resources Canada 2016c). Mexico increased natural gas production from 2009 to 2013, and the country has doubled imports from the United States through pipelines. According to Mexico's national energy

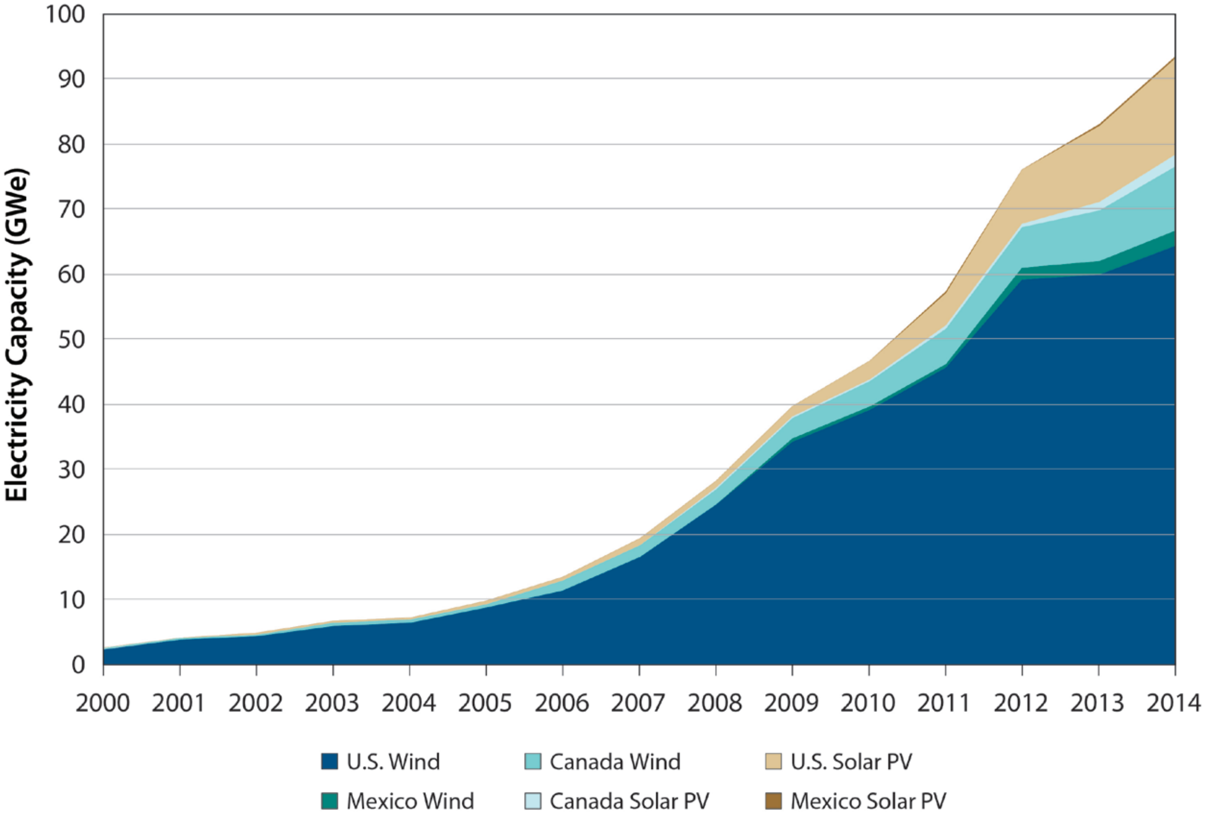


Figure 3.6. North American Wind and Solar Net Capacity, 2000 to 2014. Key: GWe, gigawatt electrical; PV, photovoltaic. [Data source: IEA 2018.]

ministry, SENER, natural gas is Mexico's largest source of electricity generation, accounting for 54% of the country's generation in 2015, up from 34% in 2005 (EIA 2017c). SENER projects that natural gas–fired capacity will account for 24.9 GW of total capacity additions from 2016 to 2029 (SENER 2015). The rest of Mexico's projected capacity additions consist of renewables (20.4 GW) and nuclear (3.9 GW) (EIA 2017c).

3.4.3 Increase in Renewable Energy

Globally, renewable-based power generation capacity increased by an estimated 165 GW in 2016, accounting for more than 66% of the additions to world power generation capacity for the year (IEA 2017d). Of the increased renewable generation capacity, 45% was from PV solar, 32% from wind, and 20% from hydropower. The growth in solar capacity was attributed largely to Chinese increases in solar installations, while the recent fall of wind installation capacity (20% from 2015) was due to cuts in China (IEA 2017d).

North America is increasing its renewable power capacity (see Figure 3.6, this page). For electricity, the contribution of nonhydropower renewables (e.g., wind, solar, and biomass) to total power generation grew from 2.4% in 2004 to 6.1% in 2013, translating into a 10.6% annual average increase, or an additional 220 PJ of renewable energy into the North American electrical system annually. In 2016, about 10% of total U.S. energy use was from renewable sources (EIA 2018a). According to IEA

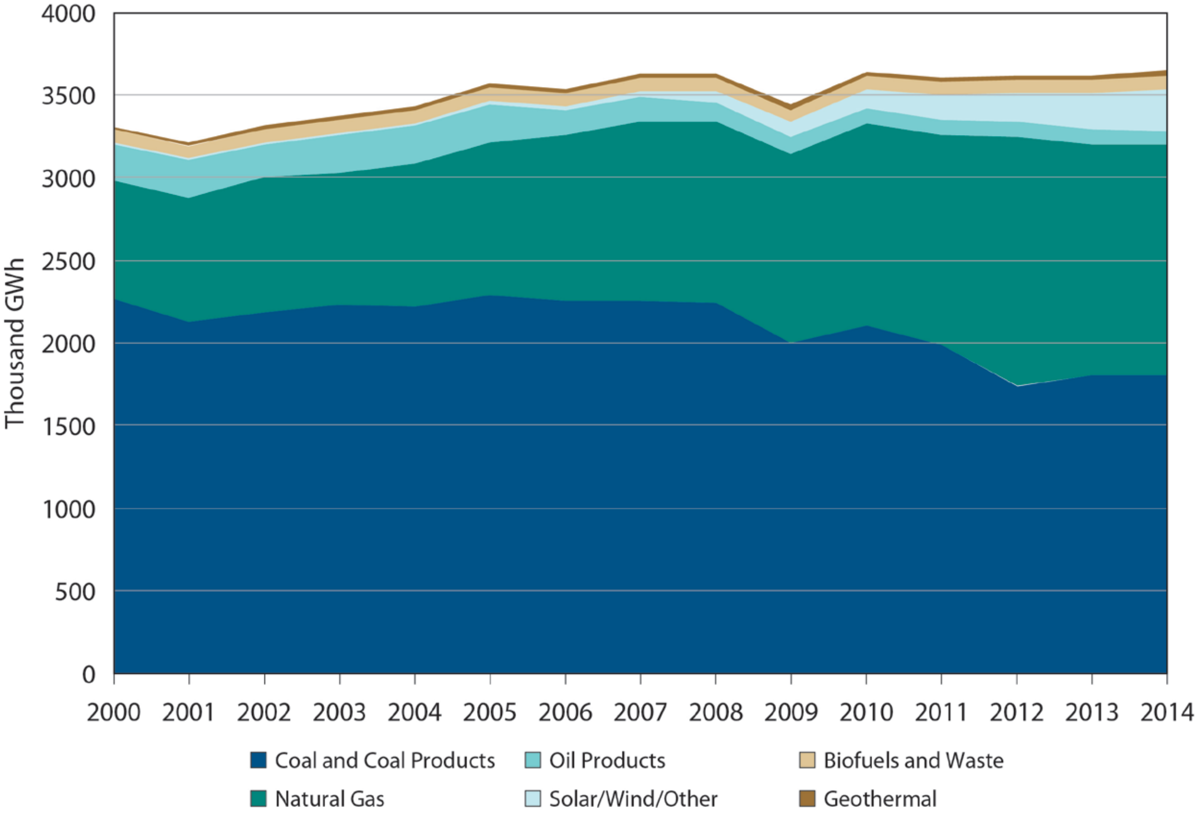


Figure 3.7. Renewable and Fossil Fuel Electricity Production in North America, 2000 to 2014. Key: GWh, gigawatt hours. [Data source: IEA 2017a.]

(2017d), North America is the world's second largest growth market for new renewable capacity, led by the United States.

Although renewables are an increasingly important component of total generation capacity, renewable energy's share of total primary and secondary energy supplies remains low (see Figure 3.7, this page).[10] For example, in 2013 the total supply of nonhydropower renewable energy (e.g., geothermal, wind, solar, tidal, wave, fuel cells, and biomass) for electricity generation in North America was 3.25 EJ. Yet, these sources together accounted for approximately 6.1% of total electricity generation, while hydropower accounted for 13.7%, nuclear 18%, and fossil fuels more than 62% (EIA 2016f, 2016g).

Nevertheless, renewable energy continues to make strides across North America. In the United States, solar electricity generation increased by 31 PJ in 2014—from 32.4 PJ to 63.4 PJ—or a 96% increase from the previous year. U.S. wind generation increased by 8%, from 604.1 PJ to 654.2 PJ (EIA 2016g). In 2015, wind's share of total U.S. electricity generation reached approximately 655 PJ, accounting for 4.7% of net electric power generation

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[10] Only since recently has the U.S. Department of Energy's Energy Information Administration (EIA) officially collected data on small-scale renewables (<1 megawatt [MW] of generation capacity), and only since 2017 have these values been added to the *Short-Term Energy Outlook* reports (EIA 2017a). The amount of small-scale renewable energy, however, is considerable. For example, EIA estimates for 2016 show that about 37% of total annual photovoltaic solar generation is from small-scale generators having a capacity less than 1 MW (EIA 2017m). Hence, the figures presented here may underestimate total renewable energy electricity generation.

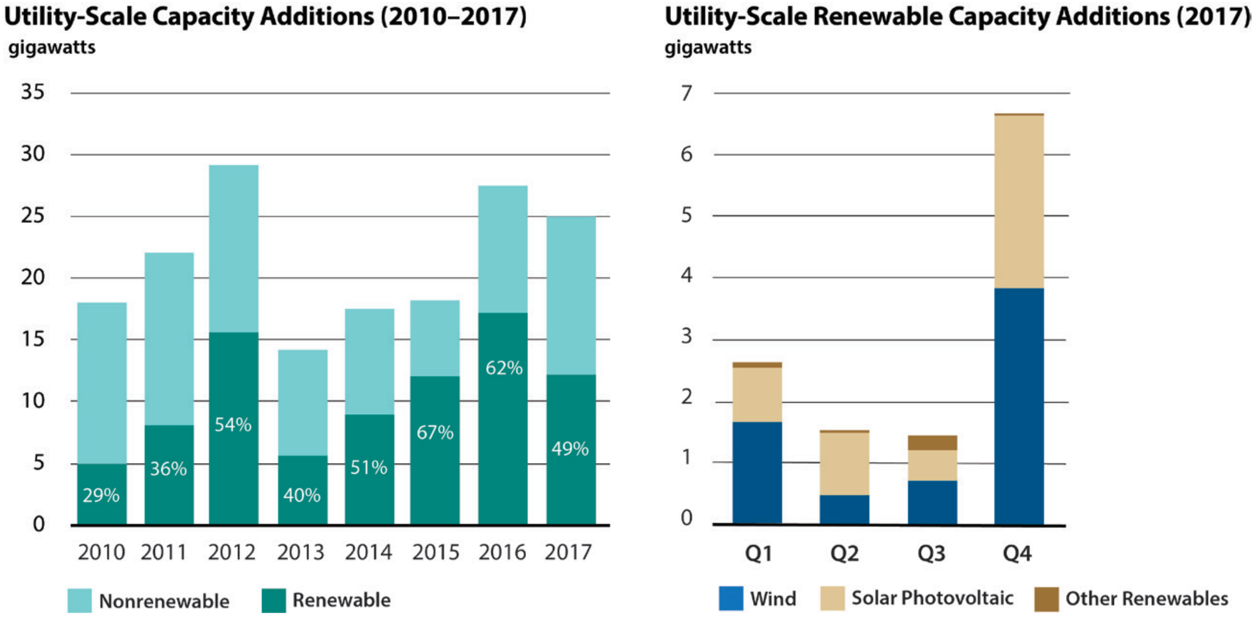

Figure 3.8. Renewable Generation Capacity (2010 to 2017) and Utility-Scale Additions, 2017. [Figure source: Redrawn from EIA 2018b.]

(EIA 2017l). By 2016, about 8.4% of electricity generation was from nonhydropower renewable sources (EIA 2017a). During 2016, renewable generation capacity accounted for most of the electricity capacity additions (EIA 2017a; see Figure 3.8, this page), and nearly half of utility-scale capacity in 2017 (EIA 2018b). By 2017, wind and solar renewable shares reached 10% of electricity generation for the first time (EIA 2017a). From 2008 to 2016, U.S. wind generation increased threefold, and solar generation expanded 40-fold (Houser et al., 2017). California and, most recently, North Carolina have added a significant portion of the increased U.S. solar capacity. Other states using policies to encourage PV installations include Nevada, Texas, Arizona, Georgia, and New Jersey (EIA 2016f, 2016g; World Energy Council 2016a). Wind development has advanced in Iowa, South Dakota, Kansas, Oklahoma, North Dakota, Minnesota, Idaho, Vermont, Colorado, Oregon, and Maine, where it exceeded 10% of total electricity generation in 2015 (EIA 2016h). Other states with significant wind programs include Texas and New Mexico (for a discussion of carbon-related subnational policies, see Section 3.7, p. 149).

Canada also has built new renewable power capacity, most of which comes from hydroelectric sources. In fact, the country is the second largest producer of hydroelectricity in the world, generating more than 1.36 EJ in 2014, or 59% of total national supply. Hydropower remains Canada's main source of electricity supply, but nonhydropower renewable electricity generation grew from 34.2 PJ in 2002 to 90 PJ in 2013, a more than 1.5-fold increase. By 2014, Canada had 9.6 GW of installed wind power capacity (Natural Resources Canada 2016c) and added another 1.55 GW of wind-generating capacity in 2015 alone, which now supplies about 5% of the country's electricity demand (World Energy Council 2016a). Canada also has significant bioenergy electrical capacity, exceeding 2 GW in 2014 (Natural Resources Canada 2016a).

In Mexico, the largest source of renewable power generation is hydropower. Hydroelectricity supplied about 10% of the nation's electricity in 2015 (EIA 2015a). Mexico has also increased its nonhydropower renewable energy but at a slower rate than that of the United States or Canada. In 2002,

the country's nonhydropower renewable energy generation was approximately 28.4 PJ and increased to 39.6 PJ in 2013 (EIA 2016d). Nonhydropower renewables represented 3% of Mexico's electricity generation in 2013. Mexico also has 980 MW of geothermal capacity, making the country fifth in terms of global geothermal capacity. In 2015, 100 MW of geothermal projects are expected to supplement the decreased power generation at the 645-MW Cerro Pietro Geothermal field in Baja California, the key component of Mexican geothermal generation. Solar power has received significant attention in northern Mexico, where the first large-scale solar power project, Aura Solar I, began operations in 2013. This project increases Mexican solar capacity by 30 MW. Several wind projects under development in Baja California and in southern Mexico aim to boost Mexico's wind-generation capacity from 2 to 12 GW by 2020. Mexico is hoping to achieve this goal by encouraging US$14 billion in investment between 2015 and 2018. In 2016, renewable capacity additions reached 0.7 GW, led by onshore wind (0.45 GW) and solar PV (0.2 GW). These additions were mostly from power purchase contracts with the Federal Electricity Commission before implementation of energy reform (IEA 2017d). Much of the current wind-generation capacity is in Oaxaca, where the Isthmus of Tehuantepec has especially favorable wind resources and has been a focus of governmental efforts to increase wind capacity. From 2010 to 2013, the Oaxaca region experienced an increase of nearly 667% in wind-generation capacity with the addition of five major projects (Oaxaca I, II, III, and IV and La Venta III), bringing the region's total wind-generation capacity to 1.75 GW (EIA 2015a). Mexico's first power auction (see Section 3.3.2, p. 118) generated a further 1.7-GW commitment to solar and wind generation, which also may affect the country's future fuel mix.

From 2003 to 2012, North American consumption of biofuels (i.e., liquid fuels such as ethanol and biodiesel derived from renewable plant sources) increased by almost 20% annually, and biofuels now constitute an important component of the continent's fuel mix. In the United States, almost all gasoline contains 10% blended ethanol (E10), the maximum level approved for use in all cars and light trucks, although higher levels could be used with appropriate adjustments. The amount of fuel ethanol added to motor gasoline consumed for transportation in the United States increased from about 1.4 billion gallons in 1995 to about 14.4 billion gallons in 2016. Biodiesel consumption increased from 10 million gallons in 2001 to about 2.1 billion gallons in 2016 (EIA 2017b). Canada's biofuel blend mandate is 5% renewable content (ethanol) in gasoline and 2% in distillate (diesel). Provincial blend mandates, however, reach as high as 8.5% for ethanol in Manitoba. Canada imports close to 20% of its domestic fuel ethanol consumption and nearly all of that from the United States (USDA Foreign Agricultural Service GAIN 2015). In 2016, Mexico released draft standard specifications for biofuels, including a proposed 5.8% ethanol blend nationwide. However, the final regulation was limited to the three largest major metropolitan areas (Mexico City, Guadalajara, and Monterrey), which represent one-third of Mexico's population (U.S. DOC 2016).

3.4.4 Growing Concern over Aging Energy Infrastructure

North America is poised for significant investment to meet the challenges of its aging transportation and energy infrastructures, including energy generation, transmission, distribution, and storage systems. A number of studies have found that energy systems in the United States urgently need upgrading (ASCE 2013; U.S. DOE 2015a). In 2008, the Edison Electric Institute estimated that by 2030 the U.S. electric utility industry would need to invest $1.5 trillion to $2.0 trillion in infrastructure (Edison Electric Institute 2008). Harris Williams & Co. (2014) suggest that an estimated 70% of U.S. transformers are more than 25 years old, 60% of distribution poles are 30 to 50 years old (relative to useful lives of 20 and 50 years, respectively), and 70% of transmission lines are also approaching the end of their useful lives of 25 years or older. In Canada, infrastructure underinvestment since the 1980s has put a strain on existing facilities (Gaudreault and Lemire 2009). The World Economic

Forum's Global Competitiveness Report for 2012 to 2013 noted that energy infrastructure is a main area of needed improvement in Mexico (Goebel and Schwandt 2013; Schwab and Sala-i-Martín 2012).

Infrastructure needs extend to electricity-generation plants. In the United States, nearly 18 GW of generating capacity retired in 2015, 80% of which is coal-fired generation (EIA 2016l, 2018c). Although current nuclear-powered electricity generation in North America is stable, there are significant retirements slated in the midterm future. The United States currently has around 99 nuclear reactors in full operation, five under construction, 25 in the planning and permitting stage, and 32 in permanent shutdown or retirement. However, there are five fewer generators operating now than at the end of 2012, corresponding to a decrease in about 3 GW of nuclear capacity. Generation has remained relatively stable because output of the operating plants has been increasing. In 2014, U.S. nuclear power accounted for 8.76 EJ, approximately 8.5% of national total primary energy. Currently, the United States accounts for more than 30% of the worldwide nuclear generation of electricity (World Energy Council 2016a). For the entire continent, nuclear power generation since 2002 has been largely flat, accounting for about 850 to 900 billion kilowatt hours (kWh; 3.04 to 3.24 EJ; EIA 2016c). Nuclear plants continue to be decommissioned, but their potential replacement by new nuclear technologies, coal- or gas-fired thermoelectric plants, or renewable resources is unclear (see Box 3.2, Potential for Nuclear Power in North America, p. 120).

ICF, on behalf of the Interstate Natural Gas Association of America (INGAA) Foundation, recently published a report estimating that necessary midstream energy infrastructure investments for the United States and Canada would be between $22.5 billion and $30 billion per year, or approximately $546 billion (US$ 2015) over the 20-year period from 2015 to 2035 (INGAA 2016). These investments include mainline pipelines; laterals; processing plants; gathering lines; compression equipment for gas transmission and gathering lines; and storage for natural gas, natural gas liquids, and oil. Nearly 50% of U.S. gas transmission and gathering pipelines were constructed in the 1950s and 1960s when the interstate pipeline network expanded in response to the thriving post–World War II economy. According to U.S. DOE (2015a), upgrading U.S. natural gas pipelines would cost an estimated US$2.6 billion to US$3.5 billion per year from 2015 to 2035, depending on the overall level of natural gas demand. Replacing cast iron and bare steel pipes in gas distribution systems would cost an estimated US$270 billion (U.S. DOE 2015a).

Studies suggest that infrastructure improvements could lower carbon emissions through reducing leaks from water supplies and natural gas transmissions, improved power plant efficiencies, increased connectivity throughout cities, improved transit, and upgraded transmission and distribution infrastructure, including biofuel refineries, liquid fuel pipelines, and vehicles that transport energy directly or indirectly (Barrett et al., 2014; U.S. DOE 2015a; World Resources Institute 2016).

3.4.5 New Understanding of Biofuel and Natural Gas Contributions to Carbon Cycle Dynamics

Biofuel mandates at both the U.S. federal and state levels target transportation fuels (Adler et al., 2012). Quantifying the degree to which the use of this energy source contributes to the global carbon cycle, however, requires a thorough accounting of both the upstream impacts of the various materials and activities required to produce the finished fuel and the emissions at the point of fuel use.

Accounting for the full life cycle of carbon emissions related to energy production and use is particularly challenging. An example is the case of biofuels, where impacts spill over into the agricultural sector via nonpoint source trace gas emissions from—and changes in carbon storage within—the agroecosystems from which feedstock biomass is sourced. Thus, those climate cycle impacts can be examined by supplementing traditional GHG inventories with consequential life cycle assessment studies

that attempt to quantify direct impacts all along the supply chain, as well as indirect effects that could erode the direct GHG mitigation benefits of an agricultural system (Brander et al., 2009; Plevin et al., 2014). Nearly four decades have elapsed since scientists first analyzed fossil energy expenditures associated with corn ethanol production to determine whether it represents a viable strategy to improve domestic energy security (Silva et al., 1978), and such energy use and associated GHG emissions are increasingly quantified with greater certainty (Farrell et al., 2006).

Understanding of other biofuel life cycle GHG emissions impacts has expanded greatly over the last decade. The research community now widely recognizes that feedstock production often results in changes in above- and belowground carbon storage and emissions of nitrous oxide (N_2O) and CH_4 relative to current or alternate land management (Robertson et al., 2011). Such biogenic impacts vary widely depending on the crop cultivated, regional climate, and site-level factors including soil properties and land-use history, and they require spatially explicit models for accurate assessment (Field et al., 2016; Sheehan et al., 2003; Thomas et al., 2013). Researchers also have explored whether conversion of limited arable land to bioenergy crops might increase agricultural commodity prices and elicit land-use changes in other regions, resulting in a leakage effect (Searchinger et al., 2008), though estimates of the magnitude of leakage have been lowered sharply over time (Wang et al., 2011; Zilberman 2017). The leakage effect occurs when GHG emissions increase in one location as a result of decreases in another.[11] Such effects might even run in the opposite direction in some scenarios; studies indicate that increased forest harvesting in response to higher demands for forest biomass is followed by expanding forest area (Galik and Abt 2016; Lubowski et al., 2008). According to U.S. EPA's Science Advisory Board, "Carbon neutrality cannot be assumed for all biomass energy *a priori*. There are circumstances in which biomass is grown, harvested, and combusted in a carbon-neutral fashion, but carbon neutrality is not an appropriate *a priori* assumption; it is a conclusion that should be reached only after considering a particular feedstock's production and consumption cycle. There is considerable heterogeneity in feedstock types, sources, and production methods, and thus net biogenic carbon emissions will vary considerably" (Khanna et al., 2012).

Taken together, these new insights reinforce the importance of accounting for land-use changes in assessing GHG profiles of biomass fuels. Studies have identified a range of sustainable cellulosic feedstock sources that likely could achieve robust GHG benefits via second-generation biofuel production (Tilman et al., 2009) and future "carbon-negative" bioenergy systems, which are predicted to play a significant role in climate stabilization scenarios (Fuss et al., 2014). U.S. EPA's Science Advisory Board emphasizes that significant methodological challenges remain in bioenergy life cycle assessments, particularly with regard to the timing of ecosystem carbon storage changes relative to other life cycle emissions (Khanna et al., 2012).

Life cycle perspectives also have highlighted how "fugitive" CH_4 emissions from natural gas production, transmission, and distribution can erode the GHG savings anticipated from the "natural gas transition" (for a detailed discussion, see Box 3.3, Methane Emissions from Oil and Gas Production, p. 137). A growing body of literature indicates that official CH_4 emissions underestimate true rates in the natural gas supply chain due to leakage (e.g., Brandt et al, 2014; Marchese et al., 2015). Leakage, in this sense, refers to direct emissions loss during production, delivery, and use of natural gas. Leakage

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[11] Leakage effects may occur for a number of reasons including 1) when the emissions policy of a political unit (such as a city, state, or country) raises local costs, subsequently giving a trading advantage to emitters from other political units with a more relaxed policy; 2) when production units in higher emissions cost areas move to locations of cheaper costs; or 3) when environmental policies in one political unit add a premium to certain fuels or commodities, with subsequent fall in demand, that is matched by increases in other political units that do not place a premium on those fuels. GHG leakage is typically defined as an increase in CO_2e emissions outside the political unit taking mitigation actions divided by the reduction in emissions within these political units (Barker et al., 2007).

Box 3.3 Methane Emissions from Oil and Gas Production

New extraction technologies recently have made exploitation of unconventional oil and gas reserves, such as tight oil and shale gas, economically feasible, resulting in a rapid and large increase in U.S. oil and gas production over the past decade. Between January 2005 and January 2016, U.S. natural gas gross withdrawals increased by more 38% (EIA 2017g). Until zero-carbon energy achieves greater market share, natural gas is regarded by some as a potential "bridge" fuel since its carbon dioxide (CO_2) emissions are half those from coal per unit of power generated (Alvarez et al., 2012). The new technologies used to extract unconventional reserves, however, have come with a host of related environmental concerns including 1) emissions of harmful pollutants such as ozone precursors and air toxics like benzene, 2) potential pollution of groundwater, and 3) seismic events related to pumping fluid into the ground. Especially in residential and suburban areas, drilling is being met with legal challenges through which the balance between surface and mineral rights is being tested.

Supply-chain leak rates from unconventional oil and gas production must be small for there to be an immediate climate benefit in switching from coal to natural gas, because the global warming potential (GWP) of methane (CH_4) is much higher than that of CO_2 on shorter timescales. The GWP for CH_4 for the 100-year and 20-year time frames ranges from 28 to 34 and 84 to 86, respectively (see Myhre et al., 2013). This suggests that CH_4 traps heat between 28 and 86 times more effectively than CO_2, depending on the analysis time frame. If CH_4 losses are larger than about 1% to 1.5%, the use of compressed natural gas for heavy-duty vehicles has a climate impact exceeding that of diesel fuel used in those vehicles; if CH_4 losses are larger than about 3%, the use of natural gas for electricity production has a climate impact that exceeds that of coal-power electricity production (Alvarez et al., 2012; Myhre et al., 2013; Camuzeaux et al., 2015). Discussed here is some of the considerable body of work since the *First State of the Carbon Cycle Report* (CCSP 2007) on the climate impact of CH_4 leakage from oil and natural gas production.

Many studies have found that emissions inventories consistently underestimate emissions of CH_4 from oil and natural gas production (e.g., Brandt et al., 2014), while other recent studies have suggested lower emissions than the inventories (e.g., Peischl et al., 2016). In the production segment, certain basins have shown lower emissions than would be expected based on national averages included in GHG inventories. Field studies also have shown that there is considerable variation in the CH_4 loss rate among production regions. Karion et al. (2013) found that emissions from the Uintah basin in Utah were about 9% of production. Peischl et al. (2015) found leak rates well under 3% of production for the Haynesville, Fayetteville, and Marcellus shale gas regions. Pétron et al. (2014) found leak rates of about 4% ± 1.5% of production for the Denver-Julesburg Basin, and Zavala-Araiza et al. (2015) found a leak rate of 1.5% (within a range of 1.2% to 1.9%) for the Barnett shale region. Based on studies at scales ranging from individual equipment to regions, Brandt et al. (2014) concluded that leakage rates are unlikely to be large enough to make the impact of natural gas to the climate as large as that of coal over a period of 100 years.

A fundamental question explored by recent studies is why some studies that use "top-down" methods to quantify basin-wide emissions, such as atmospheric observations made using light aircraft, suggest higher emissions than those estimated by official inventories, such as the U.S. Environmental Protection Agency's (U.S. EPA) Greenhouse Gas (GHG) Inventory (U.S. EPA

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2017a). Official inventories sometimes have been found to omit sources. For example, Marchese et al. (2015) found large emissions from sources in the gathering sector, which previously were not included in the U.S. GHG Inventory but have since been incorporated. However, the main source of the discrepancy may be the existence of a small number of "superemitters" (Brandt et al., 2014). For example, Zavala-Araiza et al. (2015) estimated that half of CH_4 emissions from the Barnett region were due to 2% of oil and gas facilities. They estimate that 30% of production sites emitted more than 1% of natural gas produced and that these sites accounted for 70% of emissions from production sites. The existence of superemitters raises the possibility that CH_4 emissions can be reduced with fewer, targeted actions, with adequate monitoring and maintenance of equipment.

Some studies focused on specific processes also have found lower emissions than inventories. Lamb et al. (2015) found that emissions from natural gas distribution were 36% to 70% lower than emissions from the 2011 U.S. EPA inventory that was based primarily on data from the 1990s. Marchese et al. (2015) found that emissions from processing plants were a factor of 1.7 lower than the U.S. EPA 2012 inventory and three times higher than U.S. EPA's GHG Reporting Program (U.S. EPA 2017a). On the other hand, the researchers found evidence that emissions from gathering facilities could be significantly higher than U.S. EPA estimates. Zimmerle et al. (2015) found that emissions related to transmission and storage could be lower than inventory estimates. U.S. EPA's GHG Inventory has since been updated to include data from these studies. Finally, as suggested by Schwietzke et al. (2017), top-down estimates also are subject to biases, such as sampling midday when episodic emissions from manual liquid unloadings are more likely. This study highlights the difficulty in extrapolating information that is limited in space and time, such as aircraft campaigns, to annual timescales as needed for comparison to inventories.

Based on measurements of ethane (C_2H_6) and CH_4 in the global atmosphere and firn air, Simpson et al. (2012) and Aydin et al. (2011) found that CH_4 emissions from global oil and natural gas production likely increased until the 1980s and since then have leveled off or decreased. Ethane is co-emitted by oil and natural gas production from thermogenic origin; however, it does not have microbial sources, making it a potentially useful indicator of some CH_4 oil and natural gas emissions. Schwietzke et al. (2016) used global observations of the methane isotopologue $^{13}CH_4$, which can be used to distinguish microbial and thermogenic emissions, to show that oil and natural gas CH_4 emissions have been stable over the past several decades, even as production has significantly increased, implying that fossil fuel production has become more efficient. They also found that global emissions of fossil fuel CH_4 are likely 50% to 100% higher than previous estimates, although their higher estimates include emissions from geological seeps, a source that has not been widely considered in the global CH_4 budget. Schwietzke et al. (2016) estimate that global emissions are likely to be in the range of 150 to 200 teragrams (Tg) CH_4 per year. Only a small fraction of global emissions from oil and gas production (less than 10 Tg CH_4 per year) are thought to be from the United States (U.S. EPA 2017a).

The implications of not accurately measuring and, if large, mitigating these emissions are very significant. As noted above, leakage rates of roughly 3% per year can "flip" CH_4 from a fuel cleaner than coal in immediate global warming impact to emissions larger than a conventional coal-fired power plant (see also Allen et al., 2013; Brandt et al., 2014; Howarth et al., 2011; Karion et al., 2013; Kort et al., 2008; Miller et al., 2013; Pétron et al., 2014; Schneising et al., 2014; and U.S. EPA 2013, 2014, 2015b).

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To assess the impacts of leakage on the roles of natural gas in an integrated portfolio that includes large amounts of renewable power, a series of scenarios was run within the SWITCH-WECC model to identify least-cost electric power grids capable of meeting emissions goals (Fripp 2012; Mileva et al., 2013; Nelson et al., 2012). SWITCH-WECC includes a detailed representation of existing generators, storage facilities, and transmission lines in the Western Electricity Coordinating Council (WECC), which roughly spans the western portion of North America but does not explicitly model natural gas wells, pipelines, or related infrastructure. SWITCH makes construction and dispatch decisions for renewable and traditional generators, along with transmission and storage to minimize the levelized cost of delivering electricity over its planning horizon. The WECC area provides a useful lens because the United States is the largest global consumer of natural gas and has recently set policy goals to reduce leakage as well as overall GHG emissions.

is extremely diverse in its sources and magnitudes; less than 1% of equipment can be responsible for most facility and pipeline leaks (Frankenberg et al., 2016; U.S. EPA 2006b; Zavala-Araiza et al., 2015). The overall GHG intensity of natural gas electricity is highly dependent on fugitive CH_4 emissions from leakage in the fuel supply chain. Methane, the principal component of natural gas, is a GHG that is between 28 and 86 times[12] more potent than CO_2 in 20- and 100-year time frames, respectively (Myhre et al., 2013; Stocker et al., 2013), leading to temporal accounting issues similar to those for bioenergy systems (Ocko et al., 2017).

3.4.6 Feedbacks

There are many different plausible feedback mechanisms (both positive and negative) that could affect the North American energy system's ability to continually provide sufficient, reliable, and affordable energy. Three types of energy system–related feedbacks include those associated with changes in climate, other exogenous forces, and internal dynamics. This section provides illustrative examples of each.

A changing climate is likely to affect energy demand and production, although the scale and direction of this effect are debated (Wilbanks et al., 2007). For example, increasing temperatures may reduce heating demand in high latitudes while increasing cooling demands in areas with warmer climates (Hadley et al., 2006; Zhou et al., 2013, 2014). Research in the last decade has analyzed this relationship at fine spatial and temporal scales, highlighting differences with larger-scale assessments. For example, the difference between today's annual total U.S. energy consumption and projected consumption from 2080 to 2099 is less than 2% under a changing climate, but changes per month at the scale of individual states are larger, with summer electricity demand increasing by more than 50% and nonelectric energy needs in springtime declining by 48% (Huang and Gurney 2016).

There also may be linkages between increased temperatures and thermoelectric capacity, as anticipated changes in the hydrological cycle likely will exert constraints on electricity generation. Warming is expected to lead to decreasing river discharge in some areas and increasing river temperatures (Huntington 2006; van Vliet et al., 2016). Elevated water temperatures, along with changes in urban water availability due to climate change and competing pressures on upstream water sources, are likely to make water cooling of thermoelectric power plants (both fossil and nuclear) less efficient. Furthermore, water shortages for urban residents (McDonald et al., 2011) may

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[12] The global warming potential (GWP) of methane (CH_4) varies across time because of its relatively short half-life in the atmosphere. Because this half-life changes somewhat according to carbon-climate feedbacks, CH_4 GWP for the 100-year and 20-year time frames ranges from 28 to 34 and 84 to 86, respectively (see Myhre et al., 2013).

limit their ability to allocate water resources for other uses, including electricity generation.

An example of another potential exogenous feedback mechanism in the energy system is increased disease pressure on forests and increased forest vulnerability to fire, which could reduce wood availability for those depending on bioenergy (see Ch. 9: Forests, p. 365). While these pressures may contribute to long-term bioenergy loss, they could contribute to increases in bioenergy feedstocks in the short term. However, relatively little is known, for example, about how mortality due to pine bark beetles affect important aspects of forest regeneration and hence future bioenergy resources (BANR 2017).

Finally, feedbacks created by changes in the energy system itself may become important. For example, growing fleets of plug-in electric vehicles could increase electricity demand in the transportation sector, which today is fueled mostly with petroleum. U.S. DOE (EIA 2018f) projects that combined sales of new electric, plug-in hybrid electric, and hybrid vehicles will grow in market share from 4% in 2017 to 19% in 2050, translating into a vehicle fleet of over 2 million. This increase in electric vehicle charging will be a significant new source of electricity demand and will change the dynamics and extent of peak demand. These shifts can be met with smart meters, time-based rates, and electric grid management techniques, or through costly additions to power capacity (U.S. DOE 2015b). Alternatively, if the trend toward microgrids and distributed energy increases, there could be lower levels of electricity carried throughout the national grid, leaving room for other uses. Both the forward trends and the implications of these feedback mechanisms are uncertain, and the subsequent impacts on the carbon cycle contributions from the North American energy system remain unknown. An incomplete understanding of the feedback mechanisms, therefore, poses concern for future energy planning. Follow-up studies (*sensu* Wilbanks et al., 2007), which report on the effects of climate change on energy production and use, could focus on the variety of potential feedbacks, the costs of their impact on energy systems, and subsequent potential trends in carbon contributions to the atmosphere. Furthermore, studies could explore how the outcomes of these feedbacks might affect the vulnerability of the energy system.

3.5 Global, North American, and Regional Context

North America's annual share of global CO_2e emissions reached its first peak during the 1920s, when the share ranged from 50% to 58% of total emissions, which at that time were 490 to 550 Tg C (1.8 to 2.0 Pg CO_2e). By 1945, global emissions levels reached 672 Tg C (2.5 Pg CO_2e) per year, at which point North America accounted for about 59% of total annual emissions.[13]

Thereafter, North America's annual share started a monotonic decline that, by 2008 despite reaching an absolute regional high of 1,830 Tg C (6.6 Pg CO_2e), was less than 21% of the total annual global emissions. By 2013, the North American annual share of total global emissions was down to 17%. The cumulative share from North America has been steadily falling since the late 1950s, when it was about 43%, to 2013 when it stood at around 29% (see Figure 3.9, p. 141). The declining annual and cumulative shares of North American energy-related CO_2e emissions demonstrate the growing influence of fossil fuel combustion in emerging economies.

3.6 Societal Drivers and Impacts

This section focuses on the drivers of changes in the North American energy system and how these drivers have influenced changes in carbon cycle dynamics. A driver is any natural or human-induced factor that directly or indirectly causes a change in the system (see, for example, Nelson 2005). Drivers often are divided into categories, such as direct versus indirect, proximate versus primary, and immediate versus underlying. These distinctions attempt to identify the speed and scale at which the driver operates and the driver's linkage to the environmental state.

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[13] For a discussion of how long these emissions might stay in the atmosphere, see Ch. 8: Observations of Atmospheric Carbon Dioxide and Methane, p. 337.

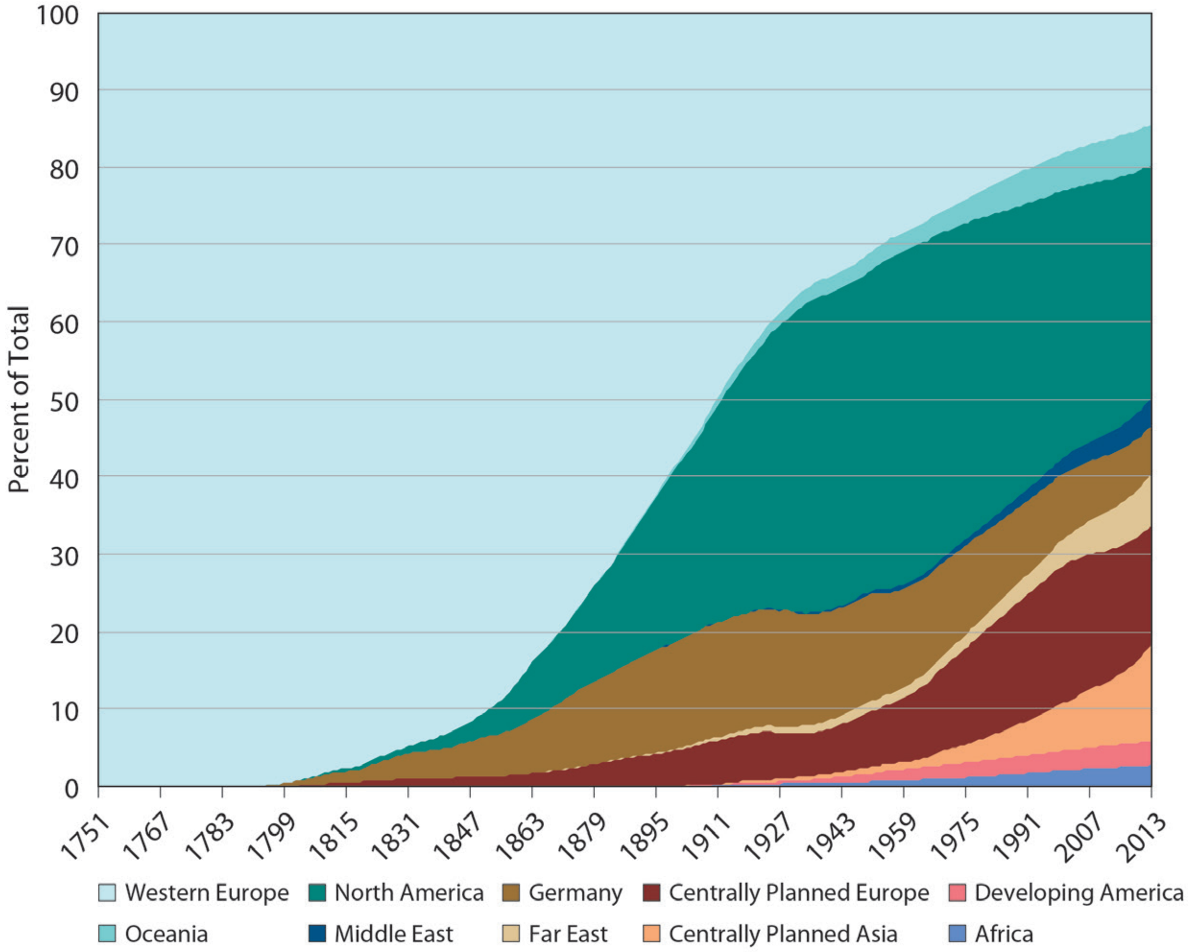

Figure 3.9. Change in Cumulative Share of Carbon Dioxide Emissions from Fossil Fuel Burning, Cement Manufacture, and Gas Flaring. Percentages are by region, from 1751 to 2013. [Data source: Boden et al., 2016.]

The first systematic discussion of drivers of environmental change emerged as the IPAT identity, where environmental impact (I) was estimated by multiplying the population (P) by affluence (A) and by technology (T; for a review, see Rosa and Dietz 2012). Subsequently, the drivers (PAT) were identified as primary or indirect, given that they work largely through other drivers. For example, with increasing affluence, households have more expendable income to consume energy (via air conditioning, for example) and subsequently increase their energy use (Sivak 2013; Davis and Gertler 2015). The point is that increasing affluence operates through both population units (households) and increases in energy consumption via more expendable income. The IPAT equation has expanded into a much more complex set of influences that help to explain environmental change (see, for example, Reid et al., 2005; Marcotullio et al., 2014).

The IPAT equation was the model for the Kaya Identity, named after Yoichi Kaya, which provides similar multiplicative elements to help explain the change in CO_2 emissions (Rosa and Dietz 2012; EIA 2011b).

$$F = P \times G/P \times E/G \times F/E$$

The formula for primary drivers of carbon emissions (F) includes population (P), GDP per capita

(G/P), energy per GDP output (energy intensity, E/G), and carbon emissions per energy input (carbon intensity, F/E). Often the formula also includes sectoral structural changes. The variables in the equation are factors that include a much larger number of proximate or direct influences such as fuel price, resource availability, infrastructure, behavior, policies and other processes, mechanisms, and characteristics that influence emissions (see, for example, Blanco et al., 2014; Table 3.3, p. 127). The Kaya Identity accounting categories often are used in the decomposition of emissions and provide an overarching framework for examining societal influences as well as a template for scenario development (Nakicenovic 2004). This section addresses the main factors identified in the Kaya equation. For a discussion of local influences on the carbon cycle, see Ch. 4: Understanding Urban Carbon Fluxes, p. 189; for social and behavioral influences on the carbon cycle, see Ch. 6: Social Science Perspectives on Carbon, p. 264; for policy influences from respective governmental policies at the international, national, and state or provincial levels, see Section 3.7, p. 149.

Figure 3.10, p. 143, presents the factors of the Kaya Identity, along with total energy use, in a simple decomposition analysis for the North American region. Several points become evident in this graph, including those between 2007 and 2015: 1) population and GDP per capita increased by approximately 8% and 18%, respectively; 2) energy intensity and carbon intensity decreased by about 25% and 6.4%, respectively; and 3) emissions and energy use decreased by around 11% and 4.5%, respectively. That is, since 2007, while regional population and GDP per capita increased, energy use and energy-related CO_2e emissions decreased. The following subsections examine the factors in more detail to explain what happened. Each subsection includes a description of the factor and how it theoretically affects energy and emissions levels, along with a review of what actually happened, at the regional scale and for each economy.

3.6.1 Population Growth

The current population of North America is almost half a billion people and growing. The most populous nation in the region, the United States, continues to grow and is projected to do so at an annual rate of 0.34% through the end of this century, when population is estimated to reach approximately 648 million (UN 2015). Although growing populations can increase energy use and subsequent carbon emissions, this is not universally true. Increases in population do not necessarily produce proportional changes in environmental stress. Thus, population may have an elastic (greater than 1) or inelastic (less than 1) effect on emissions. If the impact is elastic, greater population will produce more problems such as traffic congestion, resulting in greater emissions than expected based merely on the proportion of increased population. The larger the city, the greater the congestion, and therefore the impact may be disproportionate compared to the growth of the population. Alternatively, larger populations may induce economies of scale and enable more efficient use of resources, thereby lowering the impact on emissions levels. In this case, the impact of population growth would be inelastic.

Between 2005 and 2015, North America grew by an estimated 45 million people (approximately 1.0% annually), and yet energy use and CO_2e emissions have declined. Alternatively, Mexico's population has increased commensurately with national energy use and carbon emissions. During this period in Mexico, however, emissions first increased with population and then decreased even as population continued to increase.

3.6.2 Financial Crisis and Declines in GDP Growth

Increasing affluence can either increase emissions levels through increased consumption per capita or mediate emissions through shifts in the scale or composition of consumption. In 2008, the world experienced the global financial crisis, which hit particularly hard in North America. Feng et al. (2015, 2016) argue that the economic crisis, through

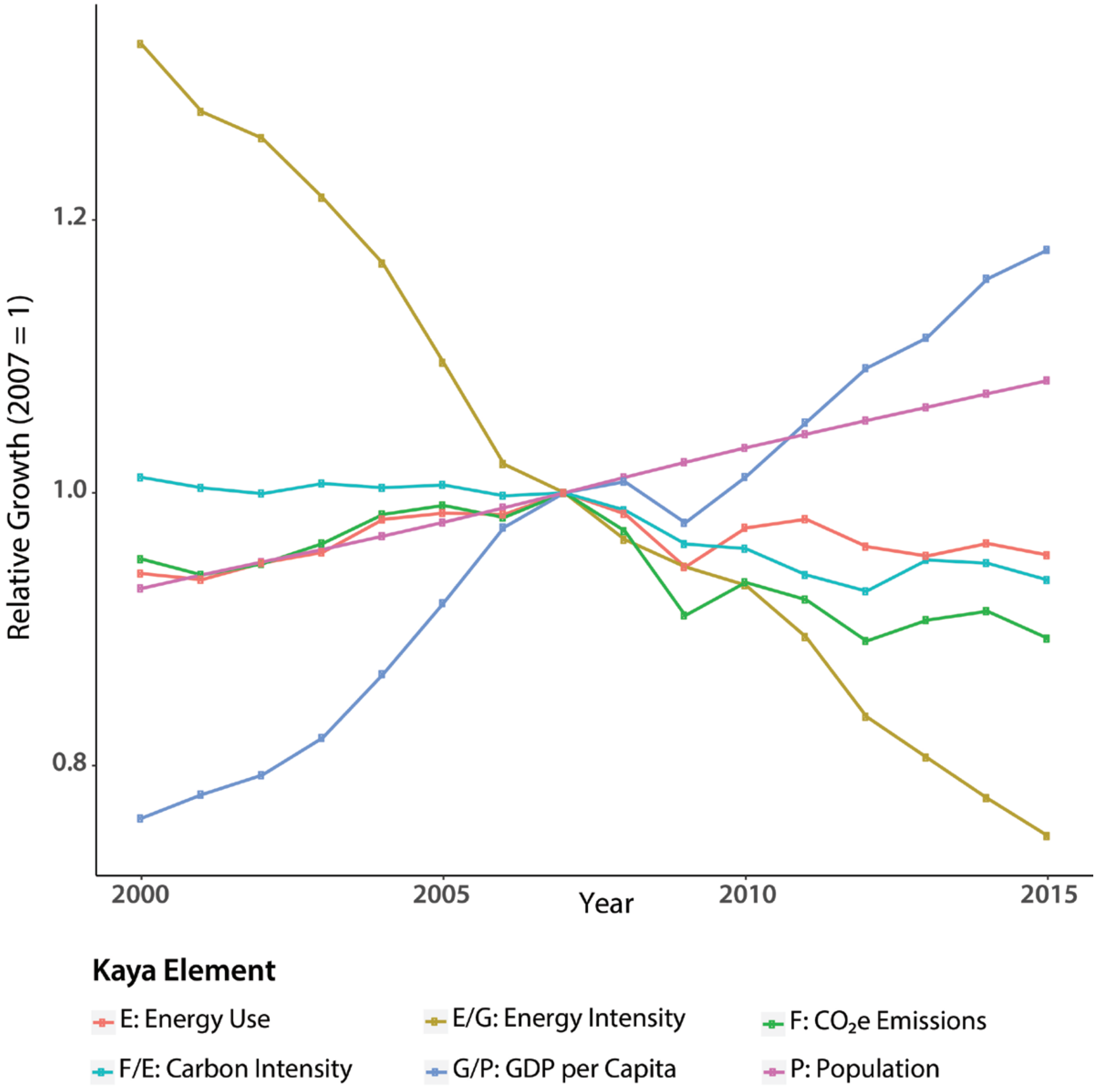

Figure 3.10. Kaya Identity Decomposition, 2000 to 2015. Key: CO_2e, carbon dioxide equivalent; GDP, gross domestic product. [Data sources: EIA 2017i and World Bank 2017.]

lowering GDP per capita, also decreased the volume of consumed goods and services and was responsible for 83% of the decrease in U.S. emissions from 2007 to 2009, which totaled around 0.6 Pg CO_2e (164 Tg C), or 9.9% of the nation's total. This decrease makes up the bulk of the regional change during that period.

However, according to the World Bank (2016c), the GDP for North America in 2007 was $17.7 trillion; after declining for several years, it rebounded by 2013 to reach $18.7 trillion (all values in this paragraph are in US$ 2010). By 2016, the region's GDP was $19.9 trillion, or over 20% higher than in 2007. The per capita GDP by country also followed the

same trajectory. In 2007, the approximate GDPs per capita were $48,600 for Canada, $9,300 for Mexico, and $50,000 for the United States. After falling to lows of $46,500, $8,700, and $47,600 respectively, in 2009, each country's GDP per capita figures had equaled or exceeded 2007 levels by 2012. By 2015, Canada's GDP per capita was $50,300, Mexico's was $9,600, and the United States' was $52,000 (World Bank 2018). Despite increases in GDP combined with population growth, energy use and CO_2e emissions have remained below 2007 levels. According to Shahiduzzaman and Layton (2017), from 2010 to 2014 real GDP per capita growth and population factors (without any mitigating effects) would have resulted in yearly CO_2 emissions increases of 25.5 Tg C annually (14.8 Tg C due to increases in GDP per capita and 10.8 Tg C due to population increases). Over the 5-year period from 2010 to 2014, therefore, an increase of approximately 127 Tg C was offset by other factors. Clearly, while the economic downturn was significant for the initial change in emissions trend, it does not account for the continued reduced energy use and GHG emissions from North America's energy systems.

3.6.3 Reduced Energy Intensity

Energy intensity is the amount of energy per GDP output (E/G). When economic growth outpaces the increase in primary energy supply, energy intensities decrease. Therefore, lowering energy intensities can represent mitigation gains, if benefits of efficiencies are not offset by greater use. Over the long term, energy intensities in Canada and the United States have been declining, due partly to increases in the efficiency of fuel and electricity use, including a shift from large synchronous generators to lighter-weight gas-fired turbines and new fuel sources (e.g., renewables; U.S. DOE 2015b; see Section 3.4.3, p. 131), and partly to changes in economic structure and saturation of some key energy end uses.

In the United States, from 1950 to 2011, energy intensity decreased by 58% per real dollar of GDP and is projected to drop 2% annually to 2040 (EIA 2015c). U.S. energy intensity in 2011 was approximately 7.73 megajoules (MJ) per US$1 purchasing power parity (PPP). Since 2004, the United States experienced a 1.6% drop annually in its energy intensity. Canada has some of the highest energy intensities of the IEA countries (IEA 2010). Canada's energy intensity remains the highest among the regional economies and in 2011 was approximately 11.2 MJ per US$1 PPP. Canada's geography, climate, and industrial structure, including its export-oriented fossil fuel industry, make it a highly energy-intensive country. Like the United States, however, its energy intensities also experienced significant decreases over the last half of the past century (EIA 2016c). Over the past decade, Canadian energy intensity dropped 1.5% annually, and since 1971 it has dropped by 39%. Decreases have been attributed largely to increased contributions of low energy–using commercial activities relative to high energy–using manufacturing, as well as the rapid growth of the Canadian economy compared to population growth (Torrie et al., 2016). These economic structural changes are more important to the nation's falling energy intensity than increasing energy efficiencies. Recently, Mexican energy intensity also has been falling, but only slightly. Mexico, an emerging economy, had been increasing its energy intensity, but over the past decade it fell by 0.04% annually. Mexico's energy intensity is now about 5.5 MJ per US$1 PPP.

An examination of the efficiency gains across sectors of the North American energy system demonstrates structural changes in end-use energy sector components. For example, reduced energy intensity in the electricity-generation sector can be tracked by heat rates. Average operating heat rates for coal and oil power plants for 2015 in the United States are 32.5% and 31.9% efficient, respectively, for power plant type. Average U.S. operating heat rates for gas-fired plants are around 43% efficient (EIA 2016a). However, gas turbine and steam generators typically have the lowest efficiencies, while combined-cycle plants have the highest. For example, in 2016, gas turbines were 25.2% and 30.4% efficient for oil and gas energy sources, respectively, while combined-cycle plants reached efficiencies of 34.6% and 44.6% for oil and gas, respectively (EIA 2018d). The

Table 3.4. LEED-Certified Buildings and Gross m^2 Coverage in North America (2016)[a,b]

Area	Certified		Registered		Grand Total	
	Number	m^2 (millions)	Number	m^2 (millions)	Number	m^2 (millions)
Canada	399	3.97	218	5.01	617	8.98
Mexico	172	2.46	496	11.83	668	14.29
United States	24,777	299.28	31,212	447.26	55,989	746.54
North America	25,348	305.71	31,926	464.10	57,274	769.81

Notes

a) Source: United States Green Building Council 2016, www.usgbc.org/advocacy/country-market-brief.

b) LEED, Leadership in Energy and Environmental Design.

increased share of natural gas–fired plants and the greater use of high-efficiency combined-cycle plants have helped to reduce the overall energy intensity of the U.S. electricity-generation system (Nadel et al., 2015). Notwithstanding the importance of economic structural changes in Canada's decline in energy intensity, business energy intensity experienced a decline from 1995 to 2010 (22% of total decline), and increases in efficiencies in power generation contributed to this decline but only slightly (5% of total decline; Torrie et al., 2016). Mexico is undergoing a major set of policy reforms to open up its power sector, including the electricity system. Actions focused on reducing generation costs include reducing heat rates and losses from transmission and distribution, all of which will improve the electricity system's energy efficiency (CEE and ITAM 2013; Robles 2016).

Energy-efficiency improvements in appliances and utilities, residential and commercial buildings, industrial, and transportation sectors also have slowed growth in North American energy demand and helped to decouple energy demand growth from GDP. The U.S. national efficiency standards implemented since 1987 have saved consumers 9.22 GJ or 21% of household electricity usage in 2015 (deLaski and Mauer 2017). Further, these efficiencies are expected to save 74.9 EJ of energy (cumulative from 2015) by 2020 and nearly 149.8 EJ through 2030 (U.S. DOE 2017b). The cumulative utility bill savings to consumers are estimated to be more than $1 trillion by 2020 and more than $2 trillion by 2030 (U.S. DOE 2017b). Utility energy-efficiency programs for the residential sector are achieving incremental savings of about 30.6 PJ annually, equivalent to 0.7% of all electricity sales with a cumulative impact many times this value, most at a cost of US$0.030 per kWh (Hoffman et al., 2017). While these savings are impressive, energy consumption for appliances and electronics continues to rise and the increasing number of devices has offset gains in appliance efficiency (EIA 2013a).

Independently, building codes reduced residential electricity consumption in the United States by 2% to 5% in 2006 (CEC 2014). Energy savings through building codes have been supplemented by the increase in green buildings. For example, from 2003 to 2016 the number of Leadership in Energy and Environmental Design (LEED)–certified buildings in the United States increased from 116 to over 24,700, those in Canada increased from 3 to 399, and the number in Mexico increased from 0 to 172 (see Table 3.4, this page). The United States Green Building Council estimates that green building, on average, currently reduces energy use by 30%, carbon emissions by 35%, and water use by 30% to 50%, also generating waste cost savings of 50% to 90%. A rapidly increasing market uptake of currently available and emerging advanced energy-saving technologies

could result in annual reductions of 1.7 Pg CO_2e (464 Tg C) emitted to the atmosphere by 2030 in North America, compared to emissions under a "business-as-usual" approach (Commission for Environmental Cooperation 2008). In Canada from 1990 to 2013, residential- and commercial-sector energy efficiencies improved by 45% and 33%, respectively. Canadian space heating energy intensity alone was reduced by over 38% as households and commercial and institutional offices shifted from medium- to high-efficiency furnaces, improved thermal envelopes for buildings (e.g., insulation and windows), and increased efficiencies of various energy-consuming items such as auxiliary equipment and lighting (Natural Resources Canada 2016b). In Mexico, energy efficiency in the residential and commercial sector has focused on lighting, appliance, and equipment replacement (IEA 2015b). In the United States, the share of space heating and cooling for residential energy consumption has been falling due in part to the adoption of more efficient equipment and better insulated windows. An increasing number of residential homes are built to ENERGY STAR® specifications (U.S. EPA 2015c), lowering their energy consumption to 15% less than that for other homes. U.S. households are increasingly incorporating energy-efficient features; in 2011, ENERGY STAR® homes made up 26% of all new homes constructed (EIA 2011c, 2012a).

Industries also have experienced lower energy intensities through shifts in technologies and greater efficiencies. For example, energy use in U.S. steel production has been declining. From 1991 to 2008, there has been a 38% decline in the total energy consumption used in the industry. The largest portion, 34% of the decline in the total energy consumption, occurred between 1998 and 2006 (EIA 2017f). In Mexico, the efficiencies of thermal power generation and of the power sector as a whole have been increasing rapidly since 2002 (from 38% to 45% in 2010 in the case of thermal power generation). This recent improvement is due to a switch in the power-generation mix to natural gas and to the spread of gas combined-cycle plants. In 2010, the gas combined-cycle power capacity accounted for 43% of the total thermal capacity. The country's chemical industry also has experienced drops in energy intensity, falling by nearly 7% per year between 1994 and 2009 (ABB 2012). In Canada, industrial oil production has been driven primarily by a rapid rise in the extraction of bitumen and synthetic crude oil from the nation's oil sands operations, where total output has increased by 140% since 2005. This has contributed to the 37-Tg increase in CO_2e (10.1 Tg C) emissions from mining and upstream oil and gas production from 2005 to 2015. However, from 2010 to 2015 the emissions intensity of oil sands operations themselves have dropped by approximately 16% as a result of technological and efficiency improvements, less venting emissions, and reductions in the percentage of crude bitumen being upgraded to synthetic crude oil (ECCC 2017b).

In the North American transportation sector, there have been considerable improvements in efficiency over the past decade as well as reductions in fuel use in vehicle miles traveled. The on-road transportation sector, in particular, has seen reductions in fuel use for both total and per capita vehicle kilometers traveled, as well as reductions in emissions of CO_2e. According to the U.S. Department of Transportation (U.S. DOT; U.S. DOT 2016), from 2005 to 2015 total average kilometers traveled per passenger vehicle dropped from approximately 20,100 to 18,200 and total average fuel use per passenger vehicle dropped from around 2,100 liters (L) to 1,800 L. As a result, total average kilometers per liter (km/L) of fuel consumed increased from 9.4 to 10.1. These efficiencies have been driven by changes in vehicle weight and power and by corporate average fuel economy (CAFE) standards. For example, according to U.S. DOT (2014), CAFE fuel standards have increased from 11.7 km/L in 2010 to 14.5 km/L in 2014 (based on projected required average fuel economy standard values and model year [MY] reports). In 2015, while total U.S. vehicle travel distance was 4% higher than that in 2007, CO_2e emissions for transportation were 1.73 Pg CO_2e (472 Tg C), or about 8% lower compared with 1.89 Pg CO_2e (515 Tg C) in 2007 (U.S. EPA 2016).

Motor gasoline consumption has not exceeded the previous 2007 peak (EIA 2016i). From 1990 to 2013, Canada also experienced energy-efficiency improvements in the transportation sector by 27%, while energy use in the sector increased during this period by 20% (Natural Resources Canada 2016b). From 2004 to 2013, Canadian transportation energy use and emissions stayed fairly level at approximately 0.17 Pg CO_2e (46.4 Tg C; ECCC 2016b). Similar to the United States, the majority of transportation emissions in Canada are related to road transportation. The growth in road transportation emissions for the country is due largely to more driving. Despite a reduction in kilometers driven per vehicle, the total vehicle fleet has increased by 19% since 2005, most notably for both light- and heavy-duty trucks, leading to more kilometers driven overall (ECCC 2017b). According to IEA (2017a), from 2007 to 2013, Mexico's transportation CO_2e emissions increased by 2.2% annually, amounting to 10% of the total increases during this period. Emissions for this sector are expected to increase further to 2040 as demand for personal vehicles increases in Mexico (SEMARNAT-INECC 2016).

Similar trends in the United States and Canada can be seen in freight rail transport, with decreases in U.S. freight rail fuel consumption and small increases in Canada (Statistics Canada 2016; U.S. DOE 2014a). Substantial increases in fuel consumption in the international aviation sector have occurred over the past decade for both U.S. and Canadian flights (Natural Resources Canada 2016d; U.S. DOE 2014b).

Overall, in both Canada and the United States, a large portion of fuel and electricity use, associated with residential energy use and personal transportation, is weakly coupled with positive change in GDP. Research in Canada suggests that personal transportation and household energy, which compose about a third of the nation's total energy use, are not coupled to GDP growth, resulting in an overall decrease in energy intensity when GDP rises, even if there is no economic structural change or efficiency improvement (Torrie et al., 2018). This result has been a major contributor to declining energy intensities in Canada and possibly also in the United States during recent decades.

In summary, energy-intensity decreases have been an important factor in the current trends of CO_2e emissions for North America. Shahiduzzaman and Layton (2017) calculated that, between 2005 and 2010 and between 2010 and 2014, decreases in energy intensity of output were responsible for annual reductions of 19.2 Tg C and 21.7 Tg C from the U.S. energy system, respectively. Over the 10 years of these two periods, this trend translates to about 409 Tg C, which is offset by decreases in energy intensity.

3.6.4 Decreasing Carbon Intensity

The carbon intensity (F/E in the Kaya Identity) of energy use is another factor, like energy intensity, that affects the overall level of emissions from the energy system. Different fossil fuels have different carbon intensities (e.g., per unit of energy, coal emits about 50% more CO_2 than that by refined petroleum products), and some energy forms, like solar, wind, and nuclear, do not emit CO_2 at all. The mix of fuels being used in a society changes over time and with it the carbon intensity of the energy system. Changes in the carbon intensity of the North American energy system over the past decade have been significant and mostly evident in the United States and Canada, although Mexico also has contributed to the decreasing trend.

In the United States, carbon intensities for all major energy sectors have been dropping steeply since 2005. The greatest declines were experienced by the industrial and electricity sectors. The industrial sector produced the least amount of CO_2 per unit of primary energy consumed in 2016, with emissions of 41.5 kg CO_2e per GJ. The electric power sector, which is second only to the transportation sector, produced 45.3 kg CO_2e per GJ in 2016, which is now below the commercial and residential sector's carbon intensities (EIA 2017j). Shahiduzzaman and Layton (2017) calculate that U.S. carbon intensity

reductions have offset approximately 287 Tg C from the U.S. energy system over the past 10 years.

Canada's carbon intensities have also been decreasing. Similar to the United States, decreasing energy generation from coal and oil and increasing generation from hydropower, nuclear, and wind were the largest drivers of the 31% decrease in emissions associated with electricity production between 2005 and 2015. The permanent closure of all coal-generating stations in the province of Ontario by 2014 was an important factor in changing the national fuel mix (ECCC 2017b).

After falling during the 1990s, Mexico's carbon intensity increased between 2000 and 2010 (OECD 2013). Mexico's CO_2e emissions profile is heavily skewed toward transportation and the power sector. The ongoing effort to switch from oil- to gas-fired generation has reduced the carbon intensity of Mexico's electricity sector by 23% since 2000, and further improvements are expected (IEA 2016b).

Changes in the carbon intensity in North America are related to several trends, some of which have already been discussed in detail.

- The natural gas boom, including the shift from coal to cheaper and cleaner natural gas for electricity production and industrial processes (EIA 2017j), with the critically important caveat that venting, flaring, and fugitive emissions may be underestimated (see Section 3.4.2, p. 129, and Box 3.3, p. 137).
- Increased renewables in the fuel mix in all North American countries, including wind, solar, and bioenergy (with caveats mentioned for this last source; see Sections 3.4.3, p. 131, and 3.4.5, p. 135), driven, in part, by declining costs and changing fuel prices.
- A wide range of new technologies including grid-scale electricity storage and alternative fuel vehicles.

Many new technologies affect the potential of others. For example, improvements in electric vehicle battery technology help support improvements in utility energy storage. Energy storage improves grid stabilization and buffers peak electricity demands that, in turn, help support a larger share of renewables in the electric grid.

Other important technologies include the grid-scale electricity storage (i.e., previously mentioned new battery storage for wind and solar) and alternative fuel vehicles. Grid-scale electricity storage currently includes pumped hydroelectric storage but, in the future, also may be enhanced by a wide variety of technologies that serve an array of functions within the electric power system (EIA 2011a). There are currently 40 pumped storage plants in the United States totaling more than 22 GW of capacity (about 2% of the nation's generating capacity; EIA 2013b). Canada has one pumped storage facility in Ontario with a 174-MW capacity, and Mexico is currently exploring the possibility of developing this technology.

With the transportation sector having the highest carbon intensity in the region, use of alternative fuel vehicles can help make significant reductions. These vehicles are designed to operate on fuels other than gasoline and diesel, including compressed natural gas, propane, electricity, hydrogen, denatured ethanol, and other alcohols and methanol. An example of the increase can be seen in the electric vehicle stock. Globally, electric vehicles surpassed 1 million in 2016. In the United States, there have been recent increases in the number of electric vehicles on the road from around 23,000 in 2011 to 118,000 in 2015, and Canada's electric vehicles jumped from fewer than 1,000 to almost 7,000 during this same period (EV-Volumes 2017). Mexico currently is focusing on increasing biofuels for its vehicle fleet. With the 2017 launch of the Tesla Model 3, the number of electric vehicles may increase (Marshall 2017).

Notwithstanding the emergence of these new technologies, an important influence that has underpinned the current decrease in carbon intensity is falling energy prices. Among different fossil fuel

choices, falling prices for one fuel relative to another provide incentives to consumers to shift fuels. According to Houser et al. (2017), the surge in U.S. natural gas production due to the shale revolution made coal increasingly uncompetitive in U.S. electricity markets. Coal also faced growing competition from renewable energy.

Oil, gas, and coal prices have all dropped recently. From 2014 to 2015, world oil prices dropped dramatically and, to a lesser extent, so did natural gas and coal prices. From 2010 to mid-2014, global crude oil prices were relatively stable but historically high, at more than US$100 per barrel. In June 2014, Brent crude oil, a key global crude oil pricing benchmark, traded above US$110 per barrel. Later in 2014, oil prices began to drop, and, by January 2015, prices had declined by about 60% to under US$46 per barrel. Both Brent and West Texas Intermediate, a benchmark for U.S. crude oil, remained in the range of US$40 to US$60 per barrel for much of 2015 (National Energy Board 2016). The collapse in prices was driven by a marked slowdown in demand growth and record increases in supply, particularly tight oil (sometimes called shale oil) from North America, as well as a decision by the Organization of Petroleum Exporting Countries (OPEC) not to try to rebalance the market through cuts in output (IEA 2015a).

Differing from oil, there is no global pricing benchmark for natural gas. Instead, the three major regional markets (North America, Asia-Pacific, and Europe) have different pricing mechanisms. In North America, gas prices are determined at hubs and reflect local gas supply and demand dynamics. Notwithstanding the different market conditions, the surge in natural gas production within North America has reduced prices. While natural gas prices declined globally, the pace and extent were dramatic in North America. In the United States, for example, the average price for natural gas to power plants dropped from $10 per thousand cubic feet (ft^3) in 2008 to $3 in 2016, a 71% decline (US$ 2016). During this period, despite falling coal prices, the average delivered cost of coal to power plants decreased by only 8% in real terms (Houser et al., 2017; IEA 2015a).

The increase in low-carbon energy sources also has been driven in part by falling costs of renewables. Globally, bioenergy-for-power, hydropower, geothermal, and onshore wind projects commissioned in 2017 largely fell within the range of generation costs for fossil-based electricity. Drivers of cost reductions include technological improvements, competitive procurement, and a large and growing base of experienced project developers (IRENA 2018a). In North America, between 2008 and 2016, the price of onshore wind declined by 36%, and the price of solar PV modules fell by 85% (Houser et al., 2017), prompting expansion in these PV sources. Wind prices are projected to be competitive with natural gas by 2050 (U.S. DOE 2017a). The cost of distributed generation, specifically distributed rooftop PV systems, also is declining. Median installed prices for distributed PV systems declined 6% to 12% per year from 1998 to 2015, and the decline was faster after 2009 (Barbose and Dargouth 2016).

Declining costs of renewable power generation along with increased competition from cheap natural gas are responsible for 67% of the decline in U.S. domestic coal consumption (Houser et al., 2017). Although low prices in natural gas relative to those of oil and coal have helped to reduce carbon intensities, continued low fossil fuel prices also can decrease pressure to develop renewables, possibly pushing carbon intensities in the opposite direction. IEA (2017a) suggests that this dynamic will affect conditions in the near future, unless the price of fossil fuels increases.

3.7 Carbon Management Decisions

Historically, governmental management and policy have been capable of changing the North American energy system in significant ways including, for example, the creation of the Tennessee Valley Authority in the United States; construction of the U.S. national highway system and the Grand Coulee and Hoover dams; development of the National and Pacific railroads in Canada; and Mexico's national highways development and, until recently, governmental control of Mexico's oil, gas, and electric energy system. Governmental carbon management decisions can be identified through plans and commitments, investments in infrastructure and research and development, market-based tools, and regulations and standards at multiple levels of government. Indeed, over the past decades, there have been significant international, national, subnational or state, and city actions and commitments that have shaped the current regional carbon management system. Over the past year in the United States, however, national energy policy has been changing (EY 2017). This section reviews selected international, national, and state or subnational governmental actions in North America and their effects on energy use and carbon emissions trends.

3.7.1 International Carbon Management Decisions and National Responses

Parties to the Paris Agreement[14] are required to submit mitigation contributions that describe national targets, policies, and plans for reducing carbon emissions. The targets in these contributions are "nationally determined" and not legally binding. Over 190 countries have submitted nationally determined contributions under the Paris Agreement including GHG emissions reduction targets and related actions (UNFCCC 2015; IEA 2015a; World Resources Institute 2016a). In North America, Canada has announced a GHG emissions reduction target of 30% below 2005 levels by 2030. Mexico has announced a GHG emissions reduction target of CO_2e and short-lived climate pollutant reductions of 25% by 2030 with respect to a business-as-usual scenario, as well as additional reductions possible in the context of international financial support. Prior to the adoption of the Paris Agreement, the United States put forward a nonbinding Intended Nationally Determined Contribution (INDC) of reducing emissions 26% to 28% below 2005 levels by 2025. On June 1, 2017, President Trump announced that the United States intends to withdraw from the Paris Agreement, unless it identifies better terms for participation, and that the United States would cease implementation of this nationally determined contribution (Executive Office of the President 2017).

In 1994, Canada, Mexico, and the United States established the North American Agreement on Environmental Cooperation (NAAEC) to ensure that economic activities among the countries would not come at the expense of the environment. NAAEC provided for the establishment of the Commission for Environmental Cooperation (CEC), the first collaborative trilateral venue promoting a cooperative approach to environmental protection in the region. The strategic priorities for 2015 to 2020 include climate change mitigation and adaptation. The initiatives under this priority include developing, comparing, and implementing actions to mitigate CO_2e emissions, consistent with international commitments and piloting protocols in key sectors (e.g., waste management, the food industry, and transportation) to reduce emissions of short-lived climate pollutants, such as black carbon and CH_4 (Commission for Environmental Cooperation 2015).

In 2012, national climate action plans described commitments and strategies for reducing carbon emissions and are coordinated through policies to meet countries' announced GHG reduction targets and actions. Mexico in 2012 became the first emerging economy to pass comprehensive climate change legislation, and in 2015 it became the first emerging economy to release its post-2020 climate action plan. Mexico is undergoing a process that further details what the announced emissions target and actions mean at the sectoral level. The country's Energy Transition Law (*Ley de Transición Energética*) of 2015, as part of its energy reform program (*Reforma Energética*) that started in 2013, includes clean (i.e., low- or no-emission) energy targets of 25% of electricity generation by 2018, 30% by 2021, and 35% by 2024. The way in which this law is implemented will affect Mexico's emissions pathway. Canada's action plan includes working with provinces and territories to establish

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[14] The Paris Agreement (UNFCCC 2015) resulted from the United Nations Framework Convention on Climate Change (UNFCCC) 21st Conference of the Parties (COP21).

a pan-Canadian framework for addressing climate change, including carbon pricing; investments in clean energy technology, infrastructure, and innovation; and a Low-Carbon Economy Trust Fund to support provinces and territories in achieving emissions reductions and transforming their economies toward a low-carbon future (ECCC 2016a). In the United States, a number of climate action policies have been put in place to encourage energy efficiency and renewable energy generation. Recently, the United States announced an energy policy, defined in the *America First Energy Plan*, aimed to promote domestic energy generation, including oil, coal, and natural gas extraction and use, as part of a broader strategy of energy security and independence. Because this strategy is still under development, it cannot be evaluated in this report.

3.7.2 National Energy and Carbon Management Decisions

Investments to increase energy efficiency and lower carbon emissions were promoted in recent economic recovery acts in Canada and the United States. In the United States, the American Recovery and Reinvestment Act (ARRA) of 2009 provided US$17 billion for energy efficiency and US$26 billion for renewable energy investment. Federal support for clean energy technology across agencies totaled an estimated US$44 billion and grew to US$150 billion from 2009 to 2014 (Banks et al., 2011). These actions played a role in reducing the levelized cost of energy (LCOE) for onshore wind technologies and lowering the capital costs of wind and solar PV technologies. ARRA also funded US$4.5 billion for smart grid demonstration projects, US$700 million for alternative fuel vehicles, and US$400 million for U.S. DOE's Advanced Research Projects Agency-Energy (ARPA-E) and allowed energy-efficiency improvements to be eligible for billions of dollars in investment for federal agencies. Within the United States, discussions of improving infrastructure have focused on roads, bridges, airports, and other public works, possibly including energy infrastructure. As highlighted earlier, rebuilding the country's aging energy infrastructure also would increase energy efficiencies.

Similarly, Canada's recovery plan included a 2-year stimulus package worth CAD$35 billion. Approximately CAD$12 billion was earmarked for infrastructure, launching one of the largest building projects in the country's history (Whittington and Campion-Smith 2009). More than CAD$300 million was designated for the ecoENERGY Retrofit program, which provides financial support to homeowners, small- and medium-sized businesses, public institutions, and industrial facilities to help them implement energy-saving projects that reduce energy-related GHGs and air pollution. Approximately CAD$1 billion was apportioned for clean energy research, development, and demonstration (RD&D) projects (Department of Finance Canada 2009). As with the United States, infrastructure improvements are likely to alter future energy-use trajectories.

Although Mexico did not implement a recovery act, in December 2013 it passed an energy reform bill as part of the *Reforma Energética,* which opened the country's energy sector for significant regulatory, financing, and infrastructure changes for both renewable and nonrenewable sources to meet the reform bill's promised increase in production. The Mexican *National Infrastructure Program 2014–2018*, in adherence to the *National Development Plan 2013–2018*, promotes development of energy generation, transmission, and distribution facilities that will make use of potential renewable energy and has invested an estimated US$46 million in 138 strategic electricity infrastructure projects (PricewaterhouseCoopers Mexico 2014). Additionally, recent partnerships with private companies and finance have spurred infrastructure expansion (Zborowski 2015).

A number of market-based tools are also available to governments. At the national scale, Mexico passed a carbon tax in 2014 on fossil fuel sales and imports (natural gas and jet fuel were exempted) as part of broader fiscal reform. The tax is set at approximately US$3.50 per megagram CO_2e. Firms are allowed

to use credits from a domestic clean development mechanism offset program to fulfill their tax liability, but the operating rules for this mechanism have yet to be published (ICAP 2016). Canada recently announced the implementation of a national carbon tax. Prime Minister Justin Trudeau said a minimum price of US$10 per ton of CO_2e would be implemented in 2018, rising to US$50 per ton by 2022.

The United States imposes few energy-related "green taxes" at the federal level. An exception includes the "gas guzzler" tax on new automobiles that exceed fuel efficiency standards (Cohen et al., 2015). Rather, the United States uses tax credits, subsidies, and support services to incentivize targeted investments. These include the investment tax credit (ITC), which is a key driver for solar energy. The credit provides a 30% tax credit for solar energy systems for residential and commercial buildings. The tax credit has played a role in the increase of solar investments, which have grown by more than 1,600% from 2006 to 2014 (SEIA 2014). The production tax credit (PTC) also supports the development of renewable energy, most commonly wind, though it also applies to geothermal and some bioenergy systems. The PTC provides an incentive of 2.3 cents per kWh, for projects under construction in 2015, for the first 10 years of a renewable energy facility's operation and is adjusted over time, reducing the value of the incentive to 40% of the PTC for projects that start construction in 2019 (Union of Concerned Scientists 2014).

Subsidies are an important way that governments continue to promote their energy policy. In 2009, according to IEA et al. (2010), global fossil fuel subsidies were estimated at US$312 billion and rose to US$409 billion in 2010 (up almost 30% from 2009), six times the amount allotted for renewable energy support (IEA et al., 2011). Eliminating these subsidies globally would cut energy-related CO_2 emissions by an estimated 13% (Ball 2013). In the United States, subsidies for fossil fuels from 2002 to 2008 reached US$72 billion, with an additional set of subsidies for renewable fuels totaling US$29 billion (Environmental Law Institute 2009). Canada also subsidizes fossil fuel industries for around CAD$3.3 billion for oil and gas producers (Touchette 2015). One result of the restructuring of Mexico's state-run energy program is that fossil fuel subsidies have dropped from US$19.1 billion in 2012 to US$5 billion in 2014 (IEA 2015c).

Governmental agencies may provide support services with goals to enhance investment, research and development, and collaboration with private-sector firms. U.S. DOE's Office of Energy Efficiency and Renewable Energy (EERE), for example, was created to promote and sustain leadership in the transition to an economy powered by clean, affordable, and secure energy. This program's goal is to accelerate the development and adoption of fuel-efficient and nonfossil fuel transportation technologies, renewable sources of electricity, energy efficiency in residential and commercial buildings, reductions in life cycle energy consumption of manufacturing processes, and new grid technologies (U.S. DOE 2015c). EERE's SunShot program was developed with the goal of reducing solar costs to US$1 per watt for utility-scale solar systems (and US$1.50 per watt for residential) by 2020. However, in 2017 U.S. DOE announced that the solar industry had already achieved the SunShot Initiative 2020 solar cost targets, bringing the costs of utility-scale solar to $0.06 per kWh. Models of the impact of this price change on the U.S. energy sector suggest solar power can cost effectively provide up to about one-third of national electricity capacity by midcentury (Mileva et al., 2013). The rapid deployment of distributed generational solar power systems over the past 5 to 10 years has both highlighted challenges and demonstrated many successful examples of integrating higher penetration levels than previously thought possible (Palmintier et al., 2016). Not only is future expansion of solar possible, but this expansion potentially could provide a significant number of jobs in energy sectors of the country and the world (Wei et al., 2010; IRENA 2018b).

Regulatory approaches also can have an impact on the energy sector. The U.S. Clean Air Act (CAA), for example, was established in 1963 but

strengthened in 1970 in conjunction with the creation of U.S. EPA to carry out programs to regulate air pollution nationwide. CAA authorizes EPA to set national standards for clean air, and, as of 2009, the legal foundation was established for U.S. EPA to regulate GHGs under CAA. CAA benefits have been massive, estimated to reach approximately (US$ 2006) $2 trillion in 2020 with costs of only (US$ 2006) $65 billion (U.S. EPA 2011). In 2012, Canada passed regulations to establish a regime for reducing CO_2 emissions resulting from electricity production that uses coal as a fuel; these regulations took effect in 2015.

Governments commonly use regulatory standards to enforce policy goals. Since 1987, for example, national standards for appliance efficiency have been developed and subsequently expanded to more than 50 categories of products used in homes, businesses, and industry (de Laski and Mauer 2017). Another important example in the United States consists of CAFE standards (dating back to the 1970s), which were designed to improve vehicle fuel economy. U.S. EPA and U.S. DOT's National Highway Traffic Safety Administration (NHTSA) issued final rules extending the national program to further reduce GHG emissions and improve fuel economy for MYs 2017 through 2025 light-duty vehicles. U.S. EPA established national GHG emissions standards under CAA, and NHTSA established CAFE standards under the Energy Policy and Conservation Act, as amended by the Energy Independence and Security Act. The new standards are estimated to lead to corresponding reductions in CO_2 emissions totaling 491 Tg C during the lives of light-duty vehicles sold in MYs 2017 to 2025 (U.S. EPA and U.S. DOT 2012). As of March 2017, however, EPA reopened a midterm review of U.S. CAFE standards that would require the industry to deliver a fleet average of at least 23 km/L (54.5 miles per gallon) by 2025. The type of changes introduced to these regulations during the review and their impacts are not yet clear.

Canada established the Company Average Fuel Consumption (CAFC) targets and harmonized them with CAFE standards in the United States. The main difference between Canada's CAFC regulations and the U.S. CAFE program was that Canada's standards remained voluntary for 25 years. The Motor Vehicle Fuel Consumption Standards Act of 1982 set legally binding standards parallel to U.S. CAFE regulations, but lawmakers did not officially implement the program until 2007. In 2010, new regulations were the first in Canada to limit GHG emissions from the automotive sector under the Canadian Environmental Protection Act of 1999. The final Passenger Automobile and Light Truck Greenhouse Gas Emission Regulations set fuel economy targets for passenger vehicles and light-duty trucks similar to those of the United States (Feldman 2009). In 2013, the Mexican government published final standards regulating CO_2e emissions and the fuel economy equivalent for new passenger vehicles, including cars, pickup trucks, and sport utility vehicles. The final standard will apply to vehicle MYs 2014 to 2016. Taking into account all annual credits (except credit banking and trading), the standard is expected to result in a new car fleet average fuel economy of 14.6 km/L in 2016 (ICCT 2013). These laws put all three countries on track for a target of 20.9 km/L of gasoline equivalent by 2025 (ICCT 2013).

3.7.3 Subnational Energy and Carbon Management Decisions

While U.S. federal actions discussed in the previous section have prompted changes in national carbon management and may change the direction of future trends, important carbon management decisions also happen at the subnational level in states and localities (see Ch. 4: Understanding Urban Carbon Fluxes, p. 189, for elaboration on the urban carbon management initiatives). For example, in Canada, the provinces have been active in setting carbon taxes, fuel economy standards, and emissions controls prior to the national government's actions (IEA 2010). In the United States, state governments have implemented policies on energy and GHG emissions including GHG targets, caps, and pricing; renewables; CCS; nuclear power; transportation; energy efficiency; methane and hydrofluorocarbons; and forestry and land use (America's Pledge 2017). Some states have developed and implemented several

multistate carbon cap-and-trade partnerships. One of the most notable multistate programs is the Regional Greenhouse Gas Initiative, which began as a collaboration between 10 northeastern states to cut their CO_2 emissions. At the state and provincial level, renewable portfolio standards (RPS) have been implemented as a mechanism to encourage the uptake of renewable energy in the United States as part of federal policy, but the details of implementation are left to the states to choose. As of 2013, 29 states plus Washington, DC, have some form of enforceable RPS, and eight other states have nonbinding renewable portfolio goals (EIA 2012d). Energy-efficiency resource standards also have been popular in subnational units. In 1999, Texas became the first state to establish an energy-efficiency resource standard. As of 2015, 25 states have adopted such a standard. The American Council for an Energy Efficient Economy found that most states are on target to meet their goals (Sciortino et al., 2011). Many tribes are also prioritizing energy-efficiency and renewable-energy projects (Norton-Smith et al., 2016). More than 275 American cities, counties, tribes, and states have created green building codes, which have promoted energy efficiency in this sector. Leading states include California, Virginia, and Washington.

Other subnational carbon management programs include energy-efficiency standards; public benefit funds; electric grid standards; feed-in tariffs;[15] on-bill financing;[16] property-assessed clean energy; and the use of subsidies, tax credits, and rebates to promote clean energy. In Mexico, the Federal District of Mexico City has implemented Bus Rapid Transit routes and created emissions standards for vehicles (see Ch. 4: Understanding Urban Carbon Fluxes, p. 189). U.S. states and Canadian provinces also have been active in promoting transportation policies, including procurement of hybrid or electric vehicles for their fleets, creating strict emissions standards for cars and light trucks, promoting low-emissions vehicle standards and zero-emissions vehicle promotions and production requirements. For example, California's "Advanced Clean Cars Program" allows the state to set and enforce vehicle emissions standards more stringent than standards set by U.S. EPA. Whether and how this law will be affected by the revision to U.S. federal CAFE regulations is not yet clear. Finally, many states have set emissions-reduction plans to reach a goal of 30% or more reduction of CO_2e emissions by 2030 (Cohen et al., 2015). For example, New York state has implemented a plan to reduce GHG emissions by 40% from 1990 levels by 2030 and 80% by 2050 (NYSERDA 2015). In 2006, California passed the Global Warming Solutions Act and, subsequently, the Climate Change Scoping Plan as the roadmap to achieve reductions of 30% from business-as-usual emissions projected for 2020. The law spells out a range of measures to expand energy-efficiency programs; achieve a renewable energy mix; and develop a cap-and-trade program that covers 85% of the state's emissions, such as electricity generation, large industrial sources, transportation fuels, and residential and commercial uses of natural gas. In 2014, California linked its program to Canada's program in Quebec (Cohen et al., 2015).

In summary, a variety of policies at multiple levels of government have helped shape the patterns of energy use and carbon emissions in the region over the past decade. Recently, however, the U.S. federal government appears to be prioritizing energy resource extraction and use; how these policies will affect future trends remains uncertain.

3.8 Future Outlook

The future outlook for the North American energy system is based on scenario analyses. Scholars have argued that scenarios are a good tool to analyze future trends while addressing uncertainties (Peterson et al., 2003; Schoemaker 1991; van Vliet and Kok 2015; van't Klooster and van Asselt 2011). Several different approaches to scenario

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[15] Feed-in tariffs (FIT) are policy mechanisms used to encourage deployment of renewable electricity technologies. FITs typically guarantee that customers who own a FIT-eligible renewable electricity-generation facility, such as a rooftop solar photovoltaic system, will receive a set price for their utility for all the electricity they generate and provide to the grid.

[16] On-bill financing refers to loans made to utility customers, the proceeds of which would pay for investments in energy efficiency improvements. Regular monthly loan payments are then collected by the utility on the utility bill until the loan is repaid.

development exist, however (Amer et al., 2013; Börjeson et al., 2006; van Notten et al., 2003). While there are no consensus universal typologies, the review literature often includes three distinct types of scenarios: predictive, exploratory, and backcasting scenarios. This section describes these different scenario types, discusses the advantages and disadvantages of each approach, and reviews scenario results applied or related to the North American energy system and GHG futures. The scenarios reviewed provide information on energy and GHG predictions based on historical and current policies, the future range of plausible outcomes defined by variations in energy and emissions drivers, and the costs of mitigating carbon emissions to create average global temperature increases of not more than 2°C.

3.8.1 Energy and Carbon Emissions Forecasts

Predictive scenarios comprise two different types—forecasts that address how the future will unfold, based on likely development patterns and "what if" scenarios that respond to changes in specified events or conditions (Börjeson et al., 2006). Forecasts typically provide a reference case result that may be accompanied by outcomes of high- and low-type scenarios, indicating a span of options. Sometimes probabilities are employed in attempts to estimate likelihoods of outcomes. Predictive scenarios are useful to stakeholders for addressing foreseeable challenges and opportunities and can increase the awareness of problems that are likely to arise if specific conditions are fulfilled. This type of scenario attempts to answer the question, what *will* happen? (Quist 2013).

An important criticism of predictive scenarios is that they have a self-fulfilling nature resulting from assumptions of continuity based on past and current trends. Predictive scenarios are based on historical data that define the trends and model parameters that do not change over the course of the scenario timescale (i.e., no policy changes are identified initially), preventing the possibility of transformational changes.

The forecasts examined here include national future projections of CO_2e for Canada (ECCC 2016c), the United States (EIA 2017k), and Mexico (IEA 2016b). Each projection set includes a reference case and a defined set of high- and low-emissions scenarios. In all cases, the figures are modeled as projections of "what if" forecasts, given certain assumptions about drivers. The methods and assumptions among the projections presented are neither standardized nor bias-corrected. Despite uncertainties in combining figures, these aggregate national projections are useful in signaling the variety of potential futures for North American energy system emissions.

In its *Annual Energy Outloo*k, EIA (2017k) provides a "Reference" case projection as a business-as-usual trend estimate, given known technology and technological and demographic trends. It generally assumes that current laws and regulations affecting the energy sector, including sunset dates for laws that have them, are unchanged throughout the projection period. The potential impacts of proposed legislation, regulations, and standards are not reflected in this reference case. The cases of "High emissions" and "Low emissions" are based on different assumptions of macroeconomic growth, world oil prices, technological progress, and energy policies. "High emissions" cases include scenarios with high economic growth and those without the U.S. Clean Power Plan (CPP). "Low emissions" cases include scenarios with low economic growth and those with CPP. All projections are based on results from EIA's National Energy Modeling System (NEMS). The EIA (2017c) "Reference" case assumes that current laws and regulations remain in effect through 2040 and that CPP is implemented. The "Reference" without CPP case is the "High emissions" scenario and has similar basic assumptions to the "Reference" case, but it assumes high economic growth and no implementation of a federal carbon-reduction program. The "Low emissions" case is the low economic growth scenario and assumes GDP annual growth at 1.6% (compared with a 2.2% reference case).

The U.S. "High emissions" scenario projects an increase in emissions of 0.7% (10.4 Tg C) from 2015 to 2040, while the "Low emissions" scenario projects a decrease in emissions of 12.2% (175.3 Tg C) during this period. Across the three presented alternative cases, total energy-related CO_2e emissions in 2040 vary by more than 185.5 Tg C (14% of the "Reference" case emissions in 2040). The "Reference" case projects a decrease of emissions by 7.2% from 2015 to 2040, translating into a decrease of 103.9 Tg C. The U.S "Low emissions" case translates into an emissions reduction about equal to the current size of Canada's total energy-related emissions. Note, however, that even with the low-growth emissions case, the U.S. energy system would not meet the target of reducing emissions by 26% to 28% below 2005 levels (1,640 Tg C) by 2025 (a drop of 426 Tg C and 469 Tg C, respectively), previously proposed in the U.S. INDC (The Record 2016).[17] Although the United States has stated an intent to withdraw from the Paris Agreement, this comparison illustrates the kind of reductions needed to meet the goals of the United Nations Framework Convention on Climate Change (UNFCCC) 21st Conference of the Parties (COP21). Note that even if all signatories of the Paris Agreement met their reduction goals, it is unclear whether global temperature increases would be kept below an average temperature increase of 1.5°C above preindustrial levels (Clémonçon 2016; Rogelj et al., 2016, 2018; Obersteiner et al., 2018).

Canada's energy-related CO_2e emissions projections are published by ECCC (2016c) and derived from a series of plausible assumptions regarding, among others, population and economic growth, prices, energy demand and supply, and the evolution of energy-efficiency technologies. The projections also assume no further governmental actions to address GHG emissions beyond those already in place as of September 2015. In the Canadian projections, the "Reference" scenario represents the midrange levels for economic growth (1.5% to 2.2% GDP growth rates per year), stable population growth (1.1% to 1.3%), and slight increases in energy prices, among other factors. The "High emissions" scenario includes high GDP annual growth rates (1.3% to 2.7%) and high energy prices, among other factors. The "Low emissions" scenario includes assumptions of low GDP annual growth (0.8% to 1.5%) annually and low energy prices. Environment and Climate Change Canada uses the Energy, Emissions and Economy Model for Canada (E3MC; ECCC 2016c). Canadian emissions from stationary combustion and fugitive sources, transportation, and industrial processes are presented; emissions from agriculture and waste are excluded. Also, the Canadian projections are for the years up to 2030. The 2030 figures are used here for the 2040 North American analysis.

In the Canadian "Reference" case, Canada's energy-related emissions by 2030 are 180 Tg C, an increase of 3.6% from 2015 levels. The "High emissions" scenario projects 193 Tg C levels by 2030 (an increase of 10.8% from 2015 levels). The "Low emissions" case projects 168 Tg C by 2030 (a decrease of 3.6% from 2015 levels). The range in emissions represents 14% of the reference case emissions in 2030. Also note that for Canada, in the "Low emissions" scenario, the nation's energy system would meet its Nationally Determined Contribution (NDC) target of 142.64 Tg C by 2030 (ECCC 2017a).

IEA (2016b) recently provided projections for Mexico under a variety of scenarios. The IEA analysis includes five different scenarios: "New Policies," "Current Policies," "450 Scenario," "No Reform," and "Enhanced Growth." The "New Policies" scenario

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[17] In preparation for the Conference of the Parties for the United Nations Framework Convention on Climate Change (UNFCCC), negotiating parties were invited to submit Intended Nationally Determined Contributions (INDCs). INDCs publicly outlined what post-2020 climate actions (including targets for emissions levels) were intended by each signatory under the new international agreement. The actions were "intended" prior to the Paris Agreement, but when a country became a signatory, the plans became Nationally Determined Contributions (NDCs). The United States submitted an INDC and became a signatory to the agreement, but it has subsequently announced its intention to withdraw from the agreement, a process which cannot happen until after 2020 (https://treaties.un.org/Pages/ViewDetails.aspx?src=TREATY&mtdsg_no=XXVII-7-d&chapter=27&clang=_en). Both the governments of Canada and Mexico have ratified the Paris agreement.

reflects the way governments envision their energy sectors developing over the coming decades. Its starting point is the policies and measures that are already in place, but it also takes into account, in full or in part, the aims, targets, and intentions that have been announced. "Current Policies" depicts national energy system growth without implementation of any new policies or measures beyond those already supported by specific implementing measures in place as of mid-2016. No allowance is made for additional implementing measures or changes in policy beyond this point, except when current measures are specifically time-bound to expire. The "450 Scenario" is the decarbonization strategy, which has the objective of limiting the average global temperature increase in 2100 to 2°C above preindustrial levels. The "No Reform" case is an illustrative counterfactual case that deliberately seeks to portray what might have happened to Mexico in the absence of its energy reform initiative announced in 2013. Finally, "Enhanced Growth" uses a higher assumption of GDP. This chapter identifies the reference case as the "New Policies" scenario, "Current Policies" is the high-emissions case, and the low-emissions case is the "450 Scenario."

Among these scenarios, changes in Mexican CO_2 emissions from 2014 to 2040 range by 50%. The reference case ("New Policies") projects an increase in emissions from 118 to 124 Tg C (5.6% increase) during the period. The high-emissions case ("Current Policies") projects an increase in emissions from 118 to 140 Tg C (19% increase). Alternatively, the low-emissions case ("450 Scenario") projects a decrease of almost 34%, with levels in 2040 reaching 78 Tg C. With the 450 Scenario, Mexico still will not meet its NDC target of reducing unconditionally 25% of its GHG emissions (below the business-as-usual scenario) for the year 2030. That is, the required 25% of the business-as-usual case (i.e., reference scenario) is a reduction of 29.3 Tg C (or 25% of 117 Tg C), but the reduction by 2030 using the 450 Scenario is 20 Tg C (117 to 97 Tg C). Again, these projections demonstrate the difficulty of meeting targets set forth by the Paris Agreement.

In aggregate, the data from these various models project future North American energy-sector emissions ranging from 3.0% higher than 2015 levels to 12.8% lower than 2015 levels by 2040 (see Figure 3.11, p. 158, and Table 3.5, p. 159). The aggregate "Reference" cases project a total 5.3% decrease in emissions from around 2015 by 2040. To ascertain a sense of uncertainty of these figures, the range of emissions from this set of projections is compared with regional estimates from private-sector forecasts of BP (2016) and ExxonMobil (2017), along with those of IEA (2016a). Both BP (2017a) and ExxonMobil (2017) project decreases in North American emissions. ExxonMobil (2017) projections, which include only the United States and Canada, suggest a 14.5% decrease in emissions by 2040 compared with 2015 levels, while BP (2017a) projections, which include all three nations, suggest an 11.8% decrease from 2015 to 2035. IEA (2016a) projections, which include the United States and Canada, show emissions levels rising by 10.5% between 2014 and 2030. This comparison identifies a wider range of future energy-related carbon emissions for North America than the national projections, suggesting a large range of predicted futures. Even at the aggregate "Low emissions" projection scenario, however, the region will not be able to meet the INDC and NDC commitments by 2040 (see Shahiduzzaman and Layton 2017).

3.8.2 Exploratory Energy and Carbon Emissions Scenarios

Exploratory scenarios sketch plausible futures, showing the implications of change in external drivers (Börjeson et al., 2006). Though not necessarily for prediction, they focus on what *may* happen, ultimately exploring uncertainty in driving forces (Börjeson et al., 2006; Shearer 2005; van der Heijden 2000). Typically, a set of scenarios are constructed to span a wide scope of plausible developments over a very long time span (Jefferson 2015).

The goals of exploratory scenario development include awareness raising of potential challenges, given a wide range of policies and outcomes, and deep insight into societal process interactions and influences (Peterson et al., 2003). In an exploratory

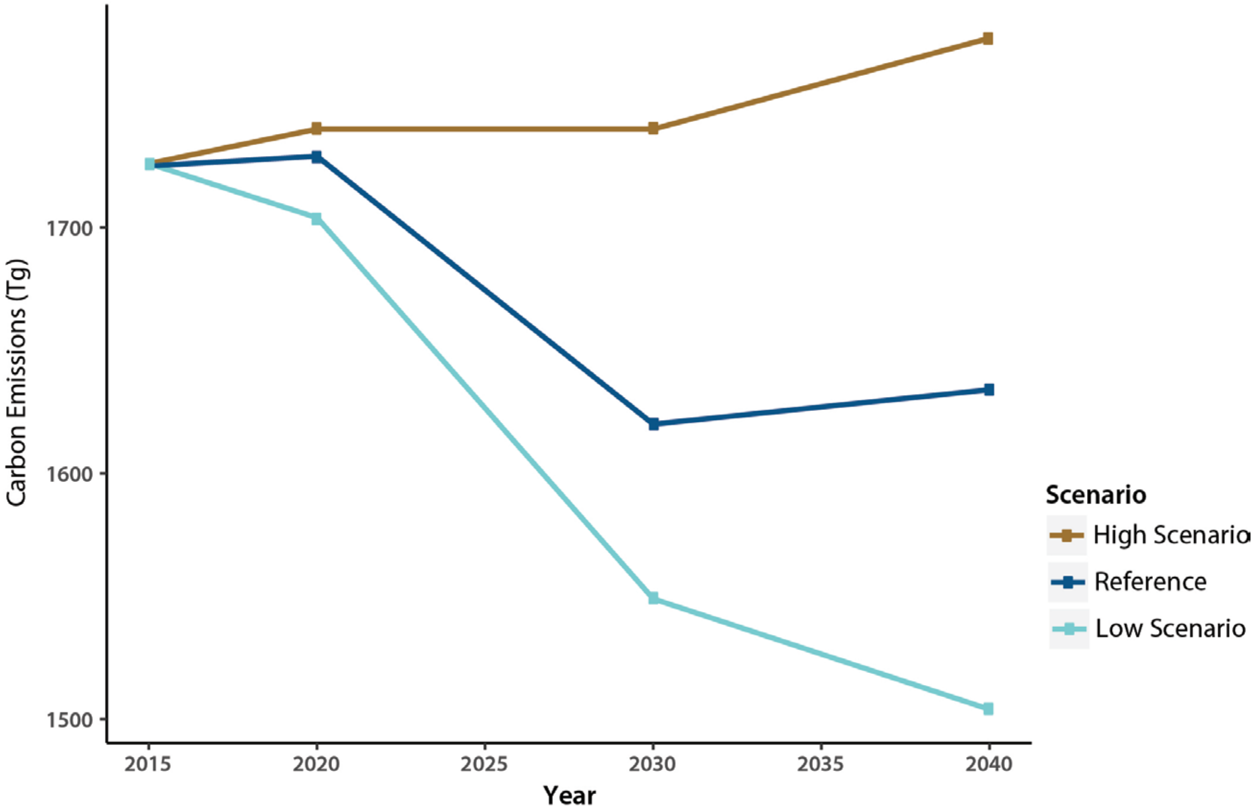

Figure 3.11. North American Energy System Carbon Emissions Scenarios in Teragrams (Tg). [Data sources: EEEC 2016c; EIA 2017k; and IEA 2016b.]

scenario exercise, the process of creating the scenarios is often as important as the product (van Notten et al., 2003). Exploratory scenarios address the question of what *can* happen in the future (Quist 2013). Besides providing a range of outcomes, from both well-understood and not so well-understood changes in conditions, exploratory scenarios have been found useful in accounting for important, but low-probability, condition changes. A criticism of exploratory scenarios is that, while they can demonstrate what might be possible, they are less useful in demonstrating how to achieve a desirable outcome (Robinson 1990).

Well-known examples of exploratory energy scenarios are those initially developed by Royal Dutch Shell and by the World Energy Council. The latest round of Royal Dutch Shell scenarios, titled *New Lens Scenarios: A Shift in Perspective for a World in Transition* (Royal Dutch Shell 2013), propose multiple lenses through which to view the future. The two pathways in the scenarios are called "Mountains" and "Oceans." These pathways are defined by different approaches to three key contemporary paradoxes (i.e., prosperity, connectivity, and leadership) and by how societies navigate the tensions inherent in each of these paradoxes. The "Mountains" pathway includes a world locked in *status quo*, tightly held in place by the currently influential powers. The rigid structure defined by the pathway is created by the demand for energy stability, which results in the steady unlocking of resources, but which also dampens economic dynamism and stifles social mobility. In the "Mountains" pathway, with the global energy supply remaining largely dominated by oil, natural gas, and coal, the world

Table 3.5. Projected Greenhouse Gas Emissions for North America (2015 to 2040)[a]

Economy	2015 (Tg C)[b]	2040 Reference Scenario (Range, Tg C)[b]	2015 to 2040 Percent Change in Reference Scenario (Range, Tg C)[b]
Canada (2015 to 2030)	173	180 (168 to 193)	3.6 (–3.6 to +10.8)
Mexico (2014 to 2040)	118	124 (78 to 140)	5.6 (–33.9 to +19.0)
United States (2015 to 2040)	1,434	1,330 (1,259 to 1,445)	–7.2 (–12.2 to +0.7)
North America	1,725	1,634 (1,504 to 1,777)	–5.3 (–12.8 to +3.0)

Notes

a) Sources: EIA 2017k; ECCC 2016c; IEA 2016b.

b) Tg C, teragrams of carbon.

overshoots the 2°C trajectory. During the second half of the century there remain opportunities for CCS technologies and zero-CO_2 electricity, but only if mandates promote policies for managing net global emissions.

The “Oceans” pathway, on the other hand, defines a world where power is devolved among competing interests and compromise is necessary. Economic productivity surges with waves of reforms, but social cohesion is sometimes eroded, resulting in political destabilization. In this pathway, market forces have greater prominence over governmental policies. In “Oceans,” biomass and hydrogen play linchpin roles in energy systems by 2100, as oil, natural gas, and coal account for less than 25% of the world’s energy supply, while solar, wind, and biofuels account for about 55%. Because of higher energy use, however, cumulative CO_2 emissions are 25% higher in “Oceans” than in “Mountains,” and also, as in the “Mountains” pathway, global CO_2 emissions exceed the 2°C threshold. Thus, one of this study’s key findings is that accelerated proactive and integrated policy implementation is necessary to avoid overshooting 2°C of globally averaged warming.

The World Energy Council (2016b) produced world energy scenarios to explore what the council called the “grand transition,” which was emerging from underlying drivers that are reshaping energy economics. The outline of this transition is based on three exploratory scenarios projected to 2050: “Modern Jazz,” “Unfinished Symphony,” and “Hard Rock.” The “Modern Jazz” scenario represents a digitally disrupted, innovative and market-driven world. “Unfinished Symphony” defines a future where intelligent and sustainable economic growth models emerge as the world moves to a low-carbon future. The “Hard Rock” scenario imagines a world of weaker and unsustainable economic growth with inward-looking national policies. Similar to the work of Royal Dutch Shell, mentioned previously, a key finding from the council’s work is that limiting global warming to an increase of no more than 2°C will require an exceptional and enduring policy effort, far beyond already-pledged commitments and with very high carbon prices.

There also have been recent exploratory scenarios developed specifically for economies in North America. The Pew Center on Global Climate Change (Pew; Mintzer et al., 2003) and an Energy Modeling Forum (EMF) study (Clarke et al., 2014; Fawcett et al., 2014a), for example, explore plausible futures for the U.S. energy system. The Pew study describes three divergent paths for U.S. energy supply and use from 2000 to 2035. The creators argue that taken together, these scenarios identify key technologies, important energy policy decisions, and strategic investment choices that could enhance energy

security, environmental protection, and economic development over a range of possible futures. The first Pew scenario, called "Awash in oil and gas," describes a future of abundant supplies of oil and natural gas that are available to consumers at low prices. In this scenario, energy consumption rises and conventional technologies dominate the energy sector. This low–energy price pathway provides few incentives to improve energy efficiency and little concern for energy use. Carbon emissions rise 50% above the 2000 level by 2035. Pew calls the second scenario "Technology triumphs," which describes a future with a large, diverse set of drivers, converging to accelerate successful commercialization in the U.S. market of many technologies that improve energy efficiency and produce lower carbon emissions. U.S. companies play a key role in the subsequent development of an international market for these technologies. Sustained economic growth and increases in energy consumption are accompanied by a 15% rise in carbon emissions from 2000 levels by 2035. Finally, in Pew's "Turbulent world" scenario, U.S. energy markets are repeatedly battered by unsettling effects on energy prices and threats to U.S. energy security. High energy prices and uncertainty about energy supplies slow economic growth as the country moves from one technological solution to another, all of which have serious flaws, until finally settling on a program to accelerate the commercialization of hydrogen and fuel cells. Despite slower economic growth than in the other scenarios, carbon emissions still rise 20% above the 2000 level by 2035.

Climate change policy was deliberately excluded from the three Pew base case scenarios. To explore how these policies might affect outcomes, the project provided a climate policy overlay (described as a freeze on CO_2 emissions in 2010) and subsequent 2% per year decreases from 2010 to 2025, followed by 3% per year decreases from 2026 to 2035 for each scenario set to achieve the targeted emissions-reduction trajectory of at least 70% from 2000 levels by the end of the century. The portfolio of policies included 1) performance-based energy and emissions standards; 2) incentives to accelerate research and development into low-carbon technologies; 3) a downstream carbon emissions allowance cap-and-trade program applied to electricity generation, the industrial sector, and investment; 4) PTCs for efficiency improvements in energy and emissions technologies; and 5) "barrier busting" programs designed to reduce market imperfections and promote economically efficient decision making (for more details, see Mintzer et al., 2003). When the postulated policy overlay is applied to each base case scenario, it modifies the pattern of energy technology development and future emissions levels. In the "Awash in oil and gas" scenario, the policy overlay results in the highest costs to the economy to meet the carbon constraints with much more stringent policies than in the other scenarios. In the "Technology triumphs" scenario, the policy overlays reinforce the driving forces of the case and accelerate the commercialization of key technologies. In this case, climate policy is uncontroversial, and the United States becomes an international competitor in the development of next-generation energy supply and end-use technologies. In the "Turbulent world" scenario, the imposition of a carbon emissions constraint leads to significant reductions in oil demand and CO_2 emissions, decreases based on the emergence of new technologies that sweep the market in transportation and electricity production. All these cases demonstrate the possibility of meeting the goal of a 2°C carbon-reduction trajectory.

EMF is a structured forum for discussing issues in energy and the environment established in 1976 at Stanford University. EMF works through a series of working groups that focus on particular market or policy decisions. The EMF Model Intercomparison Project (MIP) number 24 (EMF24) was designed to compare economy-wide, market-based, and sectoral regulatory approaches of potential U.S. climate policy (Fawcett et al., 2014a).

The EMF24 project focused on policy-relevant analytics that engaged "what if" scenario analysis on the role of technology and scope of regulatory approaches. The effort used nine models to assess the implications of technological improvements

Table 3.6. Technological Assumptions in the Energy Modeling Forum Study[a]

Technology	Optimistic Technology	Pessimistic Technology
End-use energy	End-use assumptions that lead to a 20% decrease in final energy consumption in 2050 relative to the pessimistic technology, no-policy case.	Evolutionary progress. Precise assumptions specified by individual modeling teams.
Carbon capture and storage (CCS)	CCS is available. Cost and performance assumptions specified by individual modeling teams.	No implementation of CCS.
Nuclear	Nuclear is fully available. Cost and performance specified by each modeling team.	Nuclear is phased out after 2010. No new construction of plants beyond those under construction or planned. Total plant lifetime limited to 60 years.
Wind and solar energy	Plausibly optimistic technology development. Cost and performance assumptions specified by individual modeling teams.	Evolutionary technology development. Cost and performance assumptions specified by individual modeling teams.
Bioenergy	Plausibly optimistic level of sustainable supply. Supply assumptions specified by individual modeling teams.	Evolutionary technology development representing the lower end of sustainable supply. Supply assumptions specified by individual modeling teams.

Notes

a) Source: Clarke et al., 2014.

and technological availability for three scenarios: no emissions reductions (reference scenario), reducing U.S. GHG emissions 50% by 2050, and reducing U.S. GHGs 80% by 2050. The general technological assumptions include 1) an optimistic CCS or nuclear set of technology assumptions, which have pessimistic assumptions about renewable energy, and 2) an optimistic renewable energy set of technology assumptions for bioenergy, wind, and solar that do not allow CCS and phase out nuclear power energy (see Table 3.6, this page). The EMF24 scenarios allowed banking so that while cumulative emissions were consistent with an emissions cap that followed a linear path to 50% or 80% reductions (relative to 2005 levels) in 2050, actual modeled emissions could be higher. Reference scenarios did not include policies and served as counterfactual starting points for policy application. The policy assumptions explore these seven types of scenarios: 1) "Baseline with no policy," 2) "Cap-and-trade of varying stringency (0% to 80%)," 3) "Combined electricity and transportation regulatory," 4) "Electricity and transportation-sector policy combined with a cap-and-trade policy," 5) "Isolated transportation sector policy," 6) "Isolated electricity sector policy with a renewable portfolio standard (RPS)," and 7) "Isolated electricity sector policy with a clean energy standard (CES)."

The study finds that even under the most optimistic technology assumptions, no reference scenario among the different models meets the mitigation goals of 50% by 2050. The greatest average annual emissions reduction identified across models was 0.19% per year through 2050. Alternatively, every model could meet 50% reduction scenarios even under the most pessimistic assumptions about

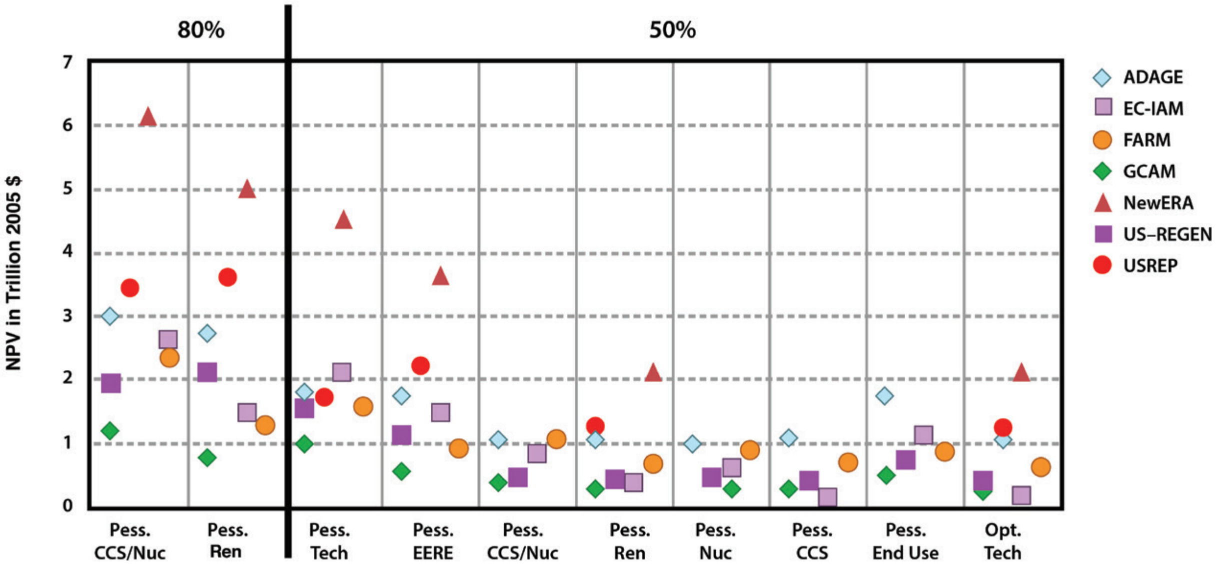

Figure 3.12. Net Present Value of Mitigation Costs from 2010 to 2050 from Seven Different Models. The measures presented are the total mitigation costs for 50% and 80% reductions in carbon emissions. Results suggest that total mitigation costs across pessimistic and optimistic technology assumptions (see Table 3.6, p. 161) are $1 trillion to $2 trillion (US$ 2005) for 50% reductions in GHG emissions and $1 trillion to $4 trillion (US$ 2005) for 80% reductions in GHG emissions. Among the caveats to these analyses, each of the models has different capabilities to calculate underlying metrics, so an assessment of costs generally must include different metrics across models, and these results do not include economy-wide impacts from the assumptions. Key: NPV, net present value; Pess., pessimistic; CCS, carbon capture and storage; Nuc, nuclear, Ren, renewables; Tech, technology; EERE, end-use energy and renewable energy; Opt., optimistic. [Figure source: Redrawn from Clarke et al., 2014, used with permission of *The Energy Journal*, conveyed through Copyright Clearance Center Inc.]

technology and produce the 80% reduction scenarios without nuclear and CCS, relying exclusively on renewable energy and end-use measures under different policy assumptions (Clarke et al., 2014). As in all other studies mentioned thus far, the EMF24 project confirms that mitigation at the 50% or 80% level will require a dramatic transformation of the energy system over the next 40 years.

Estimates from the EMF24 study indicate that the total mitigation costs of achieving 80% emissions reductions fall between $1 trillion and $4 trillion (US$ 2005) for most of the 80% emissions reduction scenarios through 2050, although one outlying model found costs as high as $6 trillion (US$ 2005) (Clarke et al., 2014; see Figure 3.12, this page). In the EMF24 study, not all models were able to report the same cost metrics due to structural differences, so the costs reported for each model reflect different ways of handling, such as the value of leisure time and costs associated with reduced service demands. A thorough description of the differences among these metrics can be found in Fawcett et al. (2014a).

Taken together, the Pew and EMF24 U.S. scenario analyses reveal three important conclusions: 1) the cumulative costs of mitigation for achieving an 80% emissions reduction (relative to 2005 levels) by 2050 fall between $1 trillion and $4 trillion (US$ 2005); 2) investment decisions today, especially those that support key technologies, will have a significant impact on North American energy-related carbon emissions tomorrow; and 3) a portfolio of policies

combining technology performance targets, market incentives, and price-oriented measures can help the United States meet complementary energy security and climate protection goals.

In summary, the differing exploratory scenarios provide a wide range of futures. All emphasize the importance of policy and technology development in guiding the world (see also IEA 2017c) and North America into a future of stable economic growth, global energy security, and reduced emissions. The finding that significant future emissions reductions require policy is further supported by the work of Shahiduzzaman and Layton (2017), who suggest that for the United States to achieve the 2025 target emissions levels, which are in line with the 2°C future world, the combined average annual mitigating contribution from energy efficiency, carbon intensity, and energy improvements will need to be at least 33% higher and as much as 42% higher than current trends portend, depending on the level of structure change in the U.S. economy.

3.8.3 Energy and Carbon Emissions Backcasting Scenarios

The third type of scenario includes normative, transformation studies. Typically, these scenarios start with the end state and work backwards, hence the name "backcasting" (Lovins 1977; Robinson 1982). Backcasting can be implemented in a large variety of ways (Quist 2007; Quist et al., 2011), although methods typically involve two steps: 1) development of desirable images of the future (visions) and 2) backwards analysis of how these visions can be realized (Höjer and Mattsson 2000; Quist 2013; Robinson 1988). Among the many advantages of employing backcasting is its capability to calculate the cost of investments, such as energy infrastructure, necessary to achieve the visionary future. Backcasting scenarios address the question, *what would need to happen to achieve a specific end state?* (Quist 2013).

A number of new backcasting studies examine "deep decarbonization" futures, which refer to the reduction of GHG emissions over time to a level consistent with limiting global warming to 2°C or less. There is extensive development of global-scale energy-environment modeling for this purpose (for a brief review, see Fawcett et al., 2014b). More recently, a body of literature also has emerged on scenario pathways consistent with a 1.5°C world (Kriegler et al., 2018; Millar et al., 2017; Rogelj et al., 2015, 2018; Su et al., 2017). There also are a significant number of studies arguing that it is possible for the United States, and the world, to significantly reduce carbon emissions by 2050 (Delucchi and Jacobson 2011; Fthenakis et al., 2009; IPCC 2011; Jacobson and Delucchi 2011; Jacobson et al., 2015; MacDonald et al., 2016; NREL 2012; Mai et al., 2014).[18] This chapter focuses on a select number of studies in North American economies with visions of a 2°C future using multiple technologies. These scenarios include those from 1) the Deep Decarbonization Pathways Project (2015; DDPP); and 2) the White House (2016) *Mid-Century Strategy* report.

The DDPP is a collaborative global initiative of the United Nations Sustainable Development Solutions Network (UNSDSN) and Institute for Sustainable Development and International Relations (IDDRI). Each of the 16 countries participating in the project explores how an individual nation can transform its energy systems by 2050 to limit the anthropogenic increase in global mean surface temperature to less than 2°C. Deep decarbonization pathways focus on a wide range of important actions, although three appear most important to the energy system: 1) high energy efficiencies across all sectors; 2) electrification wherever possible, with nearly complete decarbonization of the electricity system; and 3) reduced carbon in other kinds of fuels (Deep Decarbonization Pathways Project 2015). Included in this review are scenarios from Canada, Mexico, and the United States, each of which is engaged in its own scenario exercises and that are not official governmental exercises.

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[18] A debate has emerged in this literature concerning the portfolio of clean energy technologies and energy carriers necessary for the transformation (see for example, Clack et al., 2017).

The Canadian DDPP examines major shifts in technology adoption, energy use, and economic structure that are consistent with continued economic and population growth and a nearly 90% reduction in national GHG emissions from 2010 levels by 2050 (Bataille et al., 2014, 2015). In the reference case, national emissions are relatively stable over the forecast period, reaching 201 Tg C in 2050 (181.6 Tg C of energy emissions) with the net impact of higher oil prices and a production increase of 13 Tg C (7%) by 2050. The Canadian deep decarbonization pathway achieves an overall GHG emissions reduction of nearly 90% (178 Tg C) from 2010 levels by 2050, while maintaining strong economic growth. Over this period, GDP rises from $1.26 trillion to $3.81 trillion (US$ 2010), a tripling of Canada's economy. The reduction in emissions is driven most significantly by a reduction in the carbon intensity of energy use, as renewables and biomass become the dominant energy sources and there is broad fuel switching across the economy toward electricity and biofuels. Electricity production nearly completely decarbonizes. Overall, the carbon intensity of Canada's total primary energy supply declines by 90% between 2010 and 2050. This result is robust across different technology scenarios. For example, if biofuels are not viable, transportation could transition to increased use of electricity generated with renewables and fossil fuels with CCS, especially if better batteries become available. If CCS processes are not available, the electricity sector could decarbonize using more renewables and nuclear. End-use energy consumption rises by only 17% over this period, compared to a 203% increase in GDP. This difference is due both to structural changes in the economy and to increases in energy efficiency.

The costs of these transformations include significant restructuring of energy investments. The study found that overall incremental investment increases by around $13.2 billion (CAD$ 2014) annually (8% increase relative to historic levels), but this average increase hides sectoral differences. Consumers spend $3.0 billion (CAD$ 2014) less each year on durable goods like refrigerators, cars, appliances, and houses, while firms must spend $16.2 billion (CAD$ 2014) more. Approximately $13.5 billion (CAD$ 2014) of costs are in the electricity sector (+89% over historical levels), by far the most important shift, and $2.9 billion (CAD$ 2014) are in the fossil fuel extraction sector for the adoption of advanced low-emissions technologies such as CCS, solvent extraction, and direct-contact steam generation (+6% over historical levels) (Bataille et al., 2015).

For Mexico, the future analysis was to provide preliminary deep decarbonization routes to determine whether there are general conclusions that can be drawn at an aggregate level. The scenarios sought economic development that is low–carbon, rather than unconditional decarbonization. Therefore, Mexico's deep decarbonization project aimed to reduce GHG emissions to 50% below 2000 levels by 2050 (a target of approximately 71 Tg C), in accordance with the target set by the General Climate Change Law of 2012. The reference scenario used by the project, based on current trends and well-informed assumptions of future activity for the main drivers of CO_2 emissions, predicted emissions could reach 246 Tg C by 2050. The central deep decarbonization scenario suggests that total CO_2 emissions could reach 68.2 Tg C by 2050, including fugitive and process emissions (a 51% decline from 2000 levels), largely induced by declines in energy intensity of 59% and declines in CO_2 intensity of 66%. Final energy consumption in 2050 reaches 8.1 EJ, 35% less than in the reference trajectory, although it is an increase of 38% compared with the 2010 levels of 5.9 EJ. Costs of the transformation were not calculated. These reductions were plausible under certain assumptions, such as accelerated increases in energy-efficiency uptake across all sectors; rapid development and deployment of CCS; zero-emissions vehicles; energy-storage technologies; smart transmission and distribution (smart grids); and system flexibility to promote, adopt, and combine diverse options over the time frame of decarbonization (Tovilla and Buira 2015[eds.]).

For the U.S. DDPP, the vision is to achieve an 80% GHG reduction below 1990 levels by 2050,

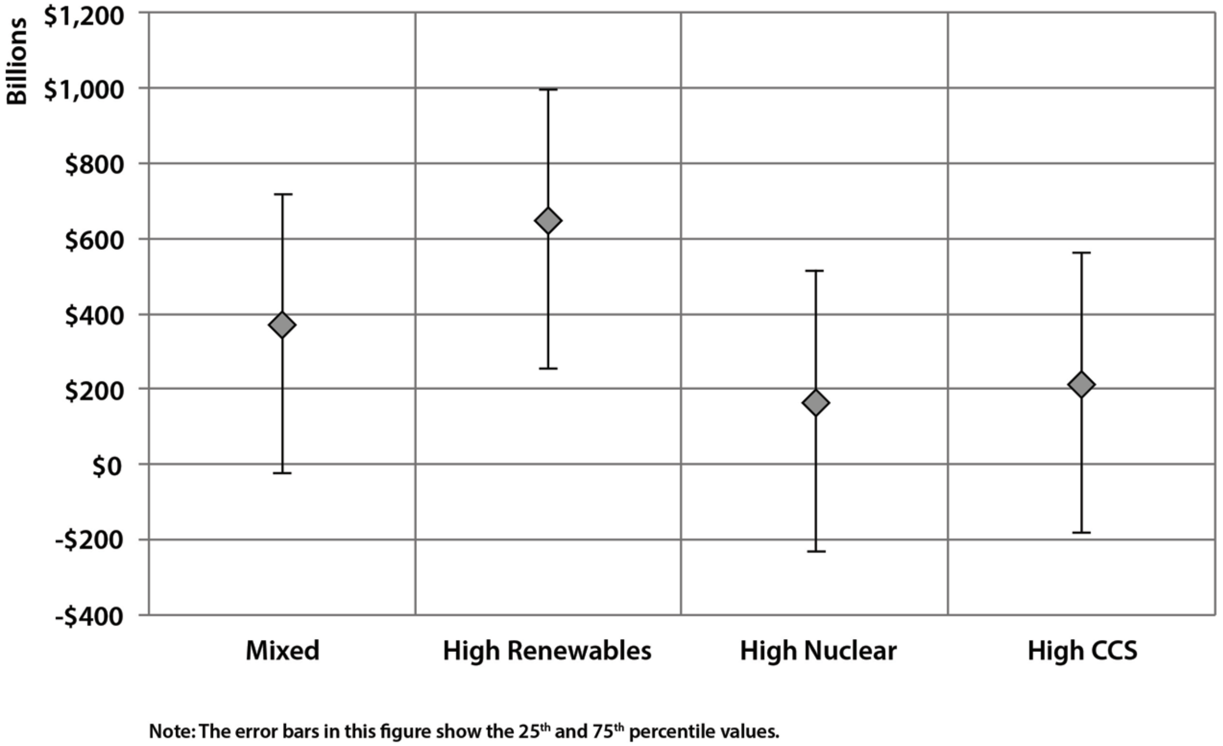

Figure 3.13. Incremental Energy System Costs in 2050. Error bars show the 25% and 75% values. Key: CCS, carbon capture and storage. [Figure source: Redrawn from Williams et al., 2014, used with permission.]

and DDPP uses multiple pathways to achieve these reductions through existing commercial or near-commercial technologies (Williams et al., 2014, 2015). The three pillars of decarbonization across all pathways are high-efficiency end use of energy in buildings, transportation, and industry; nearly complete decarbonization of electricity; and reduced carbon in fuels and electricity production. Pathways were named "High renewables," "High nuclear," "High carbon capture and storage," and "Mixed," based on the dominant strategy used for energy generation and carbon mitigation. The goal of the pathways was to reduce total GHG emissions from a net of around 1,470 Tg C and energy emissions of 1,390 Tg C to overall net GHG emissions of no more than 300 Tg C and fossil fuel combustion emissions of no more than 205 Tg C. To achieve this outcome, the vision includes a reduction of petroleum consumption by 76% to 91% by 2050 across all scenarios. The study finds that all scenarios met the target, demonstrating robustness by showing the existence of redundant technology pathways to deep decarbonization.

The costs of the transformation include incremental energy system costs (i.e., incremental capital costs plus net energy costs). These are defined by costs of producing, distributing, and consuming energy in a decarbonized energy system relative to that of a reference case system based on the EIA (2013c) report as a metric to assess the costs of deep reductions in energy-related CO_2 emissions. Based on an uncertainty analysis of key cost parameters in the four analyzed cases, the 25% to 75% range extends from negative $90 billion to $730 billion (US$ 2012) in 2050 (see Figure 3.13, this page). The median costs value is just over $300 billion (US$ 2012). This median estimate of net energy system costs is 0.8% of U.S. GDP in 2050, with a 50% probability of costs falling between –0.2% and 1.8% of GDP. Uncertainty in costs is due to assumptions about consumption

levels, technology costs, and fossil fuel prices nearly 40 years into the future. The higher end of the probability distribution (75% estimate of $730 billion) assumes little to no technology innovation over the next four decades. The overall costs of deeply decarbonizing the energy system is dominated by the incremental capital cost of low-carbon technologies in power generation, light- and heavy-duty vehicles, building the energy system, and industrial equipment. The U.S. DDPP result of total mitigation costs of $1 trillion to $2 trillion through 2050 is consistent with the EMF24 study (Williams et al., 2015).

The report suggests that the transition to a deeply decarbonized society would not require major changes in individual energy use because the scenarios were developed to support the same level of energy services and economic growth as the references case of EIA (2013c). For example, Americans would not be required to use bicycles in lieu of cars, eat purely vegetarian diets, or wear sweaters to reduce home heating loads (Williams et al., 2015).

The aforementioned White House (2016) *Mid-Century Strategy* (MCS) report charts pathways for the United States consistent with a reduction of 80% or more (relative to 2005 levels) by 2050. The MCS goal reduces annual emissions from around 1,609 Tg C in 2005 to 410 Tg C in 2050. The ensemble of scenarios used differs in regard to the reliance on key low-carbon technologies and decarbonization strategies. Three sets of MCS scenarios are 1) "MCS benchmark," which assumes continued innovation spurred by decarbonization policies and current levels of RD&D funding; 2) "Negative emissions," two alternative scenarios that explore the implications of achieving different levels of negative emissions such as no CO_2 removal technology and limited sink scenarios; and 3) "Energy technology," which comprises three scenarios that explore challenges and opportunities associated with the low-carbon energy transition: no CCS, smart growth, and limited biomass scenarios.

The study findings suggest that by 2050 energy efficiency can reduce primary energy use by over 20% from 2005 levels and that nearly all fossil fuel electricity production can be replaced by low-carbon technologies, including renewables, nuclear, and fossil fuels or bioenergy combined with CCS. Furthermore, the study argues that there are opportunities to expand electrification into the transportation, industrial, and buildings sectors, reducing their direct fossil fuel use by 63%, 55%, and 58%, respectively, from 2005 to 2050. Reaching the MCS goal requires a substantial shift in resources away from GHG-intensive activities, including increasing annual average investments in electricity-generating capacity to between 0.4% and 0.6% of U.S. GDP.

In summary, the backcasting exercises for North America and the United States suggest that reaching a goal of 80% reductions in GHG emissions (relative to 2005 levels) is plausible, although achieving the goal will require both policies and technological advances. The incremental cost of mitigation for the United States was identified as between 0.4% to 0.8% of annual GDP (Williams et al., 2014) and an annual incremental cost of $13.2 billion (CAD$ 2014) for Canada. The final numbers are comparable with the $1.5 trillion to $2.0 trillion costs identified by the Edison Electric Institute (2008) for infrastructure investments necessary to 2030 for upgrading the electricity system.

There are significant caveats to these results. Previously mentioned mitigation costs do not include direct benefits (e.g., avoidance of infrastructure damage) and co-benefits (e.g., avoided human health impacts from air pollution) of emissions reductions. These benefits and co-benefits can be substantial. For example, U.S. EPA (2015a, 2017b) estimated some of the benefits and co-benefits of climate mitigation through 2100 for the United States. In their most recent report (U.S. EPA 2017b), the agency examined 22 issue areas across the human health, infrastructure, electricity, water resources, agriculture, and ecosystems sectors. Annual cost estimates for these sectors due to climate change during the year 2050 were $170 billion and $206 billion (US$ 2015) under Representative Concentration Pathway (RCP) 4.5 and RCP8.5 conditions, respectively. By 2100, costs in these sectors due to climate change were estimated at $356 billion and $513 billion

annually (US$ 2015) under RCP4.5 and RCP8.5 conditions, respectively (U.S. EPA 2017a).

The benefits and co-benefits of mitigation may be even larger than estimated. U.S. EPA (2017b) noted that its report estimates did not include some health effects (e.g., mortality due to extreme events other than heat waves, food safety and nutrition, and mental health and behavioral outcomes); effects on ecosystems (e.g., changes in marine fisheries, impacts on specialty crops and livestock, and species migration and distribution); and social impacts (e.g., national security and violence). Other estimates at the global scale, include damages (in terms of reduced consumption) from business-as-usual scenarios (resulting in up to a 4°C warming by 2100) that range from 1% to 5% of the global GDP, incurred every year (Norhaus 2013). Costs may be even higher if temperatures continue to rise, with potential reductions of 23% of global incomes and widening global income inequality by 2100 (Burke et al., 2015a).

Additionally, the costs to mitigate may be lower than reported depending on when they appear. For example, in some studies, the majority of energy mitigation costs are incurred after 2030, as deployment of low-carbon infrastructure expands. Technology improvements and market transformation over the next decades, however, could significantly reduce these expected costs. Also important, as mentioned previously in this report, is that CO_2 removal technologies such as CCS; carbon capture, utilization, and storage (CCUS); and BECCS are not currently deployed at scale, as many of the listed scenarios mentioned. Nuclear power expansion, as envisioned in some scenarios, also faces technical and political challenges (see Box 3.2, Potential for Nuclear Power in North America, p. 120).

The changing climate also may affect energy supply and use in a variety of ways, and adapting to these changes will create future North American energy systems that differ from those of today in uncertain ways (Dell et al., 2014). While the trajectories from the outlined scenarios are "plausible," whether any of them are "feasible" depends on a number of subjective assessments such as whether Canada, Mexico, and the United States at this time or any time in the future would be willing to make the necessary transformations and how future climate change will transform both opportunities and risks (Clarke et al., 2014; Dell et al., 2014).

3.9 Synthesis, Knowledge Gaps, and Key Challenges

The North American energy system is a net source of carbon emissions to the atmosphere. Recently, however, this system has undergone dramatic changes. Since 2007, energy use and CO_2e emissions have decreased despite population and GDP per capita increases. This decrease accompanied a regional transition to greater reliance on natural gas energy sources and an increase in deployed renewable energy capacity. Early in the economic recession of 2007 to 2008, most of the decreases in energy use and CO_2e emissions were due to changes in behavior, including a slowdown in the consumption of goods and services. However, post-recession, a number of other factors have emerged that have kept emissions levels low. Growing energy efficiency and changes in regional carbon intensity were observed across all energy sectors, facilitated by new technologies and changes in the fuel mixture, particularly the increase in natural gas and renewables and the decrease in coal for electricity production, as well as industrial processes and a variety of lower carbon–intensity technologies. These dynamics have been influenced by relative changes in the price of fuels, slow growth in electricity demand, the growing importance of electricity demand for electronics, and a history of policies that promoted technology development for energy efficiency and clean energy. In Mexico, the recent *Reforma Energética* and strong leadership on environmental issues underpin energy restructuring that is prompting changes in energy use, energy intensity, and that nation's fuel mix. Across North America, state and subnational governments are increasingly involved in carbon management decisions. The result of all

these influences has been a decline in CO_2e emissions and a restructuring of the North American energy system.

Whether this trend will continue depends on both the continuation of energy system change and energy and economic policies. Furthermore, despite the decrease in GHG emissions experienced over the recent past and the recent decoupling of emissions from economic growth, all studies suggest that further efforts are needed to meet the 2°C trajectory and that these added reductions can come about only with policy intervention. Key methods for lowering carbon emissions from the North American energy system include 1) increasing energy efficiency across all sectors; 2) upgrading, modernizing, and standardizing the aging energy infrastructure; 3) reducing the use of carbon-intensive fuels and technologies; 4) transitioning to low-carbon energy sources and further developing scalable carbon sink technologies; and 5) generating public acceptance and policy effectiveness for decarbonization, whether at the national or subnational levels. In general, whether the current patterns in energy use and carbon emissions will follow historical trends and rebound to higher levels than 2007 by the early 2020s, or whether the restructuring of the energy system currently underway will be enough to change the energy use and CO_2e emissions pathways, remains an open question. Notwithstanding these uncertainties, studies suggest policy change and infrastructure investment across a wide variety of technologies can put the North American energy system on a 2°C trajectory by 2050 (80% reduction in emissions relative to 2005 levels). The costs of energy system changes in the United States are estimated to be around $1 trillion to $4 trillion by 2050, with this investment offsetting some or all of expected costs without mitigation of approximately US$170 billion and $206 billion (US$ 2015) annually by 2050.

Much is already understood about the North American energy system and its role in the carbon cycle, but significant knowledge gaps remain. Most importantly, four areas stand out that need further examination and research. First, the governance and institutional needs in the transition to a low-carbon society are not well understood. As identified herein, studies have examined the potential costs of mitigation, but much more detail is needed on the governance structures and institutions required to support navigation through the future energy transition. Second, the potential feedbacks associated with changes in the energy system in combination with climate change, exogenous and endogenous system changes, and the impacts of those feedbacks on the energy system are not clear. Third, studies have identified the potential extent of CH_4 emissions from natural gas extraction and use, putting into question the role of natural gas as a “bridge fuel.” Also, the amount of gas that escapes as leakage and fugitive emissions has yet to be measured accurately. The effectiveness of policies that increase energy efficiencies, reduce carbon intensity, and reduce emissions, while also maintaining social benefits such as environmental equity and economic growth, needs to be more fully documented. Finally, detailed comparable data for end-use energy, emissions, and projections across North American economies have yet to be compiled, and, as noted, end-use data across economies differ due to a number of factors, and thus better data could help inform evidenced-based regional policies regarding carbon management.

The North American energy system, although varied across economies, has developed into a vast, complex infrastructure and set of institutional arrangements that have consistently provided for the economic growth and well-being of the regional population. Yet, the workings of this system contribute significantly to the carbon cycle. This system may be able to continue to provide the reliable and consistent energy demanded by increasing regional activities with decreasing contributions of CO_2e to the atmosphere in the near future. Research suggests that the emissions-level targets that secure populations from predicted impacts of climate change and the potential impacts of energy system internal change cannot be met in the absence of policy drivers.

SUPPORTING EVIDENCE

KEY FINDING 1

In 2013, primary energy use in North America exceeded 125 exajoules (EJ), of which Canada was responsible for 11.9%, Mexico 6.5%, and the United States 81.6%. Of total primary energy sources, approximately 81% was from fossil fuels, which contributed to carbon dioxide equivalent (CO_2e) emissions levels, exceeding 1.76 petagrams of carbon, or about 20% of the global total for energy-related activities. Of these emissions, coal accounted for 28%, oil 44%, and natural gas 28% (*very high confidence, likely*).

Description of evidence base

Data on energy use are collected by the U.S. Department of Energy's (U.S. DOE) Energy Information Administration (EIA) and the Organisation for Economic Cooperation and Development's (OECD) International Energy Agency (IEA). Data for CO_2e were accessed from a number of sources, including the EIA, IEA, U.S. DOE Carbon Dioxide Information Analysis Center (CDIAC) database (Boden et al., 2016), and the World Resources Institute (WRI) CAIT database (cait.wri.org). All data suggest similar trends, although the exact values differ.

Major uncertainties

These datasets include uncertainties related to the amount of fossil fuel used (i.e., typically identified through sales-weighted averages to create a national average) and the carbon and heat contents of the energy reserve (e.g., U.S. EPA 2017a). According to the literature, there are further uncertainties related to lost and fugitive emissions (Alvarez et al., 2012; Brandt et al., 2014; Karion et al., 2013; Pétron et al., 2014; Zavala-Araiza et al., 2015). Estimates of fugitive methane (CH_4) levels indicate that these emissions are unlikely to substantially alter Key Finding 1 (Alvarez et al., 2012; Brandt et al., 2014). Fugitive CH_4 from oil, gas, and coal production and transportation is included in the U.S. Environmental Protection Agency (U.S. EPA), U.S. DOE, Canadian, and Mexican inventories, but there may be further emissions not yet accounted. Furthermore, while the trends are consistent across data sources, the absolute values of greenhouse gas (GHG) emissions levels from energy consumption and production vary across datasets because of differences in system boundary definitions, inclusion of industrial process emissions, emissions factors applied, and other issues.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

There is very high confidence in the likelihood that the statement is based on consistent findings across the literature.

Summary sentence or paragraph that integrates the above information

For Key Finding 1, there is incontrovertible evidence that North American energy use and CO_2e emissions have dropped over the past 10 years, specifically since 2007.

KEY FINDING 2

North American energy-related CO_2e emissions have declined at an average rate of about 1% per year, or about 19.4 teragrams CO_2e, from 2003 to 2014 (*very high confidence*).

Description of evidence base

Data on CO_2e emissions are calculated by the EIA, IEA, and CDIAC databases (Boden et al., 2016) and by the WRI CAIT database (*cait.wri.org*). All data suggest similar trends, although the exact values differ. Key Finding 2 is consistent across these sources.

Major uncertainties

These datasets include uncertainties related to the amount of fossil fuel used (typically identified through sales-weighted averages to create a national average) and the carbon and heat contents of the energy reserve (e.g., see U.S. EPA 2017a, Annex 2). According to the literature, there are further uncertainties related to lost and fugitive emissions (Alvarez et al., 2012; Brandt et al., 2014; Karion et al., 2013; Pétron et al., 2014; Zavala-Araiza et al., 2015). Estimates of fugitive CH_4 levels indicate that these emissions are unlikely to substantially alter Key Finding 2 (Alvarez et al., 2012; Brandt et al., 2014). Fugitive CH_4 from oil, gas, and coal production and transportation is included in U.S EPA and DOE and Canadian and Mexican inventories, but there may be further emissions that are not yet accounted. For U.S. DOE, fugitive emissions include the unintended leaks of gas from the processing, transmission, and transportation of fossil fuels. Furthermore, while the trends are consistent across data sources, the absolute values of GHG emissions levels from energy consumption and production vary across datasets because of differences in system boundary definitions, inclusion of industrial process emissions, emissions factors applied, and other issues.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

There is very high confidence in the likelihood that the statement is based on consistent findings across the data sources assessed.

Estimated likelihood of impact or consequence, including short description of basis of estimate

It is not appropriate to reflect on the likelihood of impacts of these trends without longer time series demonstrating that North American and international energy and industrial GHG emissions continue to decline. The total effect of energy and industrial GHG emissions on atmospheric GHG concentrations and climate change depends on total international emissions and future GHG emissions trajectories.

Summary sentence or paragraph that integrates the above information

Key Finding 2 that North American energy and industrial GHG emissions have declined since 2007 is supported by multiple datasets, with total uncertainty surrounding fugitive CH_4 and various emissions calculation approaches unlikely to alter this finding.

KEY FINDING 3

The shifts in North American energy use and CO_2e emissions have been driven by factors such as 1) lower energy use, initially as a response to the global financial crisis of 2007 to 2008 (*high confidence, very likely*); but increasingly due to 2) greater energy efficiency, which has reduced the regional energy intensity of economic production by about 1.5% annually from 2004 to 2013, enabling economic growth while lowering energy CO_2e emissions. Energy intensity has fallen annually by 1.6% in the United States and 1.5% in Canada (*very high confidence, very likely*). Futher factors driving lower carbon intensities include 3) increased renewable energy production (up 220 petajoules [PJ] annually from 2004 to 2013, translating to an 11% annual average increase in renewables) (*high confidence, very likely*); 4) a shift to natural gas from coal sources for industrial and electricity production (*high confidence, likely*); and 5) a wide range of new technologies, including, for example, alternative fuel vehicles (*high confidence, likely*).

Description of evidence base

Over the past decade, Key Finding 3 found that annual energy intensity dropped 1.5% in Canada, 0.04% in Mexico, and 1.6% in the United States. In the United States, gross domestic product (GDP) has grown by more than 10% from 2008 to 2015, while fossil fuel combustion CO_2 emissions declined 6% from 2008 to 2014. Canada's GDP grew by 11% from 2008 to 2015, while its energy-related CO_2 emissions grew roughly 2% from 2008 to 2014. In Mexico, GDP grew 15% between 2008 and 2015, and energy-related CO_2 emissions remained relatively flat, with a 0.3% decrease from 2008 to 2014 (IEA 2016a; IMF 2016).

Economic structural changes have contributed to some of this decline, with more of North American manufacturing occurring overseas, especially in East Asian countries. From 2004 to 2014, the United States exhibited net offshoring every year except for 2011 (Kearney 2015). More recently, there were reports of reshoring to the United States, although there is uncertainty in whether this will exceed or even break even with continued offshoring (Sirkin et al., 2011; Tate 2014). Today, a trend of nearshoring is projected as manufacturing costs in China rise and companies move their operations to Mexico (Kitroeff 2016; Priddle and Snavely 2015).

North American renewable energy production has increased over the past 10 years. For electricity, nonhydropower renewables, including wind, solar, and biomass, have increased from 2.4% in 2004 to 6.1% in 2013. This translates into a 10.6% annual average increase, adding approximately 220 PJ of renewable energy into the North American electricity system annually (EIA 2016c).

A large portion of Canada's 80% of nonfossil power generation comes from hydropower, while in the United States and Mexico nonfossil power contributes 32% and 22%, respectively, largely from nuclear. In total, carbon-free power sources contribute 38% of North American energy generation (EIA 2016c).

Major uncertainties

As with other contributing factors to energy and industrial emissions reductions, there is some uncertainty regarding the contribution of reduced energy intensity to emissions reductions. Kotchen and Mansur (2016) estimate reduced energy intensity contributed 6% of U.S. emissions reductions from 2007 to 2013.

The largest uncertainty surrounds the trajectory of carbon-free energy deployment in North America, which likely will depend heavily on policies that continue to incentivize lower-carbon forms of energy relative to fossil fuels. The declining cost of renewable and nonfossil technologies have made them cost-competitive with fossil fuels in some but not all regions of North America, and the future trajectories of technology cost reductions also are uncertain and dependent on public and private investment in research, development, and demonstration.

Although renewable energy deployment has been recognized as a contributing factor to GHG emissions reductions in North America, the precise scale of influence has been debated. The global financial crisis and natural gas deployment are likely to have had a larger effect than renewable energy in reducing North American energy emissions during 2007 to 2009 (Feng et al., 2015; Gold 2013; U.S. DOE 2015a), but, subsequently, changes in the energy system (including the increase in renewable energy and decrease in energy intensities) have helped to continue the trend.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

There is very high confidence in the finding based on the results of official data.

Estimated likelihood of impact or consequence, including short description of basis of estimate

Reductions in the energy intensity of economic output are very likely to be based on structural economic changes that will have lasting effects in reducing the GHG emissions from economic growth. The exception is whether "reshoring" occurs (i.e., the transfer of a business operation that had moved overseas or out of its originating country back to the country where it was originally relocated).

Increasing renewable and nuclear energy technology deployment is likely to continue based on existing and planned policies in North American countries, as well as market and technology cost trends. Increasing deployment of these technologies would have significant impacts on energy and industrial GHG emissions.

Summary sentence or paragraph that integrates the above information

In Key Finding 3, reduced energy intensity of economic output in North America is allowing for reduced energy-related GHG emissions even as the three North American economies recover from the 2007 to 2008 recession. These trends very likely reflect structural economic changes that would have a lasting effect on energy-related GHG emissions into the future and may represent a departure from the typical rebounding cycles experienced previously.

Although still a relatively small share of its energy mix, North America increased renewable energy production by about 220 PJ annually from 2004 to 2013, translating to a 10.6% annual average increase. In 2013, nonhydropower renewable fuels reached 3.25 EJ but accounted for about 6.1% of total electricity generation. Hydropower and nonfossil nuclear power sources remain the most important low-carbon energy generators, accounting for 31.7% of total electricity generation.

Renewable energy and nuclear energy technologies are a small but growing portion of the North American energy sector and are likely to have an ongoing effect in reducing energy and industrial emissions if policy, market, and technology trends hold.

KEY FINDING 4

A wide range of plausible futures exists for the North American energy system in regard to carbon emissions. Forecasts to 2040, based on current policies and technologies, suggest a range of carbon emissions levels from an increase of over 10% to a decrease of over 14% (from 2015 carbon emissions levels). Exploratory and backcasting approaches suggest that the North American energy system emissions will not decrease by more than 13% (compared with 2015 levels) without both technological advances and changes in policy. For the United States, however, decreases in emissions could plausibly meet a national contribution to a global pathway consistent with a target of warming to 2°C at a cumulative cost of $1 trillion to $4 trillion (US$ 2005).

Description of evidence base

Key Finding 4 is based on results from three different types of energy scenarios, including five projections (United States from EIA, Canada from Environment and Climate Change Canada, Mexico from IEA, and private firms BP and ExxonMobil); exploratory scenarios from Royal Dutch Shell, the World Energy Council, and the Pew Center on Global Climate Change; and backcasting scenarios from the Deep Decarbonization Pathways Project (for the United States, Canada, and Mexico), the Energy Modeling Forum (i.e., includes approximately nine different modeling groups), and the U.S. government. The statement on mitigation costs ("US$107 and $206 billion (US$ 2015) annually") is from the findings of a report by U.S. EPA (2017b).

Major uncertainties

There are significant incalculable uncertainties for futures studies. Therefore, no certainties, qualitative or quantitative, have been provided.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

With high confidence, the literature that forecasts carbon trajectories agrees generally with the outcome of the review provided.

Estimated likelihood of impact or consequence, including short description of basis of estimate

The provision of future studies is for decision making. The scenario data provide enough information for a discussion of how to mitigate carbon emissions.

Summary sentence or paragraph that integrates the above information

There are a variety of carbon futures for the North American energy system. They include higher and much lower emissions levels, depending on both current trends and potential future uses of technologies. Importantly, achieving significantly lower emissions in the near future will depend on policy, without which it will not be achieved.

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