

Canadian Climate Policy and its Implications for Electricity Grids

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Executive Summary

Along with many western developed countries, Canada has pledged to reduce its greenhouse gas emissions by 40–45 percent by 2030 from 2005 emissions levels, and to achieve Net Zero emissions by 2050. This is a huge challenge that, when considered on a global scale, will do little to stop climate change because emissions by developing countries are rising faster than emissions are being reduced in developed countries. Even so, the potential for achieving emissions reduction targets is extremely challenging as there are questions as to how and whether targets can be met and at what cost. Because electricity can be produced from any source of energy, including wind, solar, geothermal, tidal, and any combustible material, climate change policies have focused especially on nations' electricity grids.

Canada's electricity grid consists of ten separate provincial grids that are weakly connected by transmission interties to adjacent grids and, in some cases, to electricity systems in the United States. At times, these interties are helpful in addressing small imbalances between electricity supply and demand so as to prevent brownouts or even blackouts, and are a source of export revenue for provinces that have abundant hydroelectricity, such as British Columbia, Manitoba, and Quebec. Due to generally low intertie capacities between provinces, electricity trade is generally a very small proportion of total generation. Essentially, provincial grids are stand alone, generating electricity to meet domestic demand (known as load) from the lowest cost local resources.

Because climate change policies have focused on electricity (*viz.*, wind and solar energy, electric vehicles), this study employs information from the Alberta electricity system to provide an estimate of the possible costs of reducing national CO₂ emissions related to power generation. The Alberta system serves as an excellent case study for examining the potential for eliminating fossil-fuel generation because of its large coal fleet, favourable solar irradiance, exceptional wind regimes, and potential for utilizing BC's reservoirs for storage. Using a model of the Alberta electricity system, we find that it is infeasible to rely solely on renewable sources of energy for 100 percent of power generation—the costs are prohibitive. Under perfect conditions, however, CO₂ emissions from the Alberta grid can be reduced by 26 to 40 percent by eliminating coal and replacing it with wind, solar, and gas, but by more than 75 percent if nuclear power is permitted. The associated costs are estimated to be some \$1.4 billion per year to reduce emissions by at most 40 percent, or \$1.9 billion annually to reduce emissions by 75 percent or more using nuclear power (an option not considered feasible at this time). Based on cost estimates from Alberta, and Ontario's experience with subsidies to renewable energy, the costs of relying on changes to electricity generation (essentially eliminating coal and replacing it with renewable energy sources and gas) to reduce national CO₂ emissions by about 7.4 percent range from some \$16.8 to \$33.7 billion annually. This constitutes some 1–2 percent of Canada's GDP.

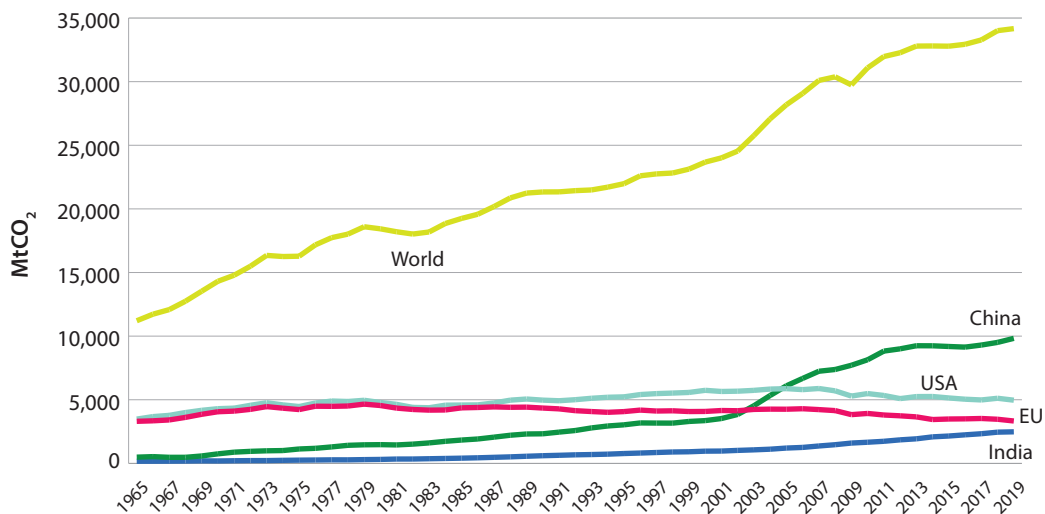
The national estimates provided here are conservative, however. They are based on removing coal-fired power from power grids throughout Canada. We could not account for scenarios where the scale of intermittency turned out worse than indicated in our dataset—available wind and solar energy might be lower than indicated by the available data. To take this into account, a reserve market is required, but the costs of operating such a capacity market were not included in the estimates provided in this study. Also ignored are the costs associated with the value of land in other alternative uses, the need for added transmission lines, environmental and human health costs, and the life-cycle costs of using intermittent renewable sources of energy, including costs related to the disposal of hazardous wastes from solar panels and wind turbines.

1. Introduction

Aside from addressing the Covid-19 pandemic, the Biden administration in the United States sees mitigation of climate change as its central task. Because climate change is impacted by global emissions of greenhouse gases (measured in CO₂ equivalents and hereafter simply referred to as CO₂), mitigation would require an unprecedented level of international cooperation that would be extremely difficult and likely impossible to achieve. At the very least, the major emitters need to fall in line, or else anything the US and European countries do to reduce emissions is undone within a few years by increases in China, India, Brazil, Russia, and Africa (**figure 1**). This is the policy environment facing the western developed countries wishing to stop or at least slow global warming.

There had been growing pressure on the Canadian government to increase its Paris target commitments. President Biden convened a climate summit on April 22 and 23, 2021, that included some 30 of 40 invited heads of state. The purpose was to lobby them to increase their climate mitigation efforts as required under the 2015 Paris Agreement. The President committed the US to reduce CO₂ emissions by 50 to 52 percent by 2030 from the base year 2005, and to make the electricity grid carbon neutral by 2035 (White House Briefing Room, 2021). For its part, the Canadian government pledged to reduce its domestic CO₂ emissions by 40 to 45 percent by 2030 compared to 2005, which is more ambitious than its previous target of a 30 percent reduction by 2030 (Newburger, 2021).

Figure 1: CO₂ Emissions by Major Emitters and Global, 1965–2019



Source: BP Statistical Review of World Energy, June 2020.

At the same summit, Japan committed to reduce its CO₂ emissions by 46 percent by 2030 compared to 2013 emissions, although emissions in 2019 were only 12.5 percent below those of 2013 and Japan is expanding coal generating capacity to make up for lost nuclear capacity. India renewed its commitment to install 450 gigawatts (GW) of renewable electricity generating capacity by 2030, while Brazil requested \$1 billion from the Biden administration to protect the Amazon rainforest (Newburger, 2021). Prior to the Biden climate summit, the EU announced that, compared to 1990 CO₂ emissions, it would reduce emissions by 55 percent by 2030, while the UK would reduce them by 78 percent by 2035; in addition, Poland committed to eliminate coal-generated power by 2049 (BBC, 2021a; European Commission, 2021).

Under the 1997 Kyoto Protocol, Canada had agreed to reduce its CO₂ emissions by 6 percent from 1990, but, as seen in [table 1](#), emissions in 2019 exceeded those of 1990 by 27 percent, while they exceeded base-year 2005 emissions by 2 percent. In contrast, US emissions in 2019 were some 15 percent below those in 2005, and about the same as in 1990. US emissions have fallen largely due to a switch from coal to natural gas, because fracking had increased the supply of gas and thus considerably reduced its price relative to coal. Meanwhile, Canadian emissions increased as a result of expanded activity in the oilsands, with energy production in Alberta and elsewhere now accounting for about one-quarter of Canada's total greenhouse gas emissions.^[1]

Table 1: Current (2019) CO₂ emissions in major jurisdictions and changes in emissions from base years 1990 and 2005

	EU	USA	UK	China	India	Japan	Canada	Russia	World
2019 emissions (Mt CO ₂)	3,330.4	4,964.7	387.1	9,825.8	2,480.4	1,123.1	556.2	1,532.6	34,169.0
% of global emissions	9.7%	14.5%	1.1%	28.8%	7.3%	3.3%	1.6%	4.5%	100.0%
<i>Change in 2019 emissions compared to those in:</i>									
1990	-23%	0.0%	-35%	+323%	+312%	+3%	+27%	-31%	+60%
2005	-22%	-16%	-33%	+61%	+106%	-14%	+2%	+5%	+21%

Source: BP Statistical Review of World Energy, June 2020.

Current Canadian climate policy will be determined by the *Canadian Net-Zero Emissions Accountability Act*, which was passed on June 29, 2021. ^[2] The Act commits Canada to achieving net-zero emissions by 2050, which implies that any CO₂ emissions at that time would need to be offset through forestry activities (e.g., tree planting) or

[1] Domestic emissions include those required to mine and export fossil fuels, including petroleum from oilsands, although emissions from burning those fuels is charged to the importing country.

[2] See <<https://www.parl.ca/LegisInfo/BillDetails.aspx?Mode=1&billId=10959361&Language=E>>.

carbon capture and storage (CCS), which is an unproven and expensive technology. [3] While forestry activities do sequester carbon, they cannot be relied upon to soak up left-over emissions, mainly due to the potential degradation of forests and an accompanying release of CO₂. Recognizing this, Canada's Nationally Determined Commitment under the Paris Agreement excludes any emissions related to wildfire or other natural disturbance (e.g., insect infestations). Meanwhile, a CCS unit can capture no more than 85 to 95 percent of the CO₂ that is produced by a thermoelectric plant, and will require some 10 to 40 percent parasitic energy (required to “scrub out” the carbon and move it to a disposal site) along with large amounts of additional fresh water (see Eldardiry and Habib, 2018).

While, according to a government report, the oil and gas industry faces a precarious future, the electricity sector will also need to be overhauled (Canadian Institute for Climate Choices, 2021: 62–68). Indeed, much discussion and most policies are directed at the electricity generation sector even though it accounts for only one-quarter of global emissions. [4] Policymakers believe that the least-cost emission reductions—the “low-hanging” benefits—are found in this sector, because electricity can be generated from any energy source, especially wind, solar, tidal, geothermal, and other non-carbon emitting sources; the latter includes nuclear power because it emits no CO₂, and hydroelectric generation, which is considered a renewable energy source. Further, because electricity systems are much more centralized from an industrial organization perspective as compared with other energy systems, governments can more easily target the electricity sector. However, government policies to increase CSS, reduce reliance on oil and natural gas for heating, and promote electric vehicles will lead to large increases in load. [5]

Fossil fuel generation of electricity will almost need to be eliminated, with any remaining such generation offset through forestry activities and CCS. Assuming there is no appetite for nuclear energy or the construction of hydroelectric dams on major rivers (viz., objections to BC's construction of Site C), the electricity sector will need to rely almost exclusively on non-hydro renewable sources of generation, meaning intermittent wind and

[3] See <<https://www.canada.ca/en/services/environment/weather/climatechange/climate-plan/climate-plan-overview.html>>. During parliamentary debate, defenders of what was then Bill C-12 indicated Canada could meet non-zero emissions as a “moon shot”, reflecting the US effort to put a man on the moon. The moon shot was more realistic than “net zero”, because most of the required technology was already in place, whereas many net zero technologies do not currently exist and may never be brought to realization because of inherent physical limitations and potentially exorbitant costs.

[4] See <<https://www.epa.gov/ghgemissions/global-greenhouse-gas-emissions-data>>. Forestry and land use account for 24 percent of global emissions, industry 21 percent, transportation 14 percent, buildings 6 percent, and other sources for the remainder.

[5] Electric vehicles (EVs) come with their own problems: they weigh about double that of a same-model vehicle with an internal combustion engine, need a long time to recharge the battery, production requires many rare earth and other minerals that are environmentally costly to access, and their manufacture relies excessively on China which has cornered the market for cobalt, an essential input (Hume, 2021; IEA, 2021a).

solar power with limited biomass. [6] Intermittent sources of electricity generation require backup from fast-responding generating assets, such as gas turbines or diesel assets, and/or from storage. Storage can take several forms—hydroelectric reservoirs and utility-scale batteries are the only realistic sources of storage as compressed air and flywheels are not truly up to this task. Pumped hydro has the potential to enhance storage, but it too is expensive in parasitic energy while suitable sites are not readily found. One study concluded that: “The round trip efficiencies for [electric energy storage] systems have been calculated as between 83% and 86%, falling to between 41% and 69% where parasitic loads are included” (Baker et al., 2014: 41; see also Lazard, 2020a). Alternatively, electricity produced by intermittent sources when it is not needed can perhaps be used to produce hydrogen for use as fuel.

The purpose in this paper is to examine Canada’s electricity grid in greater detail to determine the potential for eventually eliminating CO₂ emissions from the production of electricity, perhaps by 2035 and certainly by 2050, and provide some notion of the potential costs. Before doing so, we provide a broad brush overview of Canada’s energy needs and greenhouse gas emissions.

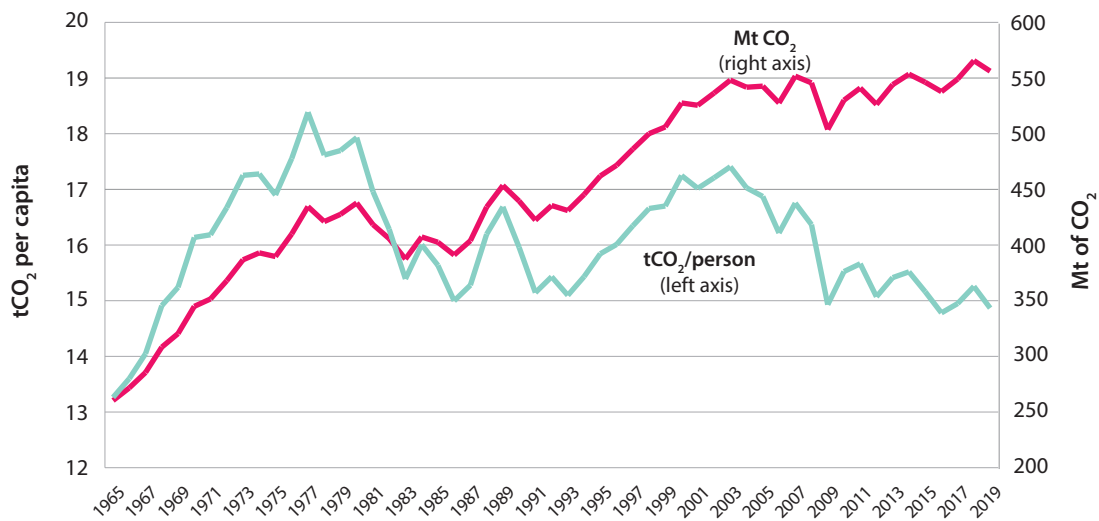
[6] Activists in the US are lobbying to remove CCS and nuclear energy from Biden’s arsenal for achieving zero emissions for the electricity sector by 2035 (Smith, 2021).

2. Canadian Energy and Carbon Dioxide Emissions

Background

We begin by examining how greenhouse gas emissions and overall energy use have changed over time in Canada. This enables us to consider the potential for reducing emissions and our reliance on fossil fuels more broadly. As indicated in **figure 2**, carbon dioxide emissions have risen steadily since 1965, although more dramatically from the mid-1980s to 2009, after the onset of the financial crisis. Much of the rise in emissions might be attributable to oilsands development as investments in the oilsands had a positive impact on the overall growth of the national economy. In 1965, per-capita emissions were slightly more than 13 tCO₂ per person, surging to more than 18 tCO₂ by 1980. Per-capita emissions remained well above 16 tCO₂ throughout much of the 1990s and into the new millennium. Emissions slowly began to decline after the financial crisis so they were slightly below 15 tCO₂ per capita by 2019. Currently, per-capita emissions remain above what they were in 1965; with a doubling of the population from 19.6 million in 1965 to 38.1 million today, it is not surprising that Canadian emissions have increased overall.

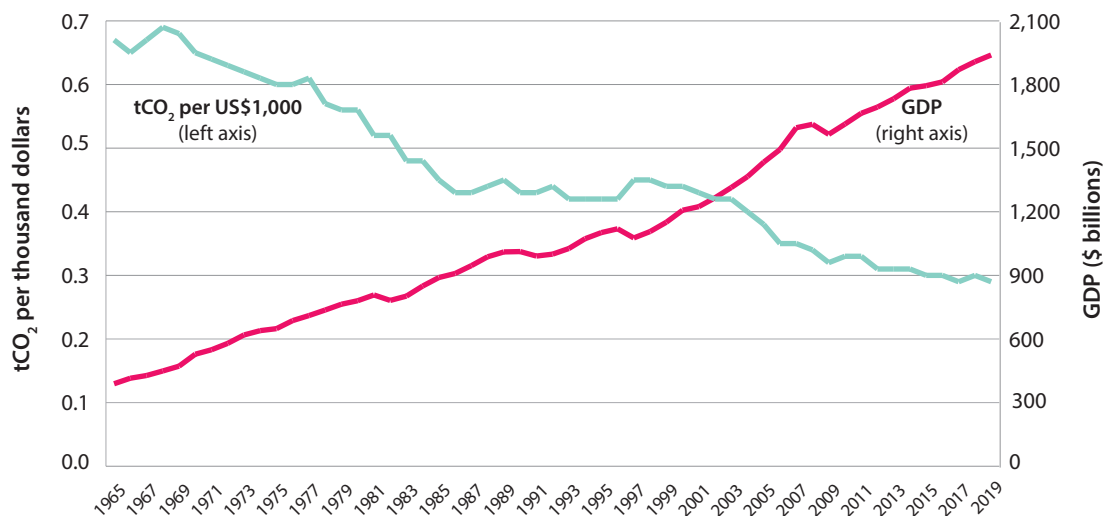
Figure 2: Total CO₂ Emissions and Emissions Per Capita, Canada, 1965–2019



Sources: Author's calculations based on data from BP Statistical Review of World Energy, June 2020, and World Bank (2021).

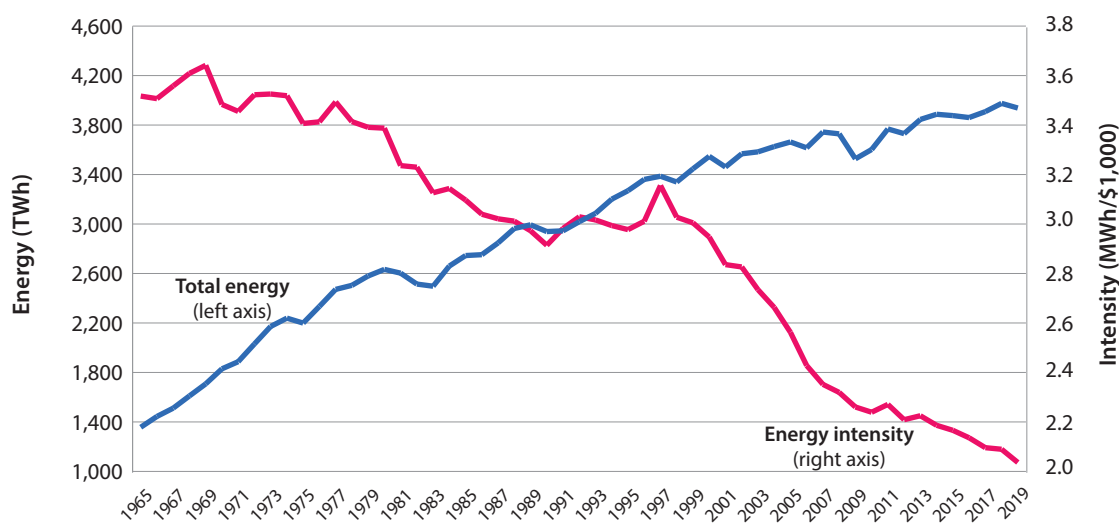
Meanwhile, emissions of CO₂ per \$1,000 of GDP fell from 0.67 tCO₂/\$1,000 in 1965 to 0.29 tCO₂/\$1,000 in 2019. The path of emissions intensity is provided in **figure 3**, which also gives the time path for GDP. This is not to be confused with energy intensity, which relates energy (measured in tons of oil equivalent or terawatt hours, TWh) to GDP, although the two measures are related (see below). Canada is among the (mostly poorer) countries with the highest energy intensity; Canada's energy intensity exceeds the global average and that of China but is below that of our large northern neighbour, Russia. Primary energy consumption in Canada increased by nearly 290 percent between 1965 and 2019, or at an annual rate of 1.98 percent. However, because real GDP increased by nearly 500 percent, or at an annual average rate of 3.02 percent, the energy required per dollar of GDP fell from 3.517 megawatt hours (MWh) per thousand dollars of real GDP to 2.036 MWh/\$1,000, or at an annual rate of about 1.0 percent (**figure 4**).

Figure 3: GDP in Constant 2010 US Dollars and CO₂ Emissions Per Thousand Dollars of GDP, Canada, 1965–2019



Sources: Author's calculations based on data from BP Statistical Review of World Energy, June 2020 and World Bank (2021).

Figure 4: Total Energy (TWh) and Energy Intensity (MWh per thousand constant 2010 USD), Canada, 1965–2019

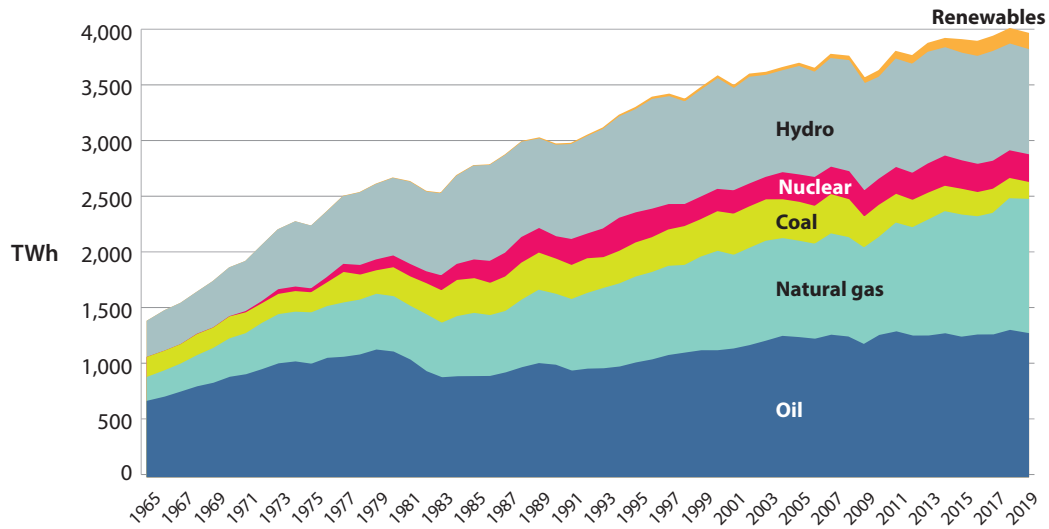


Sources: Author's calculations based on data from BP Statistical Review of World Energy, June 2020 and World Bank (2021).

Oil constituted the dominant primary source of energy in Canada over the period 1965–2019 (figure 5). Reliance on oil fell from 47 percent of primary energy consumption in 1965 to 30 percent in 1993, and remained at this proportion until the present (figure 6). From figure 5, we also see that the share of coal in primary energy fell from 13 percent in 1965 to 4 percent in 2019—coal now contributes little to Canada's energy needs and its elimination will have little impact in achieving the country's emissions-reduction targets. The importance of natural gas for heating and electricity generation rose from 15.8 percent of primary energy consumption in 1965 to 30.5 percent today, more than compensating for lost coal. Meanwhile, reliance on hydroelectric power rose from 24 percent in 1965 to 31 percent in 1985–1987, before slowly falling back to 24 percent by 2019. [7] Finally, non-hydro sources of renewable energy (termed “renewables” in figure 5) were essentially non-existent prior to the late 1970s, after which they slowly increased to nearly 4 percent of the primary energy mix in 2019; non-hydro renewable energy use had been increasing at an average annual rate of 6.7 percent since about 1980, but has slowed to 4.6 percent since 2015.

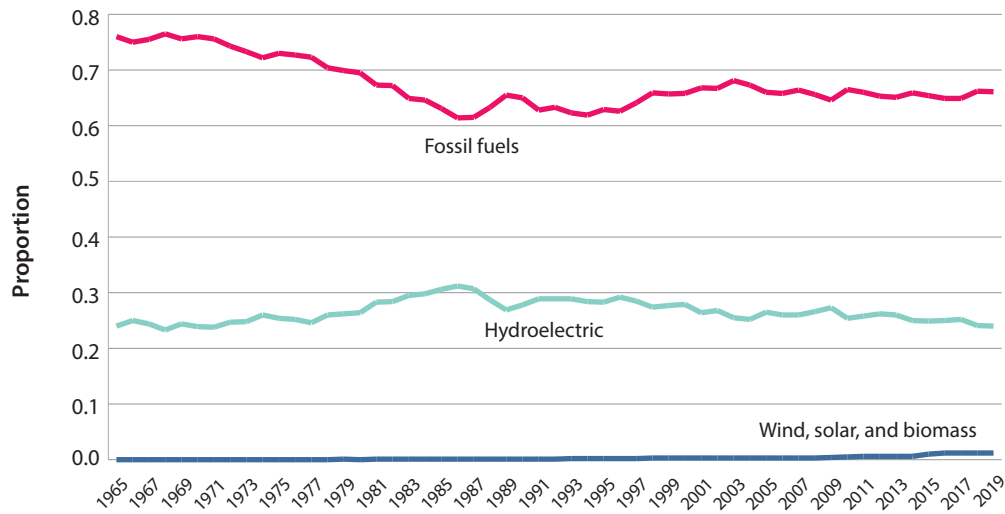
[7] It is important to note that BP Statistical Review of World Energy of June 2020 provides hydroelectric generation, equating it to consumption. However, Canada exports a significant proportion of its electricity to the US, although electricity still averaged 20 to 21 percent of domestic primary consumption during the 2000s.

Figure 5: Primary Energy Consumption in Canada by Source, 1965–2019



Source: BP Statistical Review of World Energy, June 2020.

Figure 6: Proportion of Total Primary Energy Accounted for by Various Energy Sources, Canada, 1965–2019



Source: BP Statistical Review of World Energy, June 2020.

Figures 1 through 6 are indicative of the challenge facing policymakers. Reliance on CO₂-emitting fossil fuels has changed little since the mid-1990s; while primary energy consumption has risen, consumption of fossil fuels has gone up at about the same rate. Consumption of coal has fallen somewhat, replaced primarily by natural gas; however, as an energy source, coal was never as important to the Canadian economy as it currently is in many countries, including the US, China, Russia, India, and even Germany. Rather, hydraulic energy has been an important component of Canada's primary energy mix, with nuclear energy playing an important but small role (accounting for 6.0 to 6.5 percent of total primary energy). While emissions intensity (tCO₂ per \$1,000 GDP) and energy intensity (MWh per \$1,000 GDP) have fallen at a relatively rapid pace, emissions and energy use have continued to increase, while emissions per capita have remained relatively constant over the past several decades. Population increase and economic activity, particularly related to the oilsands, are upward trends that will not be easily reversed.

Kaya Identity

A model for considering climate mitigation policy is the Kaya Identity, which is named after the Japanese economist Yoichi Kaya (Kaya and Yokobori, 1997)—

$$C = N \times Y/N \times E/Y \times C/E$$

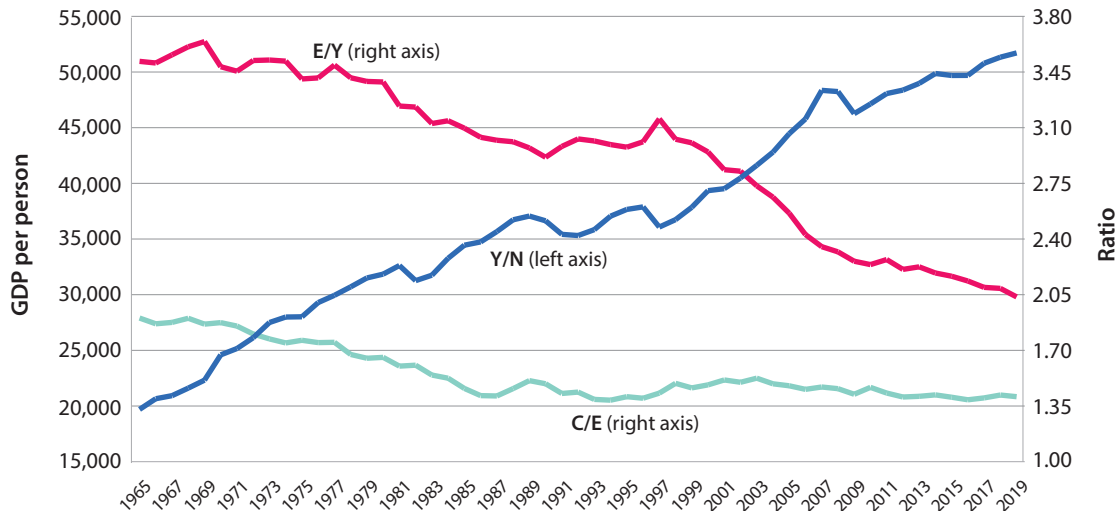
—where *C* refers to carbon emissions (measured in terms of CO₂), *N* is population, *Y* is gross domestic product (GDP), and *E* is total energy consumption. The first term on the right hand side of the identity is population, the second term is per-capita GDP (denoted *Y/N*), the third term is the *energy intensity of the economy* and the final term is the *carbon intensity of energy*. The three ratios are provided in figure 7.

The Kaya Identity indicates that there are only a limited number of ways to reduce emissions of CO₂:

- Manage population;
- Limit the generation of wealth (reduce GDP);
- Generate the same or a higher level of GDP with less energy;
- Generate energy with less CO₂ emissions; or
- Some combination of the first four factors.

Although not shown in figure 7, population has been rising at an annual rate of about 1.20 percent between 1965 and 2019, thereby nearly doubling over this period. Meanwhile, output per person has been increasing at an annual rate of 1.80 percent, while energy intensity and carbon intensity have fallen at rates of 1.02 and 0.56 percent per year, respectively. These trends have resulted in an increase in average annual CO₂ emissions of 1.42 percent.

Figure 7: Elements of the Kaya Identity: Per-Capita GDP, Y/N (left axis); Energy Intensity of Economy in MWh per \$1,000, E/Y (right axis); and Carbon Intensity of Energy in $10 \times tCO_2$ per MWh, C/E (right axis); Canada, 1965–2019



Sources: Author's calculations based on data from BP Statistical Review of World Energy, June 2020 and World Bank (2021).

Targeting Emissions Reduction

As indicated in the Introduction, Canada has agreed to reduce CO_2 emissions by 40–45 percent by 2030 from 2005 baseline emissions. In 2005, greenhouse gas emissions amounted to 542.7 Mt CO_2 equivalent compared to 556.2 Mt CO_2 in 2019, an increase of nearly 2.5 percent. Based on the lower target, emissions will need to be reduced to 325.6 Mt CO_2 by 2030, implying that emissions will need to fall by an average of 21 Mt CO_2 per year from 2019 (for a total reduction of 230.6 Mt CO_2), or at an annual rate of decline of 4.99 percent.

Assume that population growth stagnates (i.e., no net immigration) and there is no increase in GDP (so Y/N remains unchanged). Even under these assumptions, the energy intensity of the economy and carbon intensity of energy have to fall much faster than previously. Energy intensity (E/Y) will need to decline at an average annual rate of 3.22 percent rather than 1.02 percent, and carbon intensity (C/E) will need to be reduced at an annual rate of 1.77 percent rather than 0.56 percent. Given that we are already two years beyond 2019, these rates will have to be even higher, especially if Canada wishes to attain the higher level of mitigation—the 45 percent target for emissions reduction. However, when we relax our earlier assumptions and recognize that population and GDP will in fact continue to grow in Canada over the coming decades, the emissions targets will be that much more difficult to achieve.

To achieve emission reduction targets and, eventually, net zero carbon emissions, the consensus is that how we use energy will need to change dramatically. All energy will be produced as electricity, with electricity used to produce hydrogen that, in turn,

can support energy needs related to sectors that cannot possibly use electricity directly, such as air travel. It is thus necessary to electrify space heating, manufacturing, vehicles, and any other non-electrical uses of energy. Further, it will be necessary to remove all fossil fuel generation sources from the electricity grid. Is such a goal attainable? Is it even possible to reduce the electricity grid's reliance on fossil fuels by one-quarter? Is it even possible to lower the level of CO₂ emissions from power production by 40 percent by 2030? If so, what might it cost? These issues are addressed in Section 4.

3. An Overview of Canada's Electricity Grids

Before we consider some technical aspects of power generation and the costs of producing electricity, we examine the structure of the electricity grid—the assets that generate the electricity that we consume and how effective investments in renewable energy (mainly wind) sources have been in reducing our reliance on fossil fuels.

Structure of Canada's Electricity Grid: How Far Must We Go?

Each province has its own electricity grid and electricity system operator (ESO), with links between provinces and with the United States limited by the capacity of transmission interties. For example, Alberta and British Columbia currently have transmission interties that have the physical capacity to allow Alberta to import up to 1,000 MW from BC or export up to 1,200 MW to its neighbour. These amounts are comparable to a large coal-fired power plant. The potential role of transmission interties in achieving “net zero” is discussed further below.

In **table 2**, we provide the installed nameplate capacity of Canada's electricity generating sector. Hydro accounts for some 55.6 percent of total capacity, followed by natural gas with 11.6 percent, coal and oil (mainly diesel in remote areas) with 10.8 percent, and wind and solar with 10.1 percent. However, the nameplate capacity is a poor indicator of a generator's ability to deliver electricity at any given time or over a period of time. The performance of a generator on this score depends on its capacity factor. The capacity factor (CF) is calculated as the actual output (measured in MWh) of a generating asset over a period, say one year, divided by the nameplate capacity of the asset multiplied by the number of hours in the period (8,760 hours in a non-leap year).

Hydro capacity is influenced by the level of water in the reservoir, or, in the case of run-of-river assets, by the flow of water at any given time. As the water level drops or river flow diminishes, the capacity of a hydroelectric generator drops, as does its capacity factor. Likewise, the nameplate capacity of wind and solar assets might be quite high, but such intermittent assets are rarely capable of producing at or even near capacity—they are dependent on wind speed or solar irradiance, which is affected by clouds and the time of day. Average capacity factors of wind turbines rarely exceed about 40 percent, although they could be much higher at some sites and/or for short periods of time.

To get some idea of the actual impact that various assets might have in contributing to or reducing CO₂ emissions, we need to consider power generation and not only capacity. This is done for Canada in **figure 8**, which provides actual monthly generation by various fuel sources over the period 2008 to 2017. Total amounts represent the load that faces the system operators, and it varies significantly from one month to the next throughout the year. Hydro is the main source of electricity in Canada, while non-renewable

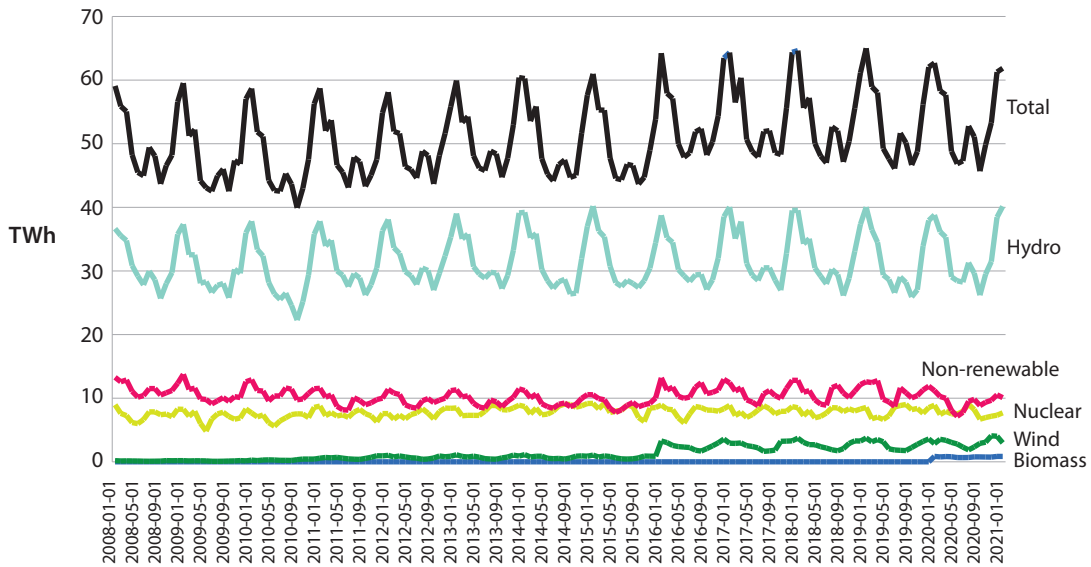
Table 2: Installed Generating Capacity by Energy Source, Canada and Region, 2017 (MW)

Region	Coal	Oil	Natural gas	Other fuel*	Hydro	Wind	Solar*	TOTAL
BC		44	578	922	15,407	714		17,665
Alberta	6,277	34	5,809	531	1,218	1,524	2	15,395
Saskatchewan	1,688	14	1,852		867	221		4,642
Manitoba	100	12	412	44	5,461	258		6,288
Ontario		2,277	7,379	1,010	9,122	5,077	2,296	40,489
Quebec		589	618	292	40,438	3,432		45,369
Maritimes	1,571	2,822	229	340	8,099	1,166	20	14,953
Canada North		232		20	151	10		413
TOTAL	9,636	6,018	16,904	3,139	80,764	12,403	2,318	145,214
% of total capacity	6.6%	4.1%	11.6%	2.2%	55.6%	8.5%	1.6%	100.0%
% of generation	9.2%	0.5%	9.6%	16.9%	58.6%	4.7%	0.5%	100.0%

Notes: "Other fuel" includes primarily nuclear (9.6 percent of total capacity, 14.6 percent of total generation) and wood biomass (1.8 percent of capacity, 2.0 percent of generation). "Solar" includes 20 MW of tidal capacity in Nova Scotia.

Sources: Statistics Canada, 2021b, 2021c; calculations by author.

Figure 8: Monthly Generation by Source, January 2008 through January 2021



Source: Statistics Canada, 2021a.

fossil-fuel sources (coal, natural gas, diesel) play only a minor role in the production of electricity. Even a smaller role is played by non-hydro renewable energy sources—biomass hardly shows up on the graph, while wind plays only a slightly more important role. Indeed, the most prominent non-CO₂ emitting source of energy outside of hydro is nuclear energy, which exceeds the sum of wind, solar and biomass generation and is almost as important as fossil-fuel (non-renewable) sources in producing power. The point is simply this: investments in renewable energy have had little effect to date on actual power generation in Canada as a whole.

Because provincial electricity grids are not well integrated (only transmission interties with limited capacities exist between provinces), it is important to examine provincial grids to obtain some notion of the challenge Canada faces in reducing emissions. British Columbia, Manitoba, Quebec, and Newfoundland and Labrador rely heavily on hydroelectric generation; graphs of monthly generation by source are provided for two of these provinces in figure 9, namely BC and Quebec. Natural gas and some diesel are used to produce electricity in BC, as are biomass (mainly from sawmill residuals) and wind; fossil-fuel generation has declined slightly in the last few years as wind and biomass have increased. However, the power generated from non-hydro sources is extremely small (**figure 9a**), with hydro tracking changes in load—acting as both a baseload and peak load asset, roles usually performed by combined-cycle and simple cycle gas, respectively.

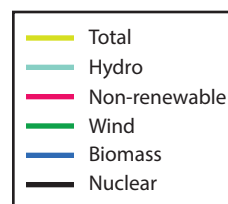
The role of hydroelectric power in Quebec is even starker—until 2016, the entire load was pretty well satisfied by hydro (**figure 9b**)—although much hydroelectric power is exported to the US. After 2016, some wind and more biomass energy (again from sawmill residues) contributed small amounts to the electricity grid.

The situation in Alberta and Ontario (as well as Saskatchewan and the Maritimes) is somewhat different from that of BC or Quebec. Alberta relies almost exclusively on fossil fuels to meet its electricity requirements, while Ontario relies on a mix of nuclear and hydro sources, with fossil fuels and renewable sources playing a minor role (**figure 10a, 10b**). Both Alberta and Ontario have seen increases in wind-generated power as well as small increases in biomass; Alberta also generates some hydroelectricity. Despite large subsidies to wind and solar energy as a result of Ontario's *Green Energy and Green Economy Act* (May 2009), only 8.8 percent of the province's electricity production in January 2021 came from renewable sources (including biomass); subsidies are estimated to cost \$2.4–\$2.6 billion annually to be paid by taxpayers, ratepayers, or some combination of these (van Kooten, 2013b). This compares with renewable sources of 13.0 percent in Alberta, 9.0 percent in BC, 3.6 percent in Quebec, and 6.3 percent for Canada as a whole. While the Alberta government did not provide subsidies for wind (or solar), although it indirectly provides a subsidy by building transmission capacity for such renewables, [8] private investment in wind capacity increased as a result of the province's excellent wind regimes, particularly in the southwestern part of the province where capacity factors can exceed 70 percent for short periods (van Kooten et al., 2016).

[8] Bryce (2021) provides an excellent overview of the costs of building transmission capacity, as well as the gathering opposition against the construction of further transmission lines.

Figure 9: Monthly Generation by Source, January 2008 through January 2021, Two Provinces that Depend on Hydroelectric Power for most of their Electricity Production

Legend for Figures 9, 10



Source: Statistics Canada, 2021a.

Figure 9a: British Columbia

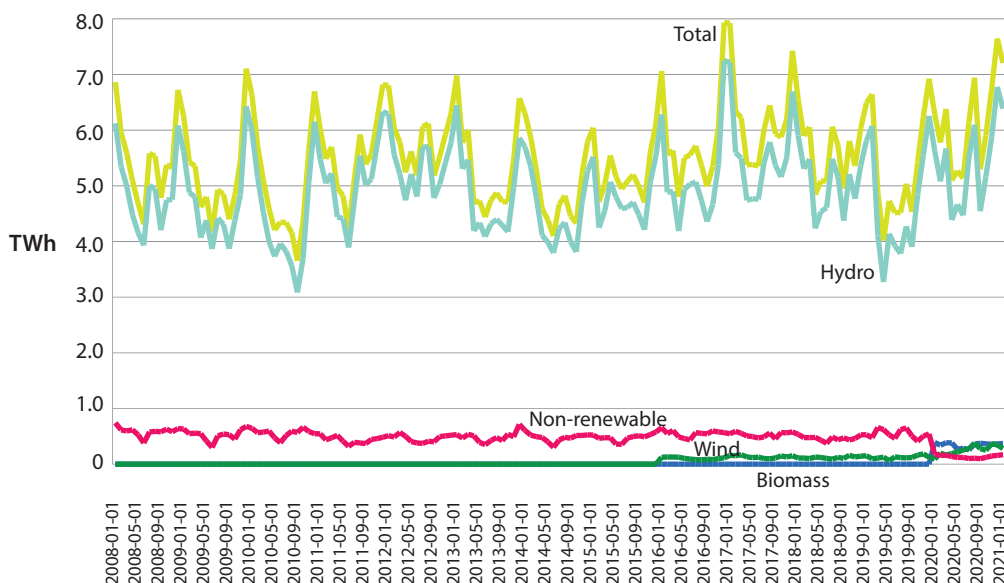


Figure 9b: Quebec

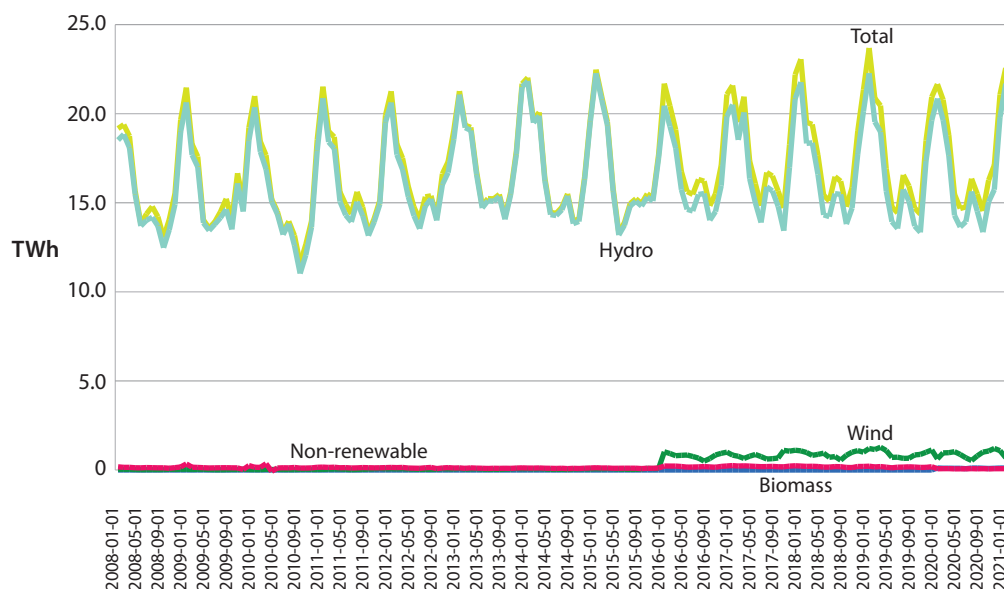


Figure 10: Monthly Generation by Source, January 2008 through January 2021, Two Provinces that Depend on Electricity Generated by Fossil Fuels (Alberta) and Nuclear Power (Ontario)

Source: Statistics Canada, 2021a.

Figure 10a: Alberta

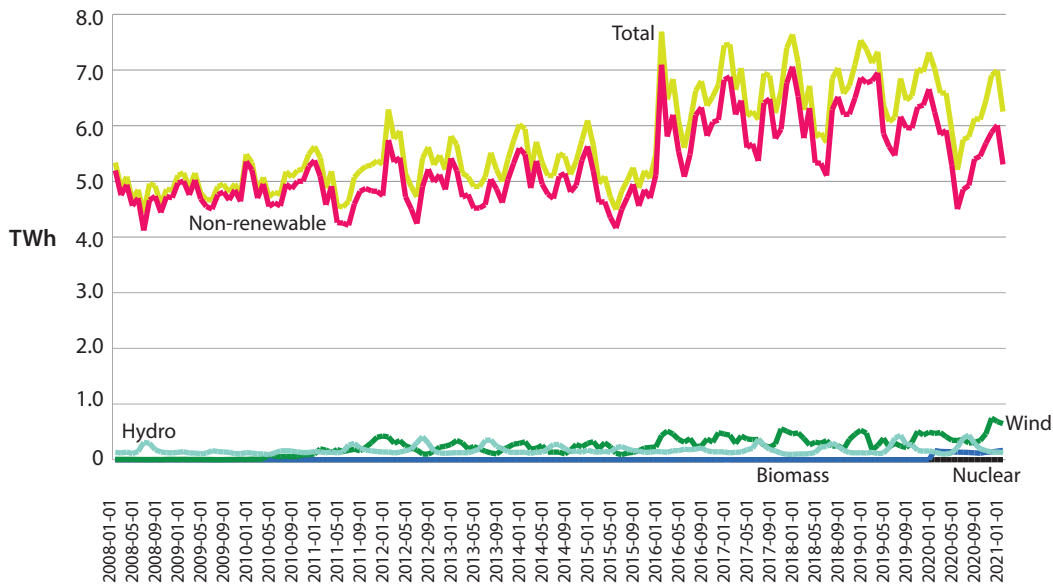
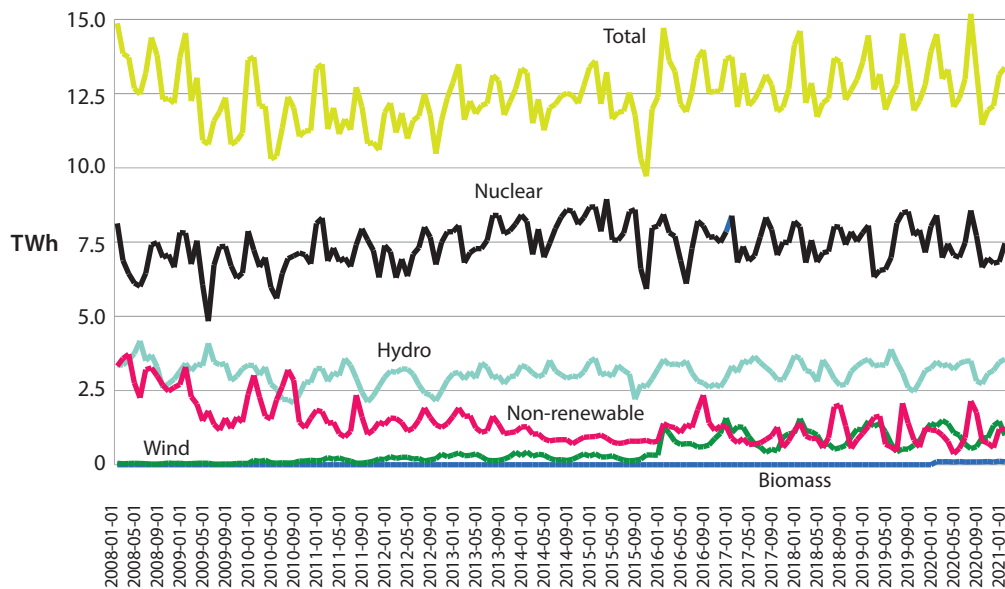


Figure 10b: Ontario



Inter-Provincial Electricity Trade and Transmission Interties

Trade of electricity between provinces is limited by capacity constraints. As noted earlier, there is an intertie rated at 1,200 MW capacity between Alberta and BC. Alberta also has an intertie with Saskatchewan rated at 150 MW and another with the US rated at 300 MW. In 2016, after 14 years as a net importer, Alberta exported more electricity to BC (556 GWh) than it imported (283 GWh) from BC; the reason was low pool prices in Alberta that resulted in reduced imports and higher exports (Mascarenhas, 2017). However, Alberta gross exports only accounted for a miniscule 0.5 percent of the province's total generation in 2016.

Alberta may sell electricity to BC at night to prevent baseload coal or combined-cycle gas turbine (CC-gas) assets from ramping too rapidly, thereby avoiding related costs of ramping down in late evening and up again in the morning. [9] Likewise, as wind capacity increases, more wind power generated at night will be sold to BC. At other times, the Alberta Electric System Operator (AESO) might purchase electricity from BC to meet peak load demand, paying a higher price than what it sells electricity for at night. As Alberta installs greater wind (and solar) generating capacity, BC hydro reservoirs provide a good storage option for intermittent wind and/or excess baseload power that is not needed at the time of generation (as discussed in the Introduction). [10] As a result, whether Alberta is a net exporter or importer, the rents associated with storage accrue mainly to BC due to the price differentials between nighttime and daytime power. Upgrading the transmission intertie will be very expensive but it will increase available rents from trade, although any investments in greater intertie capacity will require an agreement as to how the provinces intend to share the rents.

Alberta also trades electricity with the US via a dedicated 300 MW-capacity intertie (perhaps built to avoid sales of excess power to BC), or by wheeling power through southeastern BC into the US. It also trades electricity with Saskatchewan, although the capacity of the intertie is rather small. These interties serve a purpose, but cannot be relied upon to balance electricity to take advantage of large-scale investments in intermittent sources of energy because their capacity is limited.

Likewise, there is trade between Quebec and Ontario, with the latter a net importer. Imports occur along three interties with a total rated capacity of 2,115 MW, although exports can occur along an additional three interties with a total rated capacity of 530

[9] Albertans heat their homes with natural gas, so electricity demand does not rise on cold winter nights. The Alberta system can ramp at a rate of 300 MW per hour, or by about 2.5 percent per hour, compared to a hydro-dominated system that might ramp by this rate in 10 minutes or less.

[10] Reliance on passive storage of this kind could potentially lead to increased costs of producing hydroelectricity if wind generated power fluctuates too rapidly and erratically. Water must be allowed to flow past the turbine to allow the over production of wind with large hydro schemes, or the energy has to be shunted away from and then back to generator blades to act as a rapid follower. Unless there is greater vigilance in maintaining turbines, this could degrade turbine components, potentially leading to an accident such as experienced at the Sayano-Shushenskaya hydroelectric dam in Russia in August 2009 (Hasler, 2010).

MW. In 2016, Ontario imported some 3.5 TWh of electricity from Quebec, representing just over 1 percent of its total generation; in addition, Quebec “wheeled” some 3.5 TWh through Ontario into the US, paying fees to Ontario for using its transmission interties (Independent Electricity System Operator, 2017). Nonetheless, much like Alberta and for similar reasons, there are times when Ontario exported more power to Quebec than it imported. However, again as in Alberta, the intertie capacities are too small to balance electricity as required to backstop large intermittent sources of energy.

4. Challenges and Costs of Generating Electricity from Renewables

Commentators are nearly unanimous in arguing that wind and solar sources of electricity are much cheaper than any fossil fuel or nuclear alternatives. The costs to which they refer are either the levelized costs of electricity (LCOE) or the variable costs of generating electricity—in essence, the fuel costs (which are free) plus variable operating and maintenance (O&M) costs. LCOE estimates are based on capital or construction costs, fixed O&M costs (those that accrue regardless of how much power the assets generate), estimates of capacity factors (ratio of actual to potential output, which depends on wind speed and solar irradiance), and the fuel and variable O&M costs. The construction of transmission lines and decommissioning costs (which might include disposal of hazardous wastes), and the rental cost of land, are often ignored in these calculations because they vary greatly with circumstances (Bryce, 2021). Perhaps the most important component of neglected costs, however, is the interaction between renewable, intermittent sources of power and other assets that make up an electricity grid. [11]

In the absence of intermittent sources of electricity, capacity factors for baseload nuclear, coal, and combined-cycle natural gas power plants exceed 80 percent, but, when intermittent power enters the grid, such assets might operate at 60 percent or less of their rated capacity, sliding up the U-shaped average cost curve as they reduce output. The resulting inefficiency increases CO₂ emissions and costs per MWh of electricity (Dears, 2021). In addition, more frequent ramping required to track changes in the power output from intermittent renewable sources will increase wear and tear of assets, leading to higher costs. In essence, baseload plants act as load-following assets, which was never the intent.

Reducing Reliance on Fossil Fuels: The Alberta Electricity Grid as a Case Study [12]

Because of its large coal fleet, favourable solar irradiance, exceptional wind regimes, and potential for utilizing BC's reservoirs for storage, Alberta serves as an excellent case study for examining the potential for eliminating fossil-fuel generation. It is clear from our earlier discussion that, if Canada is to reduce CO₂ emissions in the electricity sector, it will need to be done primarily in Alberta. Several studies have employed information

[11] An overview of how electricity grids operate and the effect of intermittent renewable sources of energy on existing assets is found in van Kooten (2013a: 409–39).

[12] The challenges to grid decarbonization that are addressed in this section would apply just as well to Saskatchewan, New Brunswick, and Nova Scotia.

for the Alberta electricity grid to investigate the potential for intermittent wind and solar energy to replace fossil-fuel generation (van Kooten et al., 2016, 2020; van Kooten and Mokhtarzadeh, 2019; Duan et al., 2020). These studies used ten years of wind and solar data, primarily from the SW corner of the Province (near Pincher Creek) where both wind and solar potential are greatest. Annual capacity factors for wind ranged from 27 percent to nearly 50 percent, while those of solar ranged from 15 percent to 17 percent. A grid allocation model was developed to take into account ramping times for baseload (coal and CC-gas) power plants, while permitting electricity from fast-responding gas plants and battery storage to cover shortfalls in solar or wind (while keeping hydro and biomass production unchanged).

In addition to a base-case scenario using the assets available to generate electricity in 2017, three other scenarios were considered. One scenario permits only hydropower plus renewable solar, wind, and biomass energy. The remaining two scenarios eliminate coal-fired power, replacing two-thirds of capacity (CAP scenario) or two-thirds of generation (GEN scenario) with solar, wind, or biomass energy sources, while allowing the remainder to be replaced by natural gas (or renewable sources if possible). In all cases, storage was made available to deal with intermittent energy so that, when wind or solar was inadequate to meet load, power could be drawn from a utility-scale battery. A summary of the results is provided in [table 3](#).

Table 3: Costs, Emissions, Battery Size, Solar and Wind Units, Generating Capacities, and Generation, Various Scenarios

Item/Asset	Scenario			
	BASE	RNEW	CAP	GEN
Total cost (\$2015×109)	4.74	17,618	5.56	6.67
Emissions (Mt CO ₂)	35.08	–	26.13	21.21
Emission reduction (%)	–	100.0	25.5	39.5
Battery size (MW)	–	10,918	549	350
Battery size (GWh)	–	133.9	0.55	0.35
	<i>Generating Capacity (MW)</i>			
Coal	6,299	–	–	–
GT	916	–	3,450	4,878
CC	6,680	–	6,913	5,691
Wind	1,446	52,109,103	5,145	9,450
Solar	–	154,417	500	500
Total	15,341	52,263,520	16,009	20,520

Notes: Four scenarios employing 2015 wind, solar and load profiles:

BASE: baseline scenario using 2017 asset capacities

RNEW: installed wind, solar and battery capacities required for Alberta to meet load solely using renewable wind and solar sources.

CAP & GEN scenarios: Alberta policy to eliminate coal, replacing two thirds of coal capacity and two thirds of generation, respectively, with power from renewable energy sources, but allow for increased gas plant capacities.

Sources: van Kooten et al., 2020; Duan et al., 2020.

Consider first the scenario where the Alberta electricity grid relies solely on intermittent renewable sources of energy, plus limited biomass. Results indicate that it is practically impossible to rely solely on wind and solar energy sources; one reason is that this would require prohibitively large and expensive batteries, even though the model assumed a high battery round-trip efficiency of 95 percent. One important outcome from the analysis concerns renewable energy and storage: “When we forced the Alberta grid model to rely only on renewable energy sources, a battery with a capacity of 10,917.5 MW and energy storage of 133.9 GWh was required. This compares with the ‘gigantic’ 100 MW/129 MWh capacity [Tesla] battery installed to increase the reliability of the electricity grid in South Australia. The Tesla battery occupies about 0.1 km², so the battery required for Alberta would occupy between 1,000 and 10,000 hectares” (van Kooten and Mokhtarzadeh, 2019: 71–72). Given that an average soccer pitch measures about 110 m × 65 m (7150 m²), or 0.715 ha, this implies that a utility-scale battery would take up some 1,400 to 14,000 soccer fields. [13] The size of a utility-scale battery and the area it occupies might be mitigated if significant hydro storage was available in British Columbia. Regardless, a carbon-free grid based only on wind, solar and limited biomass generation, along with battery storage, would be practically impossible to achieve (van Kooten et al., 2020: 201).

Next consider Alberta’s policy to eliminate coal plants and require that two-thirds of the eliminated coal be replaced by wind and/or solar generation. The policy is unclear whether it is two-thirds of coal capacity (CAP scenario) or power generation (GEN scenario) that should be replaced by wind and solar—replacing capacity with intermittent sources of energy is much easier and less costly than replacing generation. The Alberta policy would still require the installation of between 2,000 (replace capacity) to 4,000 (replace generation) wind turbines of 3.5 MW capacity (plus a significant number of solar panels); further, it would require batteries that have a rated capacity of 350 to 550 MW and can store 0.4 to 0.6 GWh of energy (table 3). Even so, it will require a 36 to 39 percent increase in gas plant capacity—an increase of 2,800 to 3,000 MW—to back up intermittent renewable generating assets.

Finally, the wind profile employed in the above table is for the Pincher Creek region in SW Alberta. Data from 2015 are used in table 3. In 2015, the capacity factor (CF) for wind turbines in the region was 38.7 percent, compared to a capacity factor of 22.9 percent in 2010; for the decade 2006 through 2015 for which data were available, the capacity factor was less than 30 percent in five years. Hence, the emissions reductions

[13] Another way to look at this is as follows: It would require, on average, that each household in Alberta installs 7.5 Tesla Powerwalls as backup storage, each of which has a continuous power (capacity) rating of 5.0 kW, stores 13.5 kWh of energy, weighs 114 kg, and costs between \$12,000 and \$15,000, or about \$100,000 per household (see https://www.tesla.com/en_ca/powerwall). Recently, physicists have been concerned about the stability of lithium-ion batteries, suggesting that a battery of the size discussed here could potentially result in an explosion larger than the devastating explosion caused by stored ammonium nitrate in Beirut in August 2020 (Fordham et al., 2021).

indicated in table 3 are highly optimistic, while, as discussed in the next section, costs are much lower than would be experienced in most other years.

There is simply a limit on the contribution that renewables can make, even when natural gas as opposed to a storage device can be used to backstop intermittent renewables. Given our CAP and GEN scenarios, we find that renewables are only able to contribute ~18 percent (replace capacity) to 22 percent (replace generation) of Alberta's electricity needs (Duan et al., 2020). In this case, the respective associated costs would be \$72 million (reducing CO₂ emissions by 26 percent) for the CAP and \$1,181.8 million (reducing emissions by 40 percent) for the GEN scenarios. The non-linearity in moving from 18 percent (CAP) to 22 percent (GEN) of non-hydro renewable generation is due to the high costs of approximately doubling the number of wind turbines, adding additional fast-responding natural gas plants, and building larger battery capacity.

When wind and solar energy enter an electricity grid, the wholesale price of electricity falls. In general, if an ESO operates an energy market only, the pooled price would guide decisions regarding investments in generating assets. If that is the case, shortfalls in electricity (when load exceeds generation) can be met by imports; when the shortfall cannot be met by imports, grid operators have a list of mitigation measures that they employ, with rolling blackouts on a widening scale as the most extreme step as was the case for the ERCOT grid in Texas in early 2021. [14] Because wind and solar power reduce the wholesale price and the number of hours that fast-responding gas plants operate, returns to investments in gas-plant capacity are inadequate to cover fixed costs, something referred to as the “missing money” problem. As noted earlier, a similar thing happens to baseload plants as wind and solar cause them to ramp up and down more frequently and operate below their optimal capacity factor, both of which increase operating costs. When natural gas plants operate at lower levels or remain idle much of the time, it is expensive to keep such units in top condition. When standby gas facilities are required to run all out to meet a surge in demand or to back up renewable generation, they often encounter problems requiring repair. To prevent these impacts, an ESO can operate a capacity market over-and-above the energy market; the ESO will need to subsidize construction and maintenance costs of backup gas capacity, which inevitably leads to an increase in the retail price of electricity.

The game changes entirely once investments in nuclear energy are permitted. Van Kooten et al. (2016), and van Kooten and Mokhtarzadeh (2019), considered the potential for nuclear energy to reduce CO₂ emissions in Alberta. In the base scenario, it is assumed that Alberta could purchase carbon-free hydro power from BC and, if needed, employ BC's hydro reservoirs as a storage device. In the absence of financial incentives to reduce CO₂ emissions (and excluding the nuclear option), our models indicate that it would be worthwhile to install 1,446 MW of wind power but no solar panels. A significant

[14] The shortfall was exacerbated by an effort on part of the ERCOT system operator to reduce load (demand) by paying large customers to shut down; however, one or more of the customers that were shut down supplied natural gas to backup generating assets.

investment in wind energy might be worthwhile because it is less expensive in the model than other sources of energy, and because locations with excellent wind regimes can be exploited. (This might explain why Alberta relies on wind energy to a greater extent than Ontario, despite Ontario's subsidies.) Nonetheless, coal and gas plant capacities remain near current levels.

CO₂ emissions from the Alberta grid can, under perfect conditions, be reduced by upwards of 40 percent by relying on wind, solar, and gas, but by more than 75 percent if nuclear power is permitted (van Kooten and Mokhtarzadeh, 2019; van Kooten et al., 2016). According to the IEA (2020a), the costs of constructing and decommissioning nuclear power plants is higher than for most other sources of energy, but fuel and other variable costs are no worse; overall, the levelized cost of energy for nuclear plants is about the same as for gas plants (\$68 per MWh), lower than that of coal and biomass plants (\$88 to over \$100 per MWh), but higher than wind and solar (\$50/MWh). Similarly, Lazard (2020b) determines the LCOE of an existing nuclear asset to be \$29/MWh, while it is \$129 to \$198 per MWh for new construction. A main reason for these seemingly low costs is due to the long 60-year expected life of nuclear power plants, compared to 30 years for gas plants. The costs of relying on wind and solar for reducing CO₂ emissions will vary from one year to the next depending on the wind and solar regimes for that year.

With nuclear energy in the mix, wind capacity remains at 1,446 MW with no investment in solar energy, while the optimal desired storage capacity falls from 10,918 MW when coal is eliminated and at least two-thirds of coal generation is replaced with wind. Optimal storage capacity falls to 2,535 MW when baseload nuclear (or even baseload gas) power is permitted. The reason is that low-cost thermal generation can take better advantage of storage than intermittent renewables, because storage enables the capacity of thermal assets to exceed baseload, sending excess power to the battery when generation exceeds load. Baseload generation essentially outcompetes intermittent generation for battery storage.

Costs of Mitigating Climate Change

Alberta Case Studies

If one relies solely on wind and solar to replace fossil fuel generation, our modelling efforts suggest that it is possible to reduce emissions from the Alberta grid by about 26 to 40 percent at an average cost of \$1,375 million $(=(0.83+1.93)/2)$; see table 3), or \$38.0 billion over a 60-year system lifetime (using a discount rate of 3 percent). [15] If nuclear power was made available (not shown in table 3), it would cost \$1.91 billion annually to

[15] The increased cost of the CAP and GEN scenarios in table 3 are \$0.82 and \$1.93 billion, respectively. Thus, if coal-fired power is replaced by natural gas and wind (GEN scenario), it would cost \$1.93 billion annually to reduce emissions from power generation by 39.5 percent. This compares with an annual cost of some \$2.5 billion that Ontario took on just to install its wind generating capacity (as noted above).

reduce CO₂ emissions by 75.4 percent, or \$44.2 billion over the system's lifetime (van Kooten et al., 2020, 2016). Because costs of additional transmission lines, decommissioning assets at the end of their life, and land rental costs are not included, these costs likely constitute lower bound estimates. The cost of eliminating all carbon emissions using wind and solar would be prohibitive (trillions of dollars annually). Eliminating more than 75 percent but not all carbon emissions is only possible if nuclear energy enters the asset mix.

As noted earlier, the estimates provided above are for one year only. Projected costs of reducing Alberta's CO₂ emissions will vary from one year to the next depending on the mix of assets available at various times throughout the year, the system load, the available wind and solar energy regimes, and even the assumptions and parameters used in models. Weather is a major driver because it impacts load and wind/solar profiles. As indicated in **table 4**, if Alberta's annual load and wind regimes were considered over an entire decade beginning in 2006, costs would vary from \$107.94 to \$217.35 per tCO₂, while emissions reductions would vary from a low of 11.2 percent (2008) to as much as 26.3 percent (2015). Given that the US government has set the social cost of carbon at US\$51/tCO₂ for 2020, and \$85/tCO₂ for 2050 (Interagency Working Group on Social Cost of Greenhouse Gases, 2021), Alberta's costs appear to be too high and the Province should probably exercise caution in rushing to increase reliance on non-hydro renewables for generating electricity. After all, the cost of operating the grid is forecast to increase by 86 percent, without taking into account the need for a capacity market; these costs will be passed along to ratepayers who will experience a doubling or more of their electricity bills. [16]

[16] While the results presented here are based on models of the Alberta electricity grid, the experience of the UK in September, 2021 provides empirical evidence of what renewable energy policies could lead to—an unstable power supply and much higher electricity rates (e.g., Ridley, 2021; BBC, 2021b). Constable (2020) warned of this almost a year in advance.

Table 4: Average Annual Costs of Eliminating Coal-fired Capacity in Alberta and Replacing Two-Thirds of Generation with Wind and Solar Energy, and Implications for Canada's Electricity Markets, Wind and Solar Data for 2006–2015

Year	Baseline		Renewables plus gas and battery		Summary and Implications		
	(1) Total cost (\$ millions)	(2) CO ₂ emissions (Mt)	(3) Total cost (\$ millions)	(4) CO ₂ emissions (Mt)	(5) Cost (\$/tCO ₂)	(6) Emissions reduction (percent)	(7) Cost to Canada (\$ billions)
2006	954.29	27.26	1,656.44	22.62	151.33	17.0%	23.48
2007	953.41	27.16	1,675.46	22.67	160.81	16.5%	24.95
2008	928.00	23.74	1,506.15	21.08	217.35	11.2%	33.73
2009	956.91	27.62	1,760.69	22.86	168.86	17.2%	26.20
2010	971.22	29.54	1,828.80	23.75	148.11	19.6%	22.98
2011	975.59	30.18	1,839.21	23.94	138.40	20.7%	21.48
2012	981.04	31.03	1,902.90	24.10	133.02	22.3%	20.64
2013	992.85	32.63	1,951.64	24.79	122.29	24.0%	18.98
2014	1,009.32	34.86	1,985.13	25.82	107.94	25.9%	16.75
2015	1,010.94	35.08	2,015.99	25.86	109.01	26.3%	16.92
Mean	973.36	29.91	1,812.24	23.75	20.1%	7.15%	22.61
Max	1,010.94	35.08	2,015.99	25.86	26.3%	9.26%	33.73

Notes: Cost is determined as the difference in costs divided by the difference in CO₂ emissions = $[(3)-(1)]/[(2)-(4)]$; the emissions reduction is the modeled reduction in total CO₂ emissions for the Alberta electricity grid; and the cost to Canada in column (7) is the Alberta cost (\$/tCO₂) in column (5) multiplied by the required reduction of 155.18 Mt CO₂ to phase out coal generation in Canada. The emissions reduction in column (6) refers to the extent emissions are reduced in Alberta.

Source: Author's calculations based on scenarios created by Duan et al. (2020).

Potential Costs to Canada

Despite the fact that CO₂ emissions from electricity generation are only a small component of Canada's overall emissions, we can use the Alberta results to provide some preliminary estimates of the potential costs to Canada of decarbonizing its electricity markets. Before doing so, consider three important conclusions following from our modelling efforts that apply to Canada as a whole:

1. It would be prohibitively expensive to rely solely on renewable wind, solar, hydro and biomass to generate all electricity (see RENEW scenario in table 3).
2. Even replacing two-thirds of coal generation with renewable wind and solar resources will require additional natural gas generating assets to maintain system stability.
3. Even the introduction of nuclear energy fails to eliminate all carbon emissions.

Canadian primary energy consumption of fossil fuels and related CO₂ emissions for 2019 are provided in **table 5**. If all coal-fired power is eliminated by 2030, with two-thirds replaced by wind and solar sources of energy and the remainder with gas generation, this would theoretically reduce Canada's emissions by about 7.4 percent, providing 18.2 percent of the required 230.6 Mt CO₂ reduction in emissions by 2030. [17] Assuming the same average costs found in table 4 apply if we were to eliminate all of Canada's coal-fired power, the cost would be \$16.8 to \$33.7 billion annually as indicated in table 4. This constitutes some 1 to 2 percent of Canada's GDP in 2019. If nuclear power replaces coal instead of wind and solar (not shown in table 4), the annual cost is estimated to be about half as much, some \$8.3 to \$16.7 billion.

Table 5: CO₂ Emissions and Primary Energy Consumption from Fossil Fuels, Canada, 2019

Fuel	Emissions (kg CO ₂ /kWh)	Consumption (TWh)	Total emissions (Mt CO ₂)
Coal	0.33	155.56	51.33
Natural gas	0.18	1,202.78	216.50
Oil	0.24	1,250.00	300.00
TOTAL	-	2,608.33	567.83

Source: Data on emissions are from <<https://www.eia.gov/>>, but converted from lbs per btu; consumption by fuel type from BP Statistical Review of World Energy June 2020, but converted from exajoules to terawatt hours (TWh). Final column derived by multiplying previous columns. Total emissions differ slightly from those in table 1 due to different means of calculating values.

These estimates of costs should be considered a lower bound, however. Why? First, the choice of assets comprising an electricity grid needs to be based on the worst case scenario, not the average or best—based on the year with the poorest wind and solar regimes. Thus, the grid needs to be built on the basis of the 2008 outcome in table 4, and not some average or best year. And 2008 might not even be the worst year as some other or future year not considered in the analysis might have led to even higher costs.

Second, it will be necessary to incentivize the construction of wind turbines and solar panels. As noted above, Ontario's subsidies to renewable energy cost some \$2.4–\$2.6 billion annually, which would increase Canada's costs to \$19.2–\$36.3 billion, or \$0.5–\$1.0 trillion over the 60-year life of the system.

Third, to achieve Canada's emissions-reduction ambitions for 2030 and beyond (achieving net zero by 2050) will likely require greater reliance on nuclear energy, with

[17] Eliminating coal reduces emissions by 51.33 Mt CO₂, but when one-third of coal-fired generation is replaced by natural gas, it is necessary to add back emissions from 51.85 TWh (= 0.33 × 155.56 TWh) of gas-generated electricity, or 9.33 Mt CO₂ (= 0.18 Mt CO₂/TWh × 51.85 TWh). Thus, eliminating coal only reduces Canada's total emissions by 42.00 Mt CO₂, or by 7.4 percent.

some 30 nuclear power plants to be built before 2030—one nuclear power plant of 1,000 MW capacity coming online every four months between 2021 and 2030. Alternatively, it would be necessary to build 28,340 wind turbines of 2.5 MW capacity with a capacity factor of 25 percent or higher to replace all of the coal-fired power in Canada by 2030. This would require building 1,050 wind turbines (2650 MW capacity) every four months, plus associated transmission infrastructure (the costs of which have been ignored in the aforementioned studies). Hastening construction will certainly increase costs.

Fourth, wind speed data from southwestern Alberta are used in the models to investigate the potential for replacing fossil fuel generated power with renewables. This area experiences some of the best wind regimes in Canada; thus, costs would be higher if wind turbines are located elsewhere.

Finally, other factors will also increase costs. One cost relates to the gas plant capacity needed to backstop wind and solar power (as noted in point 2 above). Voorspools and D'haeseleer (2006), for example, found that 0.7–0.8 MW of gas is required as backup for every 1 MW of wind power that is installed. Construction and operation of renewable resource facilities and the needed gas plants will release significant CO₂, and the same is true of nuclear power plants (e.g., cement making releases large amounts of CO₂). This extra CO₂ will also need to be taken into account in achieving any emissions-reduction target. Further, there are the costs related to the purchase or rental of land, construction of transmission lines, disposal of hazard wastes, and so on.

On a global scale, the International Energy Agency offers the following estimates of the potential costs:

The increased use of electricity and low-carbon technologies for power generation are the largest contributors to this higher investment need, increasing investment needs in the power sector by around USD 39 trillion to 2070 (or almost USD 760 billion per year). At around USD 24 trillion, the lion's share of this cumulative additional investment is for renewable energy sources (USD 475 billion additional per year on average), followed by additional investment in the upgrade and extension of electric grids (around USD 10 trillion), CCS with coal, gas and bioenergy (USD 3.6 trillion), and electricity storage (USD 3.2 trillion). (IEA 2020b: 167–68)

5. Concluding Discussion

It is difficult to project the future. As Smil (2021) points out, economic growth is promoted by access to cheap and reliable energy; without it, developing countries cannot hope to escape poverty. Currently, the only sources of cheap energy available to developing countries are coal for generating electricity, petroleum and its derivatives for mobility, and natural gas for heating, power generation, and, along with oil, as an input into the manufacture of many commodities (including various plastics, fertilizer, etc.). Methods for bringing renewable energy sources into the economy are focused on electricity grids because any source of energy can be used to generate electricity. However, while electricity has great flexibility, it also has challenges, particularly as these relate to mobility.

First and foremost, aircraft cannot rely on electricity as batteries would simply be too heavy to enable planes to take flight—electric vehicles are nearly twice as heavy as their ICE counterparts, while the focus on EVs to the detriment of ICEs disincentivizes R&D related to improvements in internal combustion engines. Rather than storing electricity when power generated from intermittent renewables exceeds load, excess electricity can be used to separate hydrogen (H) from methane (CH₄), or even more ambitiously from water (H₂O), to make hydrogen gas (H₂) that can be used for locomotion, including air travel. [18] Fuel cell electric vehicles (FCEVs) combine hydrogen stored in a tank with oxygen from the air to produce electricity, with water as a by-product. FCEVs are not as efficient as EVs (60 percent vs 83 percent), but can power a vehicle for 500 or more kilometres and refuel at a pump similar to a gasoline pump in minutes. However, electrolysis can be expensive in terms of energy use, while processes for converting H₂O to hydrogen are still at a demonstration stage and likely to be costly.

Second, by electrifying everything that possibly can be electrified, the demand for electricity will shift outwards. This implies that it would be necessary to increase the capacity and available generation from renewable sources by a great deal more than is required to meet current needs. It is likely that, to meet newly set emission-reduction targets, a future energy system will need to rely on nuclear power. Rolling out a nuclear future will certainly take us well beyond 2050 (Smil 2017, 2021).

We conclude with some final observations about wind and solar power. Although based on studies of Denmark and the United Kingdom, they relate to the Canadian situation. These two countries have much more experience with wind and solar energy than Canada, as well as policies to reduce CO₂ emissions in the electricity sector.

[18] Only 2 percent of the H₂ produced globally uses electrolysis to split water into its constituent hydrogen and oxygen atoms. On the other hand, hydrogen produced from CH₄ is clearly not carbon neutral.

- The projected costs of achieving the UK’s Net Zero target by 2050 “have no basis in actual experience and a realistic appraisal of trends in costs, [and are] much more likely to be 10+% of annual GDP than the claimed 1–2% of GDP” (Hughes, 2020a). We estimated a lower bound for achieving 18.2 percent of Canada’s emissions-reduction target for 2030 to be some 1–2 percent of GDP. Achieving Net Zero would be an order of magnitude more expensive.
- To meet 2030 emission targets will require greatly accelerated construction of wind capacity, especially offshore wind capacity, which will be extremely expensive and technically difficult. Projections of capital costs (capex) assume that these will be lowered as a result of economies of scale, but audits of wind operations in the UK and Denmark (Hughes, 2020b, 2020c) indicate that both capital and operating (opex) costs increase over time, much like they did in the case of nuclear power. While capital costs of turbines have fallen, site costs often increase dramatically as more and more marginal sites are developed. These are sites that are increasingly more remote (further from existing transmission lines or in deeper water) and with generally poorer wind regimes. “It is plausible to assume that capex and opex costs will rise by a minimum of 20% and probably closer to 50% above the already high costs that we observe in the audited accounts” (Hughes, 2020a; also see Bryce, 2021).
- “Bailouts of wind farms and financial institutions are inevitable” (Hughes, 2020a). To incentivize construction of wind generating capacity, turbine operators are provided with subsidies, often determined through a competitive bidding process and taking the form of feed-in tariffs (FIT) or compensation for differences (CfD) between the market price and subsidized price (e.g., see van Kooten, 2013b). However, because operating costs rise over time, mainly due to high rates of equipment failure and poorer wind regimes than forecast (based on experience at existing sites), operating costs often exceed revenues after 12 to 15 years of operation. To prevent closure of wind farms, the government will have no option but to “bail out failed and failing projects to ensure continuity of electricity supply” (Hughes, 2020a). Ultimately the costs of bailouts as well as the costs of original subsidies will be paid by increased taxes and/or rates on electricity. Therefore, investors in all sectors of the Canadian economy should plan to pay much more for electricity (perhaps double or more) by 2030 if current emission reduction targets are to be met.
- What applies to wind energy likewise applies to solar. Solar panels have been extremely competitive on cost because they are made in China, perhaps using forced labor. As a result, solar facilities are dependent on China to supply panels or the materials required to produce them. However, recent research finds that the costs of properly disposing of the toxic wastes found in solar panels will increase their levelized cost of electricity by a factor of three or four, making solar much less competitive as an energy source than indicated by their current price (see Atasu et al., 2021; Shellenberger, 2021). Further,

the intermittency of solar imposes costs on baseload and other generating assets that adds to their costs, much like the case with wind.

- As rich countries, Canada, the US, the UK and the EU member states can afford to achieve a target of Net Zero emissions by 2050, and perhaps can even achieve the shorter-term, emission-reduction targets set for 2030. It could mean allocating the proceeds of 10 or 15 years of economic growth to that single goal. As Smil (2021, 2017) and Rhodes (2018) demonstrate, energy transitions take much longer than the short periods envisioned by current emissions-reduction targets; nor should governments target certain technologies, whether wind turbines or electric vehicles, as the ones to rely upon for meeting goals. “A strategy that acknowledges the real economic costs and difficulties of trying to make the transition too quickly is much more likely to be [politically] accepted and implemented” (Hughes, 2020a).
- It is clear from figure 1 and table 1 that any reduction in CO₂ emissions by Canada, the UK, or the EU will be quickly swamped by increased emissions by Russia, China, and developing nations, particularly India, but also countries in Africa and southern Asia. Indeed, when developed countries take action to reduce CO₂ emissions by incentivizing a switch to electric vehicles, for example, the demand for gasoline will fall, with the lower prices leading those in developing countries to consume more petroleum with associated CO₂ emissions—a phenomenon referred to as ‘leakage’. In essence, countries with per-capita incomes that lag those of the US and Europe are unlikely to make great efforts to rein in their CO₂ emissions, nor are rich countries likely to achieve their own outlandish targets (van Kooten, 2004).
- If one looks carefully at many countries’ Nationally Determined Commitments under the Paris Agreement, they intend to rely on carbon offsets related to forestry and on future technologies that have yet to be developed (e.g., carbon capture and storage, harvesting CO₂ from the atmosphere) for meeting Net Zero targets. Indeed, Canada has audaciously announced that it would count forest sequestration by human activities to achieve its targets, while not counting any release of carbon by natural disturbance, as if humans have no effect on what happens in the forest. [19]

In this study, we argued that the cost of partially decarbonizing Canada’s electricity sector (which could achieve 18.2 percent of the country’s 2030 GHG emissions-reduction target) will be costly—in present value terms, some \$0.5 to \$1.0 trillion. The estimates provided here are likely quite conservative. They are based on removing coal-fired

[19] The irony of this thinking and the attribution of climate change should be obvious. The Canadian position encourages natural disturbance, because there are CO₂-emissions-reduction benefits to replanting denuded sites. For example, wildfires attributable to human causes (e.g., careless disposal of cigarette butts) are treated as if they were a natural disturbance.

power from power grids throughout Canada. As evident from jurisdictions ranging from California to Germany and the UK, renewable sources of electricity require backstop natural gas capacity to avoid blackouts, because utility-scale batteries are currently not up to the task. While we took into account the need for gas to backstop intermittency, we could not account for scenarios where the scale of intermittency turned out worse than indicated in our dataset—available wind and solar energy might be lower than indicated by the available ten years of data. In this sense, the analysis was knife-edge—the models employed in this study maintained just enough gas capacity to meet load in each hour given our wind/solar profiles. To avoid the experience in other jurisdictions would require a reserve capacity market for gas, but the costs of operating a capacity market have not been included in this study.

Also ignored are the costs associated with the value of land in other alternative uses, the need for added transmission lines (which are increasingly opposed by citizens), deterioration of human health associated with wind turbines, environmental costs associated with bird and bat strikes, greenhouse gas emissions related to cement making, and the environmental costs associated with the mining of rare earth minerals. Perhaps the most important costs not considered in this study are the life-cycle costs of using intermittent renewable sources of energy, particularly the end-of-life costs related to the disposal of hazardous wastes from solar panels and wind turbines.

Unfortunately, there is something more at stake. As one can see from figures 2 through 6, and figures 8 and 9, the challenge of reducing emissions is enormous, with the transition to a carbon-free economy unlikely to occur within the next decades, let alone by 2030. Even then, it is likely that society will need to be coerced into making the sacrifices necessary to even come close to meeting CO₂ emissions-reduction targets (e.g., see Foster, 2021; Koonin, 2021; IEA, 2021). Certainly there is a better way, including the implementation of policies that incentivize adaptation to future climate change as we encounter it.

References

- Atasu, A., S. Duran, and L.N. Van Wassenhove (2021, June 18). *The Dark Side of Solar Power*. Harvard Business Review. <https://hbr-org.cdn.ampproject.org/v/s/hbr.org/amp/2021/06/the-dark-side-of-solar-power?amp_gsa=1&_js_v=a6&usqp=mq331AQFKAGwASA%3D#amp_tf=From%20%251%24s&aoh=16241641204897&csi=0&referrer=https%3A%2F%2Fwww.google.com&share=https%3A%2F%2Fhbr.org%2F2021%2F06%2Fthe-dark-side-of-solar-power>
- Baker, J., J. Cross, and I. Lloyd (2014). *Lessons Learned Report*. Energy Storage Systems. Customer-Led Network Revolution Document Number CLNR-L163. <http://www.networkrevolution.co.uk/wp-content/uploads/2014/12/CLNR_L163-EES-Lessons-Learned-Report-v1.0.pdf>
- BBC (2021a, April 21). *Climate Change: EU to Cut CO2 Emissions by 55% by 2030*. BBC. <<https://www.bbc.com/news/world-europe-56828383#:~:text=The%20EU%20has%20adopted%20ambitious,2030%2C%20compared%20with%201990%20levels>>
- BBC (2021b, September 18). *Gas Crisis Leaves Europe Searching for Solutions*. BBC. <<https://www.bbc.com/news/world-europe-58650634>>
- BP (2020, June). *BP Statistical Review of World Energy, 2020*. <<http://www.bp.com/statisticalreview>>
- Bryce, R. (2020, November 22). *Why Nuclear Power, Not Renewables, is the Path to Low-Carbon Energy: Part 1*. FreeOPP Blog. <<https://freopp.org/why-nuclear-power-not-renewables-is-the-path-to-low-carbon-energy-part-1-c0b66d4b9570>>
- Bryce, R. (2021). *Not in our Backyard. Rural America is Fighting Back Against Large-Scale Renewable Energy Projects*. Center of the American Experiment. <<https://www.americanexperiment.org/reports/>>
- Canadian Institute for Climate Choices (2021). *Canada's Net Zero Future. Finding our Way in the Global Transition*. CICC. <https://climatechoices.ca/wp-content/uploads/2021/02/Canadas-Net-Zero-Future_FINAL-2.pdf>
- Constable, J. (2020). *Skirting Disaster: Britain's Electricity Grid on the Brink*. GWPF Note 24. Global Warming Policy Foundation. <<https://www.thegwpf.org/content/uploads/2020/11/Grid-shortages.pdf>>

- Dears, D. (2021, July 9). *Objective Analysis of Wind Energy*. Power for USA: Energy Facts from Oil to Electricity Blog. <<https://ddears.com/2021/07/09/objective-analysis-of-wind-energy/>>
- Duan, J., G.C. van Kooten, and X. Liu (2020). Renewable Electricity Grids, Battery Storage and Missing Money. *Resources, Conservation & Recycling* 161: 105001. <<https://doi.org/10.1016/j.resconrec.2020.105001>>
- Eldardiry, H., and E. Habib (2018). Carbon Capture and Sequestration in Power Generation: Review of Impacts and Opportunities for Water Sustainability. *Energy, Sustainability and Society* 8: 6. <<https://doi.org/10.1186/s13705-018-0146-3>>
- European Commission (2021). Climate Strategies and Targets. <https://ec.europa.eu/clima/policies/strategies_en>
- Fordham, E., W. Allison, and D. Melville (2021). *Safety of Grid Scale Lithium-ion Battery Energy Storage Systems*. Working Paper. <https://www.researchgate.net/publication/352158070_Safety_of_Grid_Scale_Lithium-ion_Battery_Energy_Storage_Systems>
- Foster, Peter (2021, June 5). Mark Carney, Man of Destiny, Arises to Revolutionize Society. It Won't be Pleasant. *National Post*. <<https://nationalpost.com/opinion/peter-foster-mark-carney-man-of-destiny-arises-to-revolutionize-society-it-wont-be-pleasant>>
- Hasler, J. P. (2010). Investigating Russia's Biggest Dam Explosion: What Went Wrong. *Popular Mechanics*. <<https://www.popularmechanics.com/technology/infrastructure/a5346/4344681/>>
- Hughes, Gordon (2020a). *Wind Power Economics—Rhetoric and Reality*. Renewable Energy Foundation. <https://www.ref.org.uk/ref-blog/365-wind-power-economics-rhetoric-and-reality?mc_cid=561f0bd0d2&mc_eid=3e8db95649>
- Hughes, Gordon (2020b). *Wind Power Economics—Rhetoric and Reality. Volume I, Wind Power Costs in the United Kingdom*. Renewable Energy Foundation. <https://www.ref.org.uk/ref-blog/365-wind-power-economics-rhetoric-and-reality?mc_cid=561f0bd0d2&mc_eid=3e8db95649>
- Hughes, Gordon (2020c). *Wind Power Economics Rhetoric & Reality. Volume II, The Performance of Wind Power in Denmark*. Renewable Energy Foundation <https://www.ref.org.uk/ref-blog/365-wind-power-economics-rhetoric-and-reality?mc_cid=561f0bd0d2&mc_eid=3e8db95649>

Hume, N. (2021, May 12). Glencore Boss Warns of Future China Dominance in Electric Vehicles. *Washington Examiner*. <<https://www.ft.com/content/0ee4a6cb-9dbe-4fee-84d0-3f48f3190935>>

Independent Electricity System Operator (2017). *Ontario-Quebec Interconnection Capability: A Technical Review*. IESO. <<https://www.ieso.ca/sector-participants/ieso-news/2017/05/ontario-quebec-interconnection-capability---a-technical-review>>

International Energy Agency [IEA] (2021a). *The Role of Critical Minerals in Clean Energy Transitions*. World Energy Outlook Special Report. IEA. <<https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions>>

International Energy Agency [IEA] (2021b). *Net Zero by 2050 A Roadmap for the Global Energy Sector*. IEA. <<https://iea.blob.core.windows.net/assets/0716bb9a-6138-4918-8023-cb24caa47794/NetZeroBy2050-ARoadmapfortheGlobalEnergySector.pdf>>

International Energy Agency [IEA] (2020a). *Projected Costs of Generating Electricity*. 2020 Edition. IEA and OECD/Nuclear Energy Agency.

International Energy Agency [IEA] (2020b). *Energy Technology Perspectives 2020*. IEA. <<https://webstore.iea.org/download/direct/4165>>

Interagency Working Group on Social Cost of Greenhouse Gases (2021). *Technical Support Document: Social Cost of Carbon, Methane, and Nitrous Oxide Interim Estimates under Executive Order 13990*. Government of the United States of America. <https://www.whitehouse.gov/wp-content/uploads/2021/02/TechnicalSupportDocument_SocialCostofCarbonMethaneNitrousOxide.pdf>

Kaya, Y., and K. Yokobori (eds.) (1997). *Environment, Energy and Economy: Strategies for Sustainability*. United Nations University Press.

Koonin, S. E. (2021). *Unsettled. What Climate Science Tells Us, What it Doesn't, and Why it Matters*. BenBella Books.

Lazard (2020a). *Lazard's Levelized Cost of Storage Analysis—Version 6.0*. <<https://www.lazard.com/media/451566/lazards-levelized-cost-of-storage-version-60-vf2.pdf>>

Lazard (2020b). *Lazard's Levelized Cost of Energy Analysis—Version 14.0*. <<https://www.lazard.com/media/451419/lazards-levelized-cost-of-energy-version-140.pdf>>

Mascarenhas, K. (2017). *Interprovincial Electricity Trade: The British Columbia-Alberta Intertie*. CERI Electricity Report. Canadian Research Energy Institute. <https://ceri.ca/assets/files/Electricity_Report_March_2017.pdf>

Newburger, Emma (2021, April 22). *Here's What Countries Pledged on Climate Change at Biden's Global Summit*. CNBC. <<https://www.cnbc.com/2021/04/22/biden-climate-summit-2021-what-brazil-japan-canada-others-pledged.html>>

Rhodes, Richard (2018). *Energy: A Human History*. Simon & Schuster.

Ridley, M. (2021, September 21). Power Mad. *Daily Mail*. <https://www.dailymail.co.uk/news/article-10010693/Power-mad-devastating-audit-lays-bare-costly-errors.html?mc_cid=41ef2597c7&mc_eid=3e8db95649>

Shellenberger, M. (2021, June 21). *Why Everything They Said About Solar Was Wrong*. Substack. <https://michaelszellenberger.substack.com/p/why-everything-they-said-about-solar?mc_cid=c9a76abab7&mc_eid=3e8db95649>

Smil, Vaclav (2021). *Grand Transitions: How the Modern World Was Made*. Oxford University Press.

Smil, Vaclav (2017). *Energy and Civilization: A History*. MIT Press.

Smith, A. (2021, May 12). Left-Wing Activists Demand Democrats Exclude Nuclear and Carbon Capture from Climate Bill. *Washington Examiner*. <https://www.washingtonexaminer.com/policy/activists-demand-renewable-energy-standard?mc_cid=237e2f4244&mc_eid=3e8db95649>

Statistics Canada (2021a). *Table 25-10-0015-01 Electric power generation, monthly generation by type of electricity*. Statistics Canada. <<https://doi.org/10.25318/2510001501-eng>>

Statistics Canada (2021b). *Table 25-10-0022-01 Installed plants, annual generating capacity by type of electricity generation*. Statistics Canada. <<https://doi.org/10.25318/2510002201-eng>>

Statistics Canada (2021c). *Table: 25-10-0023-01 Conventional thermal, annual generating capacity by class of electricity producer and principal fuel*. Statistics Canada. <<https://doi.org/10.25318/2510002301-eng>>

van Kooten, G. C., P. Withey, and J. Duan (2020). How Big a Battery? *Renewable Energy* 146: 196–204.

van Kooten, G. C., and F. Mokhtarzadeh (2019). Optimal Investment in Electric Generating Capacity under Climate Policy. *Journal of Environmental Management* 232 (February 15): 66–72.

van Kooten, G. C., J. Duan, and R. Lynch (2016). *Is There a Future for Nuclear Power? Wind and Emission Reduction Targets in Fossil-Fuel Alberta*. PLoS ONE 11, 11: e0165822.

van Kooten, G. C. (2016). The Economics of Wind Power. *Annual Review of Resource Economics* 8, 1: 181–205.

van Kooten, G. C. (2013a). *Climate Change, Climate Science and Economics: Prospects for a Renewable Energy Future*. Springer.

van Kooten, G.C. (2013b). Economic Analysis of Feed-in Tariffs for Generating Electricity from Renewable Energy Sources. In R. Fouquet (ed.), *Handbook on Energy and Climate Change* (Edward Elgar): 224–53.

van Kooten, G. C. (2004). *Climate Change Economics: Why International Accords Fail*. Edward Elgar.

Voorspools, K. R., and W. D. D’haeseleer (2006). An Analytical Formula for the Capacity Credit of Wind Power. *Renewable Energy* 31, 1: 45–54.

White House Briefing Room (2021, April 22). *President Biden Sets 2030 Greenhouse Gas Pollution Reduction Target Aimed at Creating Good-Paying Union Jobs and Securing U.S. Leadership on Clean Energy Technologies*. Government of the United States of America. <<https://www.whitehouse.gov/briefing-room/statements-releases/2021/04/22/fact-sheet-president-biden-sets-2030-greenhouse-gas-pollution-reduction-target-aimed-at-creating-good-paying-union-jobs-and-securing-u-s-leadership-on-clean-energy-technologies/>>

World Bank (2021). World Bank national accounts data, and OECD National Accounts data file. World Bank. <<https://data.worldbank.org/indicator/NY.GDP.MKTP.KD>>

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