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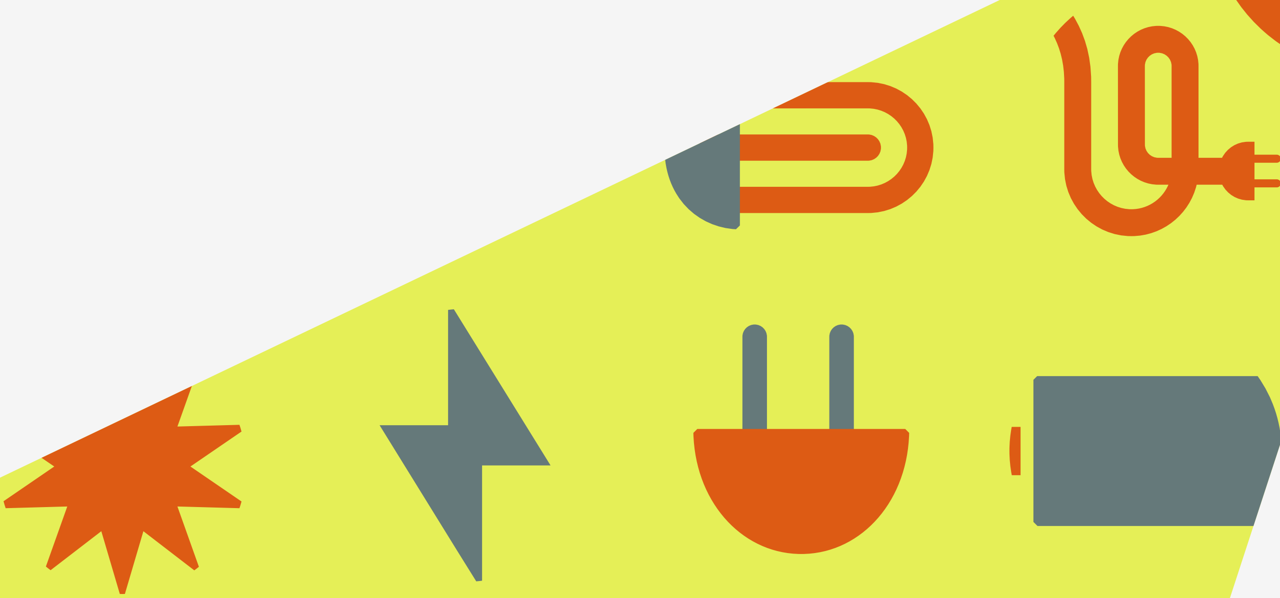

BIGGER, CLEANER, SMARTER

PATHWAYS FOR ALIGNING CANADIAN ELECTRICITY SYSTEMS WITH NET ZERO

MAY 2022

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INTRODUCTION

01 *All roads to net zero pass through electricity*

Electricity systems:
The various networks of infrastructure, institutions, and private-sector players associated with the generation, transmission, and distribution of electricity in Canada. This definition extends to the demand-side—the use of electricity—only insofar as shifts in the timing and extent of demand can effectively act as additional sources of supply. The use of the plural form—systems—is an acknowledgment that Canada does not have one single electricity system, but rather numerous regional systems, which are primarily managed at the provincial and territorial levels.

Canada has committed to dramatically reduce its emissions on a path to reach net zero emissions by 2050. Although there are many unknown twists and turns on that path, one thing is certain: all roads to net zero in Canada pass through electricity. Canadian electricity systems must transform if we are to reach our net zero emissions targets and lead the way to net zero.

Because electricity is so crucial to Canada's net zero goal, the Canadian Climate Institute has prepared two reports on aligning Canadian electricity systems with net zero, the first covering what it will entail and the second addressing the range of policies needed to get there. This is the first of these reports, finding that electricity systems must become bigger, cleaner, and smarter in order for Canada to reach net zero emissions by 2050. The companion report, *Electric Federalism: Policy for aligning Canadian electricity systems with net zero*, assesses and recommends policies to address the main challenges that stand in the way of realizing these changes.

1.1 *Electricity is the backbone of Canada's net zero future*

As our 2021 report *Canada's Net Zero Future* (Dion et al. 2021) has shown, transformational change will be required in every sector of the Canadian economy to achieve net zero emissions by 2050. Among the many variables and choices that will shape this transformation, the growth of non-emitting electricity and the expansion of electrification are central pillars. Transforming electricity systems—by growing them to support the use of more electric technologies such as electric vehicles and heat pumps, shifting to non-emitting electricity sources, and phasing out fossil fuel ones—will support the decarbonization of every other sector of Canada's economy, from transportation to buildings to agriculture.

Net zero: *To meet the threat of catastrophic climate change and drive decarbonization of the Canadian economy, the federal government has set an economy-wide target of reaching net zero emissions by 2050 and a more immediate target of achieving net zero electricity systems by 2035. Several provinces and territories have also set their own emissions reduction targets. Achieving all of these goals requires reducing emissions as close to zero as possible, while removing any remaining emissions from the atmosphere and storing them permanently. However, reaching Canada's national goal does not necessarily mean that every province and territory must reduce emissions on the same timeline—negative emissions in one province or territory could potentially be used to offset remaining emissions in another.*

International analysis confirms the central role of electricity in pursuit of net zero. For example, recent International Energy Agency (IEA) reports conclude that accelerating the decarbonization of the electricity sector is the single most significant way to reduce global emissions by 2030, and that end-use electrification is one of the most important contributors to reductions by 2050 (IEA 2021a, IEA 2021b). Furthermore, the imperative to transform electricity goes beyond net zero goals. Numerous factors are driving the need for transformation. These include:

- increasing digitalization;
- rising consumer participation in electricity production and consumption;
- the imperative to support Indigenous self-determination and reconciliation, including in the transformation of electricity systems;
- mitigating a range of risks, among them climate change and cyber security; and
- upgrading aging infrastructure.

The findings in this report are drawn from a literature review of the most significant recent studies of electricity systems transformation in Canada, as well as consultation with experts, thought leaders, and practitioners in energy and electricity. Our objective is not to paint a precise picture of electricity systems in 2050. Instead, we aim to describe the three main ways these systems must change to reach our goals—becoming *bigger*, *cleaner*, and *smarter* (as discussed in turn in Sections 2, 3, and 4). This report concludes by outlining key takeaways for policymakers in Canada (Section 5).

This is an urgent task. Transforming electricity systems to power a net zero Canada by 2050 means that electricity production itself must achieve net zero much earlier than the overall economy, something the federal government recognized in its 2021 commitment to achieving net zero electricity in Canada by 2035. Ensuring electricity production achieves net zero early on is one of three critical changes that must be made to ensure that electricity can be ready to serve as the backbone of a net zero future.

The most important conclusion of this first report, baldly stated, is that transforming electricity systems across Canada is achievable and will set the country on a path to net zero by 2050.

__Safe bets__: Safe bets are the technologies and measures that play a significant role in all credible net zero futures, according to our analysis in Canada's Net Zero Future *and other recent analyses. These solutions are especially important to meet Canada's 2030 emissions reduction target, but safe bets are essential for achieving longer-term goals as well. Examples of safe bet solutions include energy efficiency measures and equipment, electric vehicles, and heat pumps. Calling a solution a safe bet, however, does not imply that its widespread uptake is inevitable or that it won't encounter barriers and challenges, such as local opposition to renewable energy projects or rigid regulatory environments for new technologies.*

1.2 *Transforming electricity systems is both possible and necessary*

In *Canada's Net Zero Future*, we modelled more than 60 scenarios for Canada to achieve net zero emissions by 2050. To clarify the role that different emissions-reducing measures and technologies could play in meeting Canada's net zero goal, we grouped the required solutions into *safe bets* and *wild cards*. Safe bets are solutions that appear consistently across all credible pathways, relying on commercially available technologies with no significant scaling barriers. Wild cards are solutions that appear only in certain pathways, rely on emerging or demonstration-stage technologies, or face significant scaling barriers. (See side bars for more detail on the distinction between safe bets and wild cards.) This report found that both electrification and deployment of non-emitting electricity are safe bets, underscoring the central role of electricity in Canada's net zero transition.

The analysis presented in this report complements those findings—that transforming Canadian electricity systems is both technically achievable and necessary to meet broader net zero goals, and will

Wild cards: *The solutions we have identified as wild cards face uncertain prospects at present but have significant potential to contribute to reaching net zero by 2050. Examples of wild cards include advanced forms of carbon capture utilization and storage (CCUS), including those installed at power plants, and emerging technologies such as small modular nuclear reactors and long-term energy storage. A solution is not a wild card simply because it might not prove technically viable. Even technically viable solutions may still be considered wild cards if they face other types of barriers, or if they might be out-competed by more viable solutions.*

require both safe bets and wild cards. Though electrification and deployment of non-emitting electricity are both safe bets overall, they represent broad categories of solutions and within each of them there are some individual technologies and solutions that are safe bets while others that are wild cards.

We use this safe-bet-and-wild-card lens to analyze Canada's pathways for electricity systems transformation for three key reasons:

1. To contextualize the potential role of different solutions in electricity systems transformation—for instance, by clarifying whether they will play a role in every case or only under certain conditions;
2. To highlight both the nature and magnitude of barriers associated with their at-scale deployment; and
3. To set up a discussion focused on policy interventions that can address these and other barriers, in order to accelerate the needed transformation. (We take up this topic in our companion report *Electric Federalism: Policy for aligning Canadian electricity systems with net zero*.)

Our determination of which solutions are safe bets or wild cards draws from the findings of significant recent studies and analysis in *Canada's Net Zero Future*, as well as additional expert input. See the Annex for further details on the key studies used in this report.

1.3 *Canada has unique advantages in aligning its electricity systems with net zero*

Canada begins the process of transforming its electricity systems from a strong starting position, but there is much work still to do. Our analysis has found that reaching Canada's net zero goal will require a significant transformation of the country's electricity systems with three critical dimensions: Canadian electricity systems must become *bigger*, *cleaner*, and *smarter*. This transformation will mean major changes for electricity systems—but these changes are technically achievable.

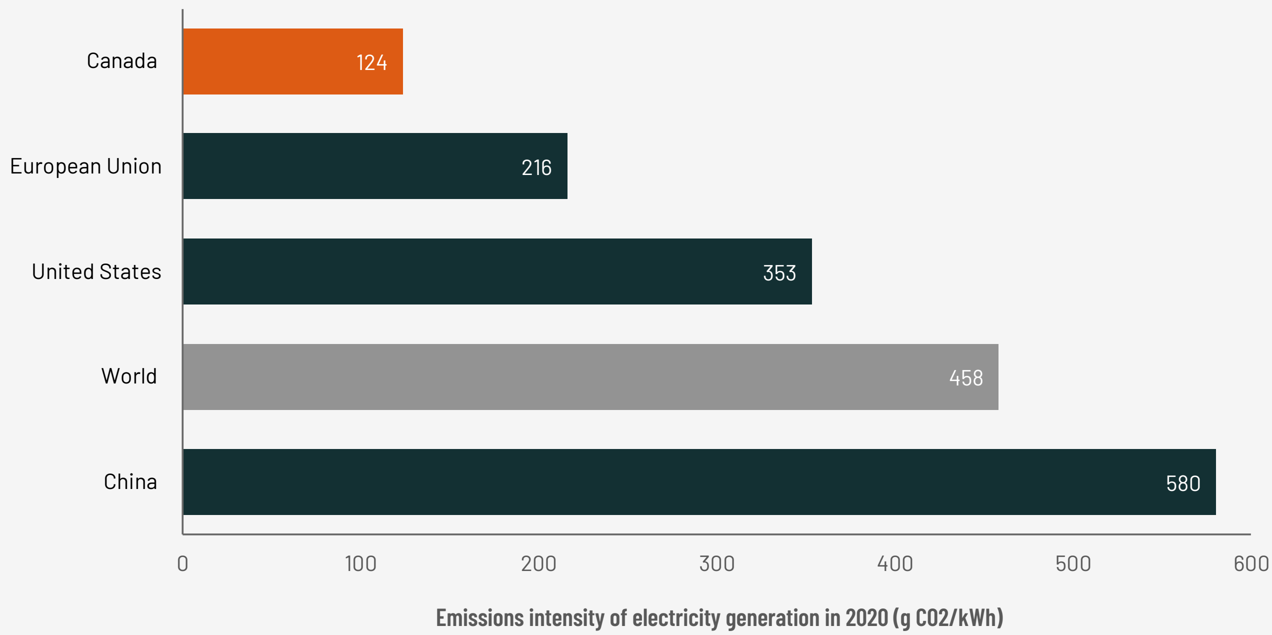
What's more, the country begins in a favourable starting position compared to many other countries. There are three main advantages to Canada's position.

First, Canada already has a relatively clean electricity generation mix. As of 2020, Canada's electricity generation emitted 124 gCO_2 per kWh, compared to a global average of 458 gCO_2/kWh (Figure 1). This advantage comes largely from Canada's rich endowment of non-emitting generation resources, including significant hydropower as well as nuclear power. As a source of firm, predictable electricity, reservoir hydropower[1] is an especially valuable resource in a net zero world, both as a source of non-emitting electricity and as a means of balancing variable generation from sources such as solar and wind. This existing

Figure 1.

Canada has one of the lowest-emitting electricity systems in the world

Thanks to its strong base of non-emitting electricity the emissions intensity of Canada's electricity generation is among the lowest in the world



Sources: IEA (2020); IEA (2021d).

1. Reservoir hydropower refers to collecting and storing water in a reservoir behind a dam and releasing it to generate electricity on demand. This is the most common form of hydropower in Canada and around the world.

base of hydropower also reduces the challenges of integrating high shares of variable renewable energy in some regions, both because smaller shares of renewables will be required and because reservoir hydropower is available to balance out this variability.

Canada is also blessed with significant renewable energy resource potential. In fact, Canada's potential for meeting domestic electricity needs with wind and solar power is among the highest in the world.[2]

Canada's second major advantage is that its electricity systems are supported by robust institutions and structures. Electricity in Canada is reliable and affordable by most standards. However, as we note in our companion report *Electric Federalism*, there remain significant challenges that must be overcome to align Canada's electricity markets and institutions with net zero goals.

Third, Canada has a strong policy foundation to support the transforming of electricity in support of net zero. Canada has implemented a rising, economy-wide carbon price and brought in regulations to phase out coal-fired power entirely. Canada has also committed to net zero electricity generation nationwide by 2035, though implementation details have yet to be worked out.

Despite this strong overall starting position, the regional picture differs (Figure 2). Provinces whose electricity systems are more reliant on fossil fuels face very different challenges than those that already operate primarily on non-emitting electricity such as hydropower and nuclear power. What's more, the differing market and policy landscapes in each province and territory mean that every region's path to net zero will include unique challenges.

Aligning electricity with net zero, is not just about the end result of eliminating emissions from the grid. The way governments across the country choose to pursue this transformation, including the extent to which measures are taken to improve resilience to climate change and other risks, has implications for decarbonization efforts

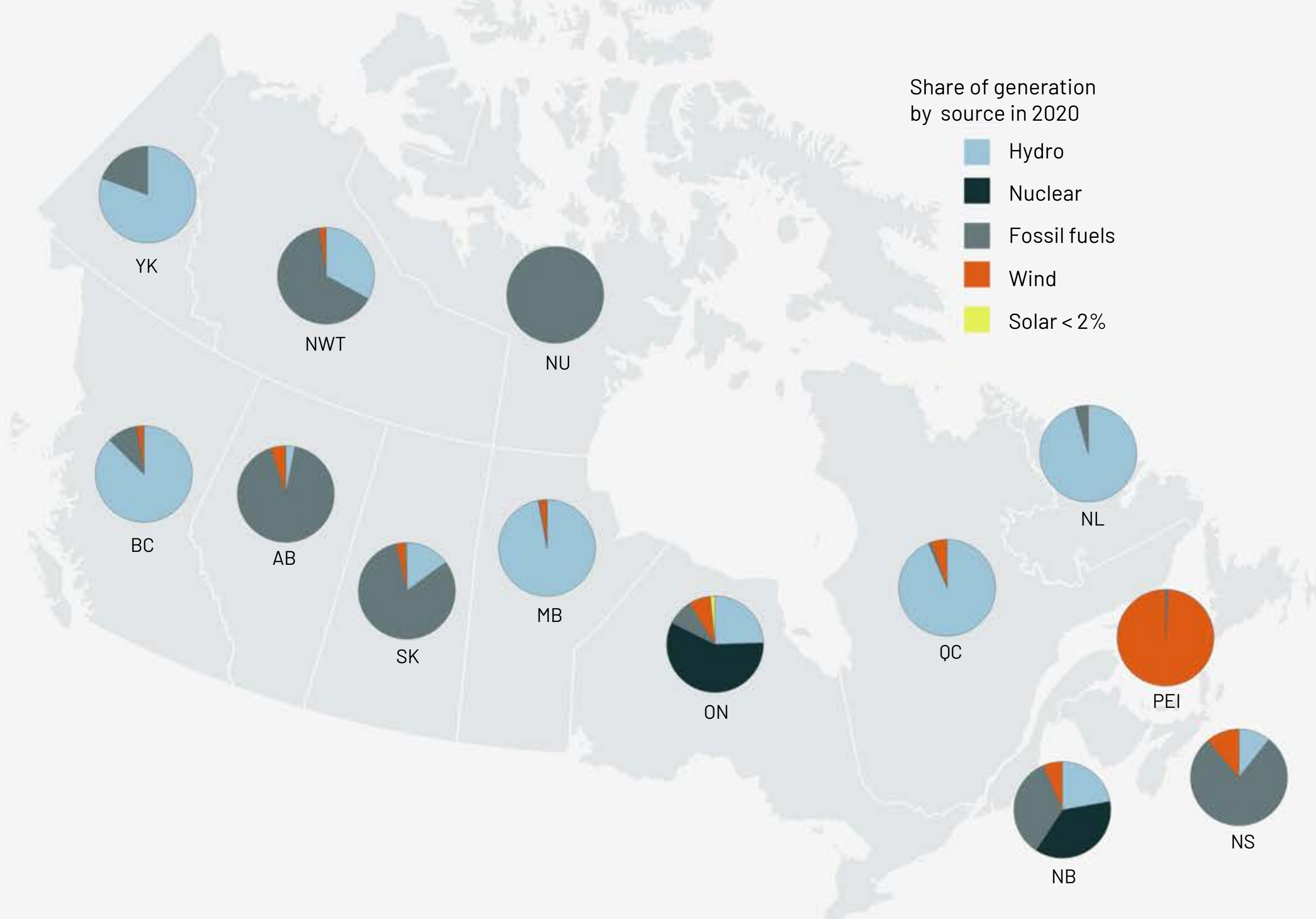
2.Tong et al. (2021) rank Canada's electricity system as the second most reliable among major countries, with a gap between electricity demand and wind and solar availability as one of the smallest of all countries assessed. They do not consider existing assets such as hydropower, which would further enhance Canada's ability to support high shares of variable renewable energy, but do assume perfect interregional transmission, underscoring the value of this measure.

in other economic sectors and significant impacts on the overall cost and fairness of the energy transition (Ness et al. 2021). If resilience-building measures aren't included, this transformation runs the risk of increasing the vulnerabilities of electricity systems to mounting climate impacts, which could have cascading consequences beyond the sector, including the provision of essential services (Clark and Kanduth 2022). Transforming electricity systems to support net zero while also bolstering their resilience to climate and other risks helps future-proof electricity systems and avoids costly (and often unfair) climate damages to these systems.

Figure 2.

Electricity generation sources differ across regions

Regions have different starting points and resources at their disposal



Source: Statistics Canada (2022). Note: PEI imports most of its electricity from neighbouring regions, notably New Brunswick

Transforming electricity also creates opportunities to advance Indigenous self-determination and reconciliation. Ensuring the participation of Indigenous Peoples—for example, through the equity ownership of clean energy projects—can create a pathway for reconciliation and self-determination. Failing to meaningfully consider Indigenous perspectives and roles in energy transitions reinforces harmful colonial relationships (Indigenous Clean Energy 2022).

Net zero electricity systems can also generate future growth opportunities by boosting the global competitiveness of low-carbon electricity, as well as the supply chains of firms that rely on it. For example, greater electrification can help reduce the emissions of carbon-intensive industrial commodities that are globally traded, such as aluminum, steel, and metals and minerals, and help to keep them competitive as global markets shift (Samson et al. 2021).

This report will now examine in detail the three main ways that Canada's electricity systems will need to transform to reach our net zero goals: becoming *bigger* (Section 2), *cleaner* (Section 3), and *smarter* (Section 4). For each of these three, we analyze which safe-bet-and-wild-card solutions could play important roles in enabling that change. Table 1 summarizes these solutions.

Table 1. **Aligning electricity systems with net zero requires making them bigger, cleaner, and smarter**

Doing so relies on both safe bets and wild cards, and each faces a range of challenges

	Technical/cost challenges	Social/political challenges	Other challenges
BIGGER			
Boosting capacity to meet growing demand (2.1)	LOW	MEDIUM: local opposition to new generation, transmission, and distribution projects	MEDIUM: resource planning may not fully consider additional supply needs due to electrification
Accelerating energy efficiency improvements (2.2)	MEDIUM: financial barriers in accessing upfront capital	MEDIUM: information barriers to benefits of efficiency and accessing policy supports	MEDIUM: regulatory barriers in utilities and markets to pursuing efficiency
CLEANER			
Boosting supply from variable renewable energy (3.1)	LOW	MEDIUM: local opposition to some projects	MEDIUM: regulatory barriers especially for small-scale generators and for flexibility measures supporting high shares of variable renewables (see Section 4)

	Technical/cost challenges	Social/political challenges	Other challenges
Enhancing hydropower generation at existing sites (3.2)	LOW	LOW	LOW
Phasing out unabated fossil fuel generation (3.3)	MEDIUM: added costs if assets retired before end of useful life	MEDIUM: opposition from incumbent fossil fuel generators	LOW
Significantly expanding large hydro or large nuclear to new sites (3.4)	MEDIUM: high capital costs and risk of cost overruns	HIGH: social opposition to some large projects	HIGH: environmental barriers; limited suitable new sites; long approval and construction times
Scaling up emerging sources of non-emitting generation (3.5) (see notes)	**VARYING** depending on the source (e.g. low for biomass, high for small modular reactors)	**VARYING** depending on the source (e.g. low for geothermal, high for small modular reactors)	**VARYING** depending on the source (e.g. environmental impacts for tidal, regulatory barriers to small modular reactors)
Equipping fossil fuel and biomass generation with CCUS (3.6)	HIGH: advanced CCUS (applied to electricity generation) currently at demonstration stage	MEDIUM: some public resistance to CCUS	MEDIUM: need for supportive infrastructure e.g. CO_2 transport
SMARTER			
Maximizing the flexibility and predictability of variable renewables. (4.1)	LOW	LOW	LOW
Optimizing existing hydropower resources to complement variable supply (4.2)	LOW	LOW	LOW
Enhancing demand-side flexibility (4.3)	LOW	MEDIUM: consumer resistance to utility-controlled load or dynamic pricing	MEDIUM: regulatory barriers to uptake of demand-side management by utilities
Deploying short-term grid-scale storage (4.4) (see notes)	LOW	LOW	MEDIUM: regulatory and market barriers to deployment, as a "non-wires" resource
Deploying long-term grid-scale storage (4.5) (see notes)	HIGH: depending on the technology, not yet commercialized or has high costs	LOW	MEDIUM: regulatory and market barriers to uptake, as a "non-wires" resource
Deploying emerging sources of non-emitting, dispatchable power (4.6)	**VARYING** depending on the source (e.g. low for biomass, high for small modular reactors)	**VARYING** depending on the source (e.g. medium for CCUS-equipped generation, high for small modular reactors)	**VARYING** depending on the source (e.g. sustainability concerns for large-scale biomass, regulatory barriers to small modular reactors)
Expanding grid integration across regions (4.7)	LOW	HIGH: political and public prioritization of electricity self-sufficiency; local opposition to construction of transmission infrastructure	MEDIUM: misaligned electricity system markets and institutions across regions

Notes: Emerging sources of non-emitting generation include small modular reactors, geothermal, second-generation biomass, and tidal. Short-term energy storage refers to energy storage of up to four hours. Long-term energy storage refers to storage longer than four hours–and sometimes much longer on the daily, monthly, or seasonal time scale.

GLOSSARY *of terms*

Generation: The amount of electricity produced during a certain time period, measured in watt-hours (e.g., kWh, MWh).

Capacity: The maximum amount of electricity that a generator can produce, measured in watts (e.g., MW, kW).

Capacity factor: The actual amount of electricity generated expressed as a percentage of the maximum possible generation during a given time period. For instance, a large nuclear plant that produces electricity almost all day and almost every day of the year operates at a high capacity factor, whereas a wind turbine whose output fluctuates due to the strength of the wind at various times of the day and year operates at a lower capacity factor.

Transmission: The "highways" of the electricity transportation network that carry bulk electricity from large generators to areas of high demand across long distances.

Distribution: The "local roads" of the electricity transportation network that connect the transmission network directly with customers.

Load (or demand): The total consumption of power at any given time.

Peak load and off-peak load: Peak load (or peak demand) refers to the highest demand for electricity within a given time period. Daily peak load generally occurs before and after the standard working day. Annual peak load generally occurs in the winter months in Canada, although rising temperatures mean that many provinces are expected to see peak load shift to summer as demand for cooling rises and winter heating demand declines. Daily off-peak load tends to be in the middle of the night.

Firm generation: Production of electricity that is expected to be available at all times during a given period. Firm or steady electricity comes from sources such as fossil fuels, nuclear, and hydropower.

Variable generation: Production of electricity that fluctuates over time, such as over the course of a day or a year. The best-known sources of variable generation are renewable-—called “**variable renewable energy**” —such as wind and solar.

Dispatchable generation: Electricity production that can be called upon as needed. Common sources of dispatchable generation in Canada include hydropower and fossil fuels.

Balancing the grid: Ensuring supply and demand meet. In systems with higher shares of variable generation, balancing resources such as hydropower, fossil fuel generation, and storage can help complement variable generation to ensure demand is met.

BIGGER

02 *Bigger: Meeting the demand created by widespread electrification*

Boosting electrification to achieve net zero in Canada will mean switching from fossil fuels to electricity for a much wider range of energy needs (see Box 1). This in turn means that in a net zero world, demand for electricity will increase significantly nationwide, and so electricity systems must grow bigger to meet that demand. Our report *Canada's Net Zero Future* identified the widespread adoption of a number of prominent technologies, including electric vehicles and heat pumps, as safe bets in this effort. Policy initiatives directed at promoting electrification and the adoption of electric technologies will be crucial, though they fall outside the scope of this study.

The effort to expand Canada's electricity grids to meet the needs of this transformation will rely primarily on two safe bets: increasing generating capacity and accelerating energy efficiency improvements. We will now look at each in turn.

BOX 1. *What is electrification and how can it help achieve net zero goals?*

Electrification refers to the process of switching energy sources from fossil fuels to electricity—for example, using an electric heat pump rather than a natural gas or oil furnace to heat a building, or switching from an internal combustion engine vehicle to an electric vehicle.

Electrification is crucial to the pursuit of net zero goals for two main reasons. First, because it involves replacing the burning of fossil fuels (e.g., gasoline in a car) with a non-emitting energy source (electricity), electrification reduces emissions, especially as electricity production also becomes cleaner. Second, electrification boosts energy efficiency, because technologies that run on electricity are often much more efficient than those relying on the combustion of fossil fuels. For example, more than 77 per cent of the electricity used by an electric vehicle becomes useful work, providing power to the vehicle's wheels, whereas only 12 to 30 per cent of the energy stored in gasoline is converted to the same end (United States Department of Energy 2021).

Electrification is not, however, a universal solution—the most efficient way to meet net zero goals is not simply to electrify all end uses. Switching to other fuels (such as hydrogen or biofuels) or even offsetting some emissions using negative emissions technologies may prove to be more viable pathways for some sectors, such as heavy industry and heavy-duty transportation.

Electrification is already underway, though the uptake at present is uneven and sometimes independent of climate policies or goals. Demand for electric vehicles and heat pumps, for example, is increasing due to sharply declining costs, while other end uses such as in industrial sectors have been experiencing a long-term trend of de-electrification. Reversing this trend is a significant challenge to be addressed.

2.1 Safe bet: *Boosting capacity to meet growing demand*

To 2050, Canada must grow its generation capacity at a rate three to six times faster compared to the previous decade.

Though there remains significant uncertainty in how the energy transition will transpire, one aspect is clear: reaching net zero will require boosting electricity supply to enable widespread electrification. Electrification will involve both increases in the absolute amount of electricity consumed and increases in electricity's share of total energy consumption. A range of studies conclude that achieving net zero will require an increase in overall electricity generation to become 1.6 to 2.1 times greater by 2050 compared to 2020 levels (Figure 3). Total electricity capacity will need to rise even more, reaching 2.2 to 3.4 times current capacity (Figure 4).[3]

In the near term, total generation must increase from 4 to 25 per cent by 2030 to put Canada on a path to net zero, translating to capacity increases of 13 to 45 per cent. Achieving this means adding between 23 to 53 GW of capacity (including storage) across Canada. To 2050, Canada must grow its generation capacity at a rate three to six times faster compared to the previous decade.[4]

Capacity expansion on this scale—which involves delivering larger amounts of electricity from sometimes remote locations—will likely need to be accompanied by the expansion of transmission and distribution grids within regions, especially as more location-specific renewable energy sources are brought onto grids. (We discuss grid expansion *between regions* in Section 4) However, expanding capacity indiscriminately could lead to inefficient overbuilding of electricity systems. Prioritizing measures such as increasing efficiency and making demand more flexible, would enable capacity to be "right-sized," and only built where it is needed.

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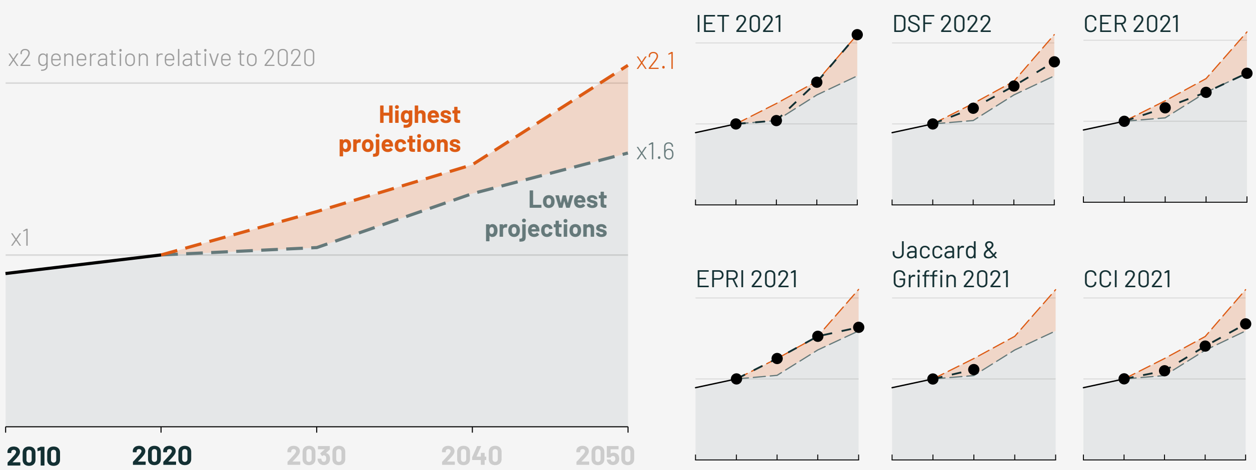
3. Capacity growth will outpace generation growth for two reasons. First, renewable power sources like wind and solar, which will contribute more and more of our electricity supply, tend to run at more variable and ultimately lower rates relative to their maximum capacity. While variable renewable energy is cost-effective even with these lower capacity factors, electricity systems will require more renewable capacity to produce the same amount of electricity as fossil fuels generated. Second, peak demand—the primary driver of capacity—is set to increase more quickly than total demand as electricity systems decarbonize, if overall load is not shifted (Bistline et al. 2021).

4. Comparing average annual net capacity additions from 2010-2020 to 2020-2050.

Figure 3.

On the path to net zero, electricity generation must grow substantially

Studies show generation will be 1.6 to 2.1 times larger by 2050 relative to today

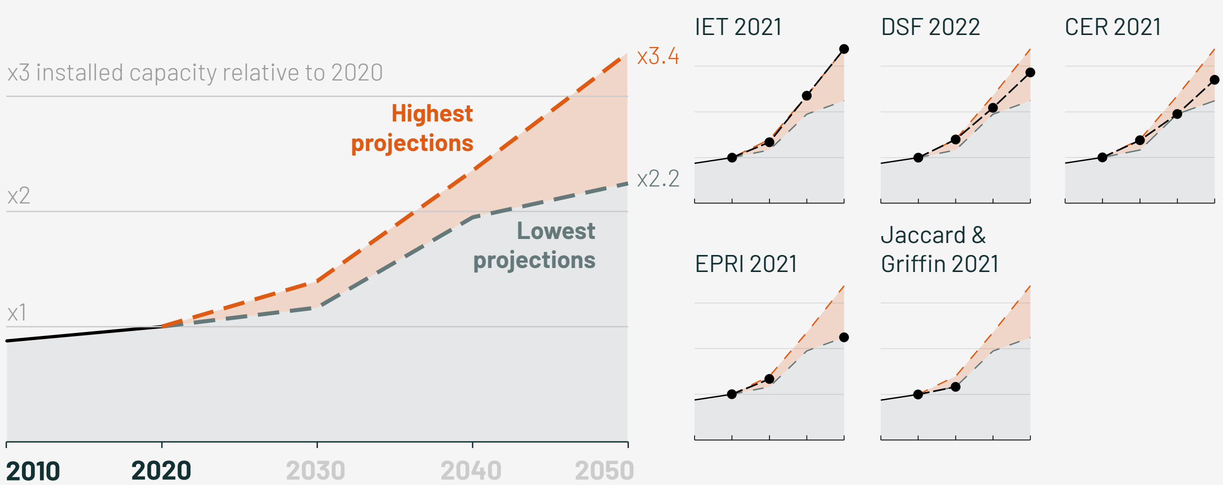


Sources: CER (2021); DSF (2022); CCI (2021); EPRI (2021); Jaccard and Griffin (2021); IET (2021); Statistics Canada (2022).

Figure 4.

On the path to net zero, installed capacity must grow substantially

Studies show capacity will be 2.2 to 3.4 times larger by 2050 relative to today



Sources: Alves (2022); CER (2021); DSF (2022); EPRI (2021); Jaccard and Griffin (2021); IET (2021); Statistics Canada (2019).

2.2 Safe bet: *Accelerating energy efficiency improvements*

Canada has one of the highest rates of energy use per capita in the world, and its potential to improve its energy efficiency in a cost-effective manner is enormous.

Energy efficiency is the quintessential safe bet, playing a critical role in every net zero future identified in our modelling for *Canada's Net Zero Future* (see Box 2). Improving end-use efficiency, primarily through the adoption of more energy efficient technologies and measures, decreases overall electricity demand and can thus reduce the amount of electricity supply required for electrification. (In this way, efficiency acts as an additional type of supply.) Demand can also be shifted to different times of the day, which can also reduce the need for new additions of capacity (see Section 4).

Most studies have found, however, that even with significant increases in efficiency improvements, Canada's electricity demand will grow overall on the path to net zero. Maximizing the technical and economic potential of energy efficiency has been shown in some studies to offset most or even all of this demand growth (Dunsky Energy Consulting 2019; IEA 2018; Robins 2017), but the scale and speed required to do so would face significant financial, behavioural, and informational barriers, and is thus less of a safe bet.

BOX 2. *Energy efficiency is the "first fuel"*

Energy efficiency improvements can be defined as reductions in the amount of energy needed to provide a given unit of energy service, such as heating a square metre of a building or driving a vehicle one kilometre. Energy efficiency involves using energy in smarter, less wasteful ways. This stands in contrast to energy conservation, which reduces the energy service provided (for example, by turning down a thermostat). We distinguish energy efficiency from demand flexibility, which focuses on shifting energy use to times when it costs less to generate, rather than reducing use (see Section 6).

In *Canada's Net Zero Future*, we identified energy efficiency improvements as a safe bet, playing a critical role across all scenarios to net zero by 2050. Energy efficiency is sometimes called a "first fuel," because reducing demand is often less expensive and complicated than the procurement of other generation sources. Canada has one of the highest rates of energy use per capita in the world, and its potential to improve its energy efficiency in a cost-effective manner is enormous, spanning all sectors, including industry, buildings, and a wide range of transportation modes.

Electrification is itself a means of improving energy efficiency because electric end-use technologies are more efficient than ones relying on fossil fuel combustion. But there are many other benefits to improving energy efficiency, including smaller energy bills, reduced vulnerability to energy disruptions, and less reliance on energy imports. By reducing fossil fuel combustion, efficiency also improves air quality, generating public health benefits.

Despite these self-evident benefits, there remains a significant "efficiency gap" between the potential energy efficiency that is economically feasible and the level of real-world uptake. The gap is created by an array of market and behavioural barriers, including:

- insufficient information on energy prices, technology options, or efficiency benefits;
- insufficient access to upfront capital to make energy efficiency investments;
- decision making by consumers not only seeking to reduce financial costs; and
- low energy prices, sometimes maintained to improve energy affordability.

To accelerate energy efficiency, policymakers must provide targeted support in line with net zero and other goals.

CLEANER

03 *Cleaner: Growing clean electricity sources and phasing out polluting sources*

Making the electricity supply cleaner is perhaps the most obvious transformation needed to achieve Canada's net zero goals. Cleaning up the country's electricity supply involves three main elements: increasing the amount of electricity produced by clean sources, reducing fossil fuel sources that emit greenhouse gases, and maintaining existing sources of non-emitting electricity. And, as we saw in the last section, this increase in clean sources of electricity must be sufficient to support higher electricity demand in a net zero world as well as replacing polluting sources of electricity currently on the grid.

Note that the net zero studies we reviewed for this analysis were published before the federal government committed to decarbonizing electricity generation by 2035. Some of their results thus could be inconsistent with this target—for example, by underestimating the growth of clean sources like solar and wind or the decline of unabated fossil fuel sources required to meet this new goal. Despite these limitations, these studies provide valuable insights into the minimum extent of transformation required in electricity systems to support net zero by 2050.

Getting cleaner will require both safe bets and wild cards. The most important safe bet solutions are boosting renewable energy supplies, enhancing existing hydropower supplies, and phasing out unabated fossil fuel use. The most promising wild card solutions are new large-scale hydro and nuclear power, fossil fuel and biomass power with CCUS, and a range of other emerging technologies. We examine each of these potential solutions in detail below.

3.1 Safe bet: *Boosting supply from variable renewable energy*

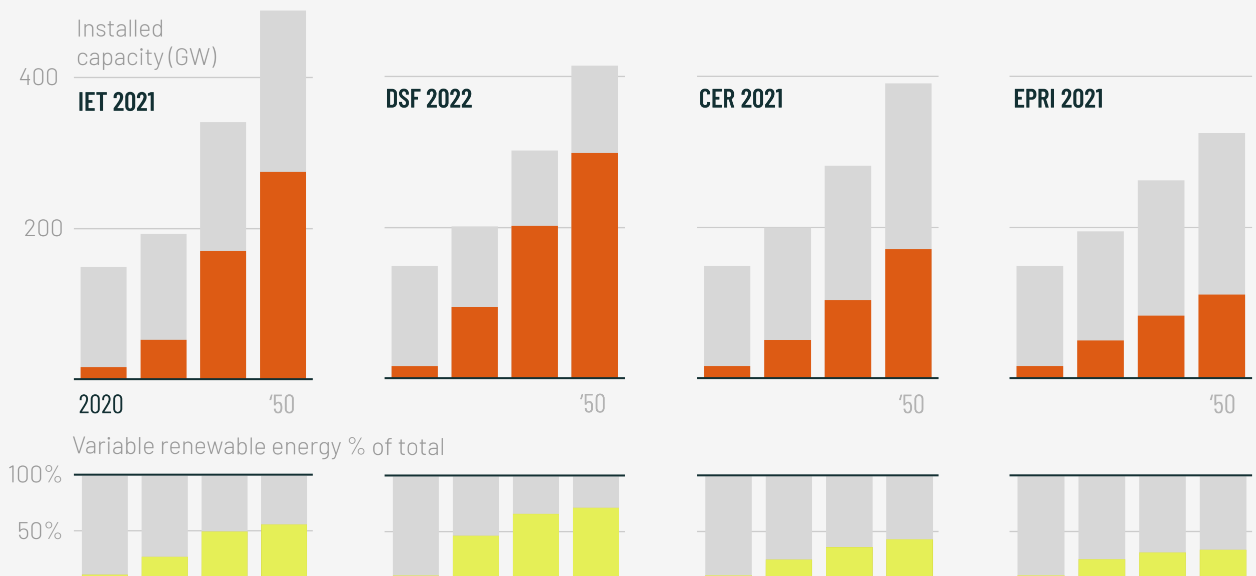
In pursuit of net zero, the share of variable renewable energy in electricity supply will have to increase in every region of Canada, placing it among the most important safe bets for transforming electricity systems. This prominent role stems from the fact that the cost of variable renewable energy—in particular solar photovoltaic and wind power—continues to rapidly decline. From 2010 to 2019 the average cost of solar photovoltaic declined globally by 82 per cent, while the costs of on-shore and off-shore wind declined by 40 per cent and 29 per cent respectively (IRENA 2021).

Studies now consistently show that significant growth in the share of variable renewable energy would occur even without major policy

Figure 5.

On the path to net zero, the share of variable renewable energy must increase significantly

Studies show wind and solar capacity combined will make up 34 to 72% of installed capacity by 2050 compared to 10% in 2020



Sources: Alves (2022); CER (2021); DSF (2022); EPRI (2021); Jaccard and Griffin (2021); IET (2021).

By 2030, 4 to 8 times more wind and solar capacity needs to be deployed compared to the last decade. By 2050, this increases to 9 to 24 times.

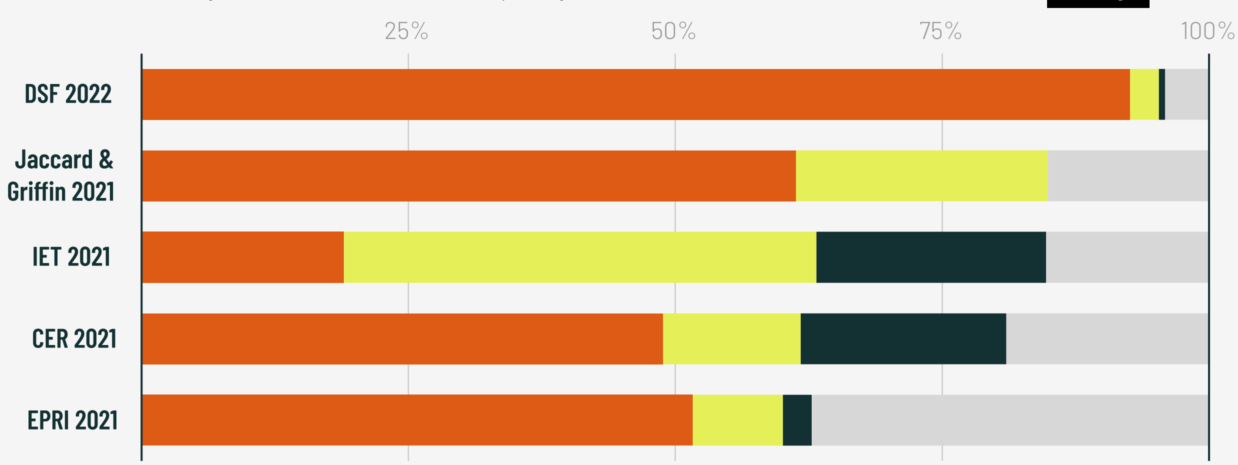
changes. Add in the need to reduce emissions to net zero, and the growth of these sources accelerates significantly (see Figure 5), though the magnitude and type of variable renewable energy uptake will vary by region. By 2030, 4 to 8 times more wind and solar capacity needs to be deployed compared to the last decade in order to support net zero. By 2050, this increases to 9 to 24 times more solar and wind capacity. This means that the large majority of capacity added to 2030 must come from solar and wind, with studies showing 60 to 95 per cent of (gross) capacity additions coming from these sources. Including storage, 63 to 96 percent of capacity additions come from these three sources (Figure 6).

Wind is likely to play a greater role in electricity supply than solar in Canada, owing to the higher potential for wind power and higher value of wind to meet demand at critical times of the day and year.[5] The *rate* of growth for solar capacity, however, is projected to be higher, as it begins from a much lower capacity level.

Figure 6.

On the path to net zero, most new capacity to 2030 must be wind and solar

Studies show that by 2030, 63-96% of new capacity additions will come from solar, wind, and storage



Sources: Alves (2022); CER (2021); DSF (2022); EPRI (2021); Jaccard and Griffin (2021); IET (2021). Note: Other capacity additions include hydropower, natural gas equipped with CCUS, and other renewables.

5. *Electrification in support of net zero can increase winter morning demand peaks—a time when wind generation tends to be higher than solar generation, increasing the value of wind compared to solar generation (GE Energy Consulting 2016).*

We have categorized boosting Canada's supply of variable renewable energy as a safe bet, but its scale-up is not without its challenges. For instance, variable renewable energy requires greater land use than fossil fuel plants to generate the same amount of electricity, creating friction with local residents. Such opposition has already slowed or halted the development of renewable energy projects—wind in particular—across Canada. Supply chain challenges can also create barriers to rapidly scaling up renewables.

The majority of new variable renewable energy capacity is likely to come from large, utility-scale projects, but many of the studies we reviewed do not explicitly consider small-scale generation. Those that do indicate that small-scale, distributed generation—rooftop solar in particular—will play a growing role to 2050 (see Box 3).

BOX 3. *Distributed energy resources play a growing role in Canada's net zero future*

Distributed energy resources include small-scale, behind-the-meter resources located on-site to serve consumer load as well as front-of-meter resources connected directly to the local distribution system. This differs from the majority of electricity generation, which is large-scale and connects to the larger transmission system.

Several types of distributed energy resources have potential in Canada:

- Supply-side: on-site (typically rooftop) solar photovoltaic panels; on-site micro-cogeneration (also known as combined heat and power) using non-emitting sources; small-scale stand-alone wind and solar farms; small-scale hydro connected directly to the distribution system.
- Demand-side: controllable loads such as electric water heaters and space heating and cooling systems.
- Storage: electric vehicle batteries can be used as storage, including those using vehicle-to-grid technologies; other battery systems located on-site and serving a consumer's load as well as small-scale, front-of-meter storage.

The use of distributed energy resources provides benefits for the broader electricity system in several ways:

- Generation: avoiding the need for peaking generation, which is often emissions-intensive as it commonly comes from fossil fuel sources.
- Capacity: avoiding costly additions of new capacity to meet future peak demand.
- Transmission and distribution: avoiding or deferring upgrades of transmission and distribution infrastructure, as distributed energy resources place more resources closer to the customers.
- Resilience: reducing the vulnerability of centralized assets to disruptions and providing backup energy.
- Locational value: expanding the diversity of locations over which variable renewable electricity is generated, reducing overall variability of generation.
- Responsiveness: they can be deployed more quickly compared to utility-scale resources.

However, there are significant challenges to the deployment of distributed energy resources. These technologies face more difficult economics compared to larger-scale projects that benefit from economies of scale, and studies have found that they can increase distribution network costs in some circumstances (Wolak 2018). Utility and market structures, which were developed to serve centralized, baseload supply, often fail to incentivize the uptake of cost-effective distributed energy resources. And increasing use of distributed energy resources can encourage defection from the centralized utility and grid, creating another disincentive for utilities to support their uptake.

At present, there is insufficient research regarding the benefits of distributed energy resources at a system scale in Canada, which vary depending on capital costs, the location of the distributed energy resources, and overall system characteristics. (Some work has been done to assess these benefits in the United States by Clack et al. 2020). Existing studies tend to consider only distributed generation without considering broader distribution systems and possible interactions with the larger grid, and they often fail to examine broader benefits of distributed energy resources such as enhanced resilience to disruptions. Research is also limited on where and at what scale distributed energy resources deployment in Canada would be most beneficial. Existing studies anticipate growth in the deployment of distributed generation (primarily rooftop solar) in Canada's low-carbon future, though their share of capacity or generation by 2050 is forecast to remain modest (EPRI 2021, Langlois-Bertrand et al. 2021, Yauch and Lusney 2021).

3.2 Safe bet: *Enhancing hydropower generation at existing sites*

Enhancing generation at existing sites of reservoir hydropower, which is non-emitting, firm and dispatchable, is a safe bet in electricity systems transformation in pursuit of Canada's net zero goals. This measure is technically and economically viable today, and it avoids the negative environmental impacts and regulatory challenges of new large-scale hydro projects. Because reservoir hydropower can be called upon to generate electricity on demand (also called "dispatchable"), it is useful as a means of balancing the variability of sources like solar and wind, filling in supply gaps when these sources cannot generate power. As wind and solar take on larger roles, dispatchable hydropower will become more valuable.

However, Canada's hydropower capacity is aging, so the first step in implementing this safe bet is refurbishing these assets to maintain or extend their lifetimes. This could include improving the performance of existing turbine-generators, replacing old turbine-generator units with more efficient ones, or adding new turbine-generators or pump-turbine units. Analysis of the potential to upgrade Canada's existing reservoir hydropower is limited at present. One study (Arjmand et al. 2019) however, identified about 1500 MW in additional capacity hydropower refurbishments by 2030. The potential for refurbishing hydropower projects in Canada is reinforced by Indigenous Clean Energy (2022), including as a means for supporting Indigenous reconciliation and participation in electricity sector transitions.

We discuss the deployment of other hydropower resources below, including the significant expansion of hydropower generation onto new sites (Section 3.4) and the deployment of pumped storage hydropower (Section 4).

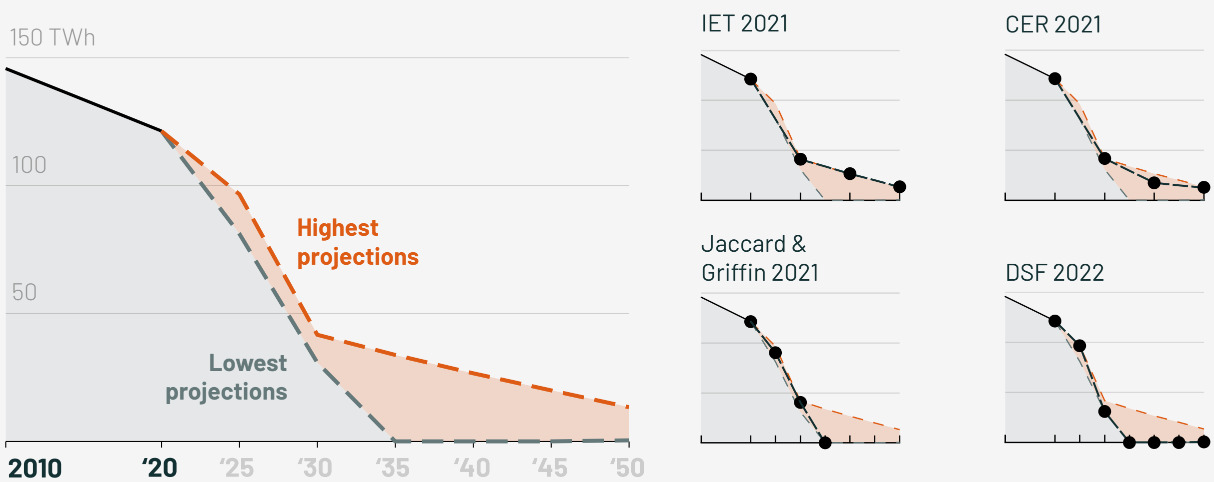
3.3 Safe bet: *Phasing out unabated fossil fuel generation*

Transforming electricity systems is not just about adding clean sources to the electricity supply but eliminating emitting sources, which is why we have assessed phasing out almost all unabated fossil fuel generation as a safe bet. Studies show that unabated fossil fuel generation (i.e., supply that isn't equipped with carbon capture, utilization, and storage, or CCUS [6]) is limited to one per cent of Canada's electricity by 2050 in order to reach our net zero goals (see Figure 7). This phase-out applies both to grid-scale generation and to smaller-scale generation such as combined heat and power or cogeneration.[7]

Figure 7.

On the path to net zero, unabated fossil fuel generation must be phased out

Studies show that unabated fossil fuel generation will reach at most 14 TWh in 2050, or 1% of total generation



Sources: CER (2021); DSF (2022); Jaccard and Griffin (2021); IET (2021); Statistics Canada (2022). Note: To meet the federal government commitment to a net zero electricity system by 2035, any remaining fossil fuel generation after 2035 shown by these studies must be offset. EPRI (2021) is excluded from this figure as its 2035 emissions are not compatible with the federal commitments. DSF (2022) and Jaccard and Griffin (2021) both achieve phase-out of unabated fossil fuel generation by 2035.

6. Because emissions capture rates are less than 100 per cent and because the utilization of carbon (the U in CCUS) potentially results in other emissions, emissions would need to be offset in other ways in order for CCUS to be compatible with net zero goals.
7. Combined heat and power generation, primarily reliant on natural gas, would need to be converted to non-emitting fuels (e.g. biogas or hydrogen) or be offset by other measures in order to be compatible with net zero.

Canada is already working to phase out coal-fired power generation that isn't equipped with CCUS by 2030. This transition is well underway nationwide and nearly completed in some provinces. The federal government has further committed to achieving a net zero electricity system across Canada by 2035, which has similar implications for natural gas-fired generation. Natural-gas generation without CCUS is thus the next challenge. The growth in unabated natural gas generation, such as that seen in Ontario, risks undermining net zero goals unless it can be phased down or retrofitted with CCUS, a step which is likely to come at significant cost even if it proves viable. Therefore, not constructing new gas-fired capacity is a critical part of this safe bet, since it will be more economical to deploy CCUS at existing facilities than to build new ones that have to be equipped with it.

There are multiple pathways to achieving a generation mix that is not reliant on fossil fuels and consistent with net zero (Figure 8). Though studies assessed show a diversity of paths, they all show that it is possible.

Because the net zero studies assessed in this analysis were all developed before the federal government committed to a goal of net zero electricity by 2035, not all of the results shown will necessarily meet this target. Meeting the new target would require any remaining fossil fuel generation by 2035 to be equipped with CCUS or offset in some other way (such as negative emissions technologies). Although studies indicate that unabated fossil fuel *generation* will be effectively phased out entirely by 2050, some show a small amount of unabated natural gas *capacity* remaining in the 2050 electricity mix (EPRI 2021; CER 2021). This would involve natural gas plants running sparingly (i.e., at lower capacity factors) as sources of dispatchable power. To be consistent with net zero, however, their emissions would have to be offset by negative emissions occurring elsewhere. Our analysis assesses both CCUS and negative emissions as wild cards.[8] (We discuss equipping fossil fuel plants with CCUS in Section 3.6 and examine the possibility of retrofitting existing fossil fuel infrastructure with alternative fuels such as hydrogen in Section 4.6).

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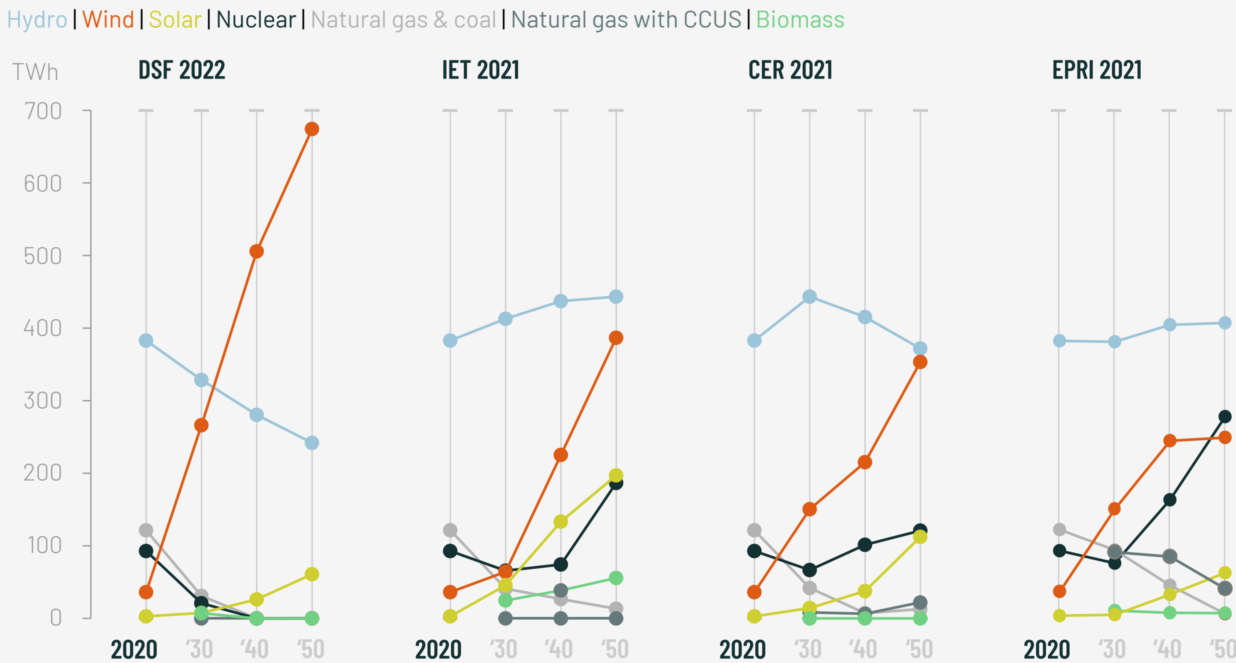
8. *We discuss negative emissions technologies as wild cards in our report* Canada's Net Zero Future.

Figure 8.

On the path to net zero, multiple sources of clean electricity displace fossil fuels

Studies illustrate a range of possible generation mixes



Sources: CER (2021); DSF (2022); EPRI (2021); IET (2021); Statistics Canada (2022).

3.4 Wild card: *Significantly expanding large hydro or large nuclear to new sites*

We consider significant growth of legacy sources of non-emitting power—namely large hydro and large nuclear power plants—to be a wild card. Studies tend to find little or no growth in these sources in net zero scenarios.

Although expanding these sources relies on commercially available technology, both new large hydro and large nuclear plants face high and uncertain costs. Beyond the challenging economics, these types of projects could encounter significant social resistance, owing to environmental and social impacts as well as concerns about cost overruns (see Box 4). Recent greenfield hydro projects have faced especially strong opposition over inadequate consideration of Indigenous rights, including land rights.

BOX 4. *The significant expansion of large hydro and nuclear supply faces challenges*

Large-scale hydro and nuclear plants have numerous obvious benefits. They provide the bulk of electricity generation in Canada today, supplying firm, non-emitting electricity. They are the primary reasons Canada's electricity generation mix is as clean as it is. And because their fuel costs are low, they have relatively low operating costs once construction is completed. Large hydro is especially easy to dispatch, meaning it can be called upon to generate electricity whenever needed—a strong asset for electricity systems that need to balance increasing shares of variable renewable energy. In addition, the existence of these significant resources of non-emitting electricity means that so long as their supply is maintained, shares of variable renewable energy need not be as high in order to achieve net zero. This can make the challenge of integrating high shares of solar and wind more manageable for certain regions.

However, despite the value of large hydro and large nuclear electricity, significantly expanding these sources faces numerous challenges. New large reservoir hydro projects can pose negative environmental impacts including disrupting river flow, damaging ecosystems, and releasing significant methane emissions when reservoirs are flooded (though this is mostly the case only if existing vegetation is not cleared). They also may face public opposition over the choice of site, in part due to impacts on Indigenous lands and livelihoods. Two of Canada's most recent hydro projects—the Muskrat Falls project in Newfoundland and the Site C dam in British Columbia—have faced construction delays and cost overruns because of these challenges. While these controversial projects have received substantial attention, others such as the Romaine Complex in Quebec, which although are not devoid of social opposition, have been completed on time and on budget.

New large nuclear projects also face high capital costs and risks of cost overruns, as well as social opposition stemming from concerns around nuclear waste and the risk of nuclear accidents. While refurbishments may face less public opposition and fewer regulatory hurdles compared to new plants, concerns about project cost overruns remain. We discuss small modular reactors in Box 8.

3.5 Wild card: *Scaling up emerging sources of non-emitting generation*

There are a number of emerging electricity sources with high potential to contribute to achieving net zero. All of them, however, face significant uncertainties regarding technical and economic viability, social and political barriers, or both—which is why we have classified them as wild cards. Some prominent examples include small-scale nuclear energy in the form of small modular nuclear reactors (see Box 8), bioenergy (such as that derived from forestry or agricultural residues), geothermal energy, and tidal power. The potential for these sources varies significantly across regions, and their deployment and scaling up would encounter significant technical barriers. All of them would also have to become much cheaper in order to be deployed rapidly and at large scale. As well, some of these emerging sources—such as small modular reactors—could face strong social opposition.

Table 2 summarizes the strengths and drawbacks of both emerging and more mature sources of non-emitting electricity in Canada.

Table 2. **There are both safe bets and wild cards in non-emitting electricity**

Variable renewable energy and additional hydropower at existing sites are safe bets; many other solutions are wild cards.

	Strengths	Drawbacks
Variable renewable energy (notably solar and wind)	Rapidly declining capital costs Low operating costs Requires less water compared to hydro-power and thermal generation	Generates electricity variably and intermittently Requires greater land use than thermal generation, and large projects may face local opposition
Reservoir hydropower: increasing generation at existing sites	Dispatchable Low operating costs Avoids flooding of new areas and associated challenges of "greenfield' hydropower developments (see next)	Limited potential to increase generation without increasing capacity Physical climate changes can affect generation
Reservoir hydropower: significant expansion to greenfield sites	Dispatchable Low operating costs (including fuel)	Best sites for both reservoir and run-of-river have been exploited; limited potential for developing new sites Social and environmental costs for some projects, including impacts on Indigenous lands and livelihoods High capital costs and cost uncertainty Physical climate changes can affect generation

	Strengths	Drawbacks
Significant expansion of large nuclear	Dispatchable Low operating costs Nuclear less geographically constrained compared to renewable energy	High capital costs, as well as cost uncertainty Low public acceptability for new plants Nuclear is less dispatchable Physical climate changes can affect generation
Small modular reactors	More dispatchable than large nuclear plants Can be co-located with demand Modular nature allows capacity to tailor to demand levels Potentially faster to build	Not yet commercially proven Possible public opposition, including safety concerns, similar to large nuclear plants Regulatory challenges to deployment High capital costs and cost uncertainty
Bioenergy (see notes)	Potential to generate negative emissions when paired with CCUS Could be used in refurbished fossil fuel plants	Challenges for securing supply in a sustainable manner Generates higher non-CO_2 emissions than other sources Requires water to produce, especially if using first-generation resources
Natural gas + advanced CCUS	Low capital costs for natural gas plants Allows for continued use of existing natural gas facilities Dispatchable Less constrained geographically	Advanced CCUS has few commercial installations Significant energy needed to achieve high capture rates and without 100% capture rates, would require residual emissions to be offset Does not address upstream emissions associated with natural gas extraction Higher non-CO_2 emissions than other sources Vulnerable to hydrologic changes affecting availability of cooling water
Geothermal	Minimal environmental or social barriers Size can be matched to demand Consistent and predictable generation, but also scalable	High capital costs Site-specific (though some advanced types may be less so if they prove technically viable)
Tidal	Consistent and predictable generation	High capital costs Negative environmental impacts including on marine life Geographically constrained
Hydrogen (an energy carrier, see notes)	Diverse applications, including storage and energy production from curtailed variable renewable electricity Can be used in refurbished fossil fuel plants	Not yet commercially proven High costs Electrolysis requires significant electricity supply

Notes: Advanced CCS refers to post-combustion carbon capture and storage, which captures flue gases from power plants following combustion of fossil fuels. We focus on second-generation sources of bioenergy including from forest and agricultural residues. Hydrogen is not technically a source of electricity but rather an energy carrier. However, since it can be used to generate electricity, we include it in this table.

3.6 Wild card: *Equipping fossil fuel and biomass generation with CCUS*

In electricity generation, the share of CCUS in a net zero future remains modest, comprising at most 4% of generation in 2050 when deployed.

Most advanced forms of carbon capture, utilization, and storage (CCUS) technology are still in the early stages of development, and we have classified it as a wild card for reaching Canada's net zero goals. (The type of CCUS used with concentrated flue gas streams generated by industrial processes is relatively advanced technologically and a safe bet, but it is not applicable to electricity generation.) Yet CCUS has enormous potential, as it would allow some fossil fuel-fired generation to become aligned with net zero goals by largely or even entirely neutralizing its emissions. [9] Its application to natural gas generation would allow natural gas to remain a valuable source of dispatchable power. Pairing CCUS with biomass-fuelled electricity could even result in net negative emissions.

Studies diverge on the role of natural gas with CCUS and biomass-fuelled electricity, largely due to the uncertainty in future costs and availability of infrastructure such as pipelines for CO_2 transport that would support CCUS deployment. Nonetheless, in electricity generation the share of CCUS remains modest across all net zero studies, with CCUS-equipped electricity generation comprising a range from less than 1 to 4 per cent of the national generation mix in 2050 (when deployed) (Figure 9). In *Canada's Net Zero Future*, we determined that in scenarios where the costs of CCUS decline rapidly and storage and pipeline infrastructure become readily available, both natural gas and (to a smaller extent) bioenergy paired with CCUS contribute meaningful shares to the 2050 generation mix. Under more conservative assumptions regarding CCUS cost decline and infrastructure availability, however, CCUS plays a more limited role. In these scenarios, a shift to a fully decarbonized electricity system without fossil fuels is more decisive. We found that such an outcome would also generate substantial health benefits through the reduction of air pollution.

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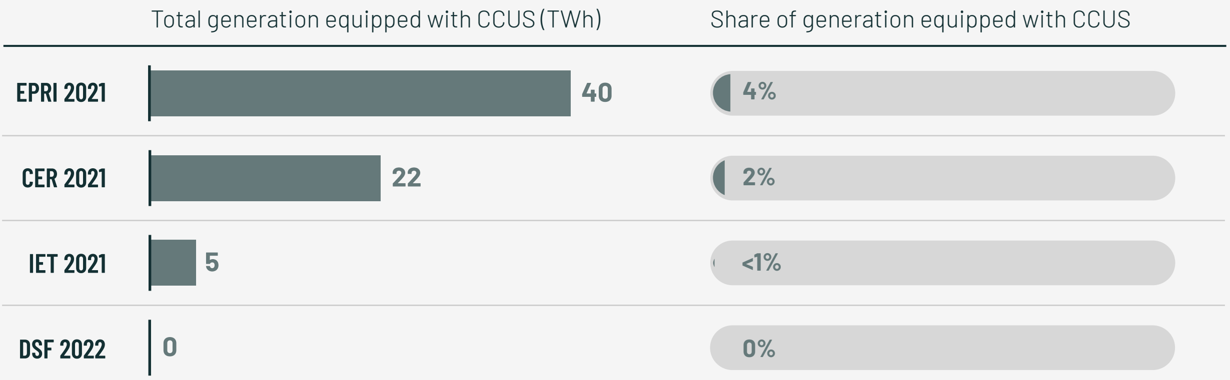
9. Due to emissions capture rates being less than 100 per cent and the utilization of carbon (the U in CCUS) resulting in potential emissions, emissions would need to be offset in other ways in order for CCUS to be net zero compatible.

Figure 9.

On the path to net zero, CCUS likely plays a modest but valuable role

Studies show that while CCUS-equipped generation can provide valuable dispatchable electricity, it contributes at most 4% of generation in 2050 when deployed



Sources: CER (2021); DSF (2022); EPRI (2021); IET (2021).

SMARTER

04 *Smarter: Making systems more flexible to support variable supply and boost resilience*

Enhancing the flexibility of Canada's electricity systems—their ability to manage variability in supply and demand in a cost-effective manner over time—is crucial to transforming electricity systems. As the country's electricity systems begin to see rising shares of variable renewable energy, the need for flexibility will grow in tandem (See Box 5). In addition to the variation in supply driven by solar and wind energy, there are other variations in both supply and demand that increase the importance of smarter, more flexible systems. Some of these can be anticipated (such as increased demand at certain times due to electric vehicle charging), while others are unanticipated (such as a supply disruption due to extreme weather). Flexibility enables grids to accommodate larger loads at different times, and it can reduce the costs of enhancing system reliability and resilience. By improving a system's response to supply disruptions caused by extreme weather and long-term seasonal weather patterns, for example, greater flexibility lowers the cost of managing climate impacts. Indeed, flexibility has always been valuable, and its value only increases as electricity systems grapple with the need to become bigger, cleaner, and more resilient due to climate change.

BOX 5. *Increasing reliance on solar and wind poses real but manageable challenges*

The primary challenge facing solar and wind is summed up in the old cliché that "the wind doesn't always blow and the sun doesn't always shine." As the share of variable renewable energy on Canada's grids increases, this variability in supply creates challenges for existing electricity systems, which were designed to work with mostly fixed and predictable production from sources of firm, centralized, and dispatchable power.

The intrinsic characteristics of variable renewable energy pose a handful of challenges for today's electricity systems:

- their production is variable throughout the day and throughout the year, and does not necessarily match demand;
- their production is constrained by location;
- they have limited dispatchability to be called upon to generate at a given time; and
- they pose other technical challenges, such as generating asynchronously with the main grid.

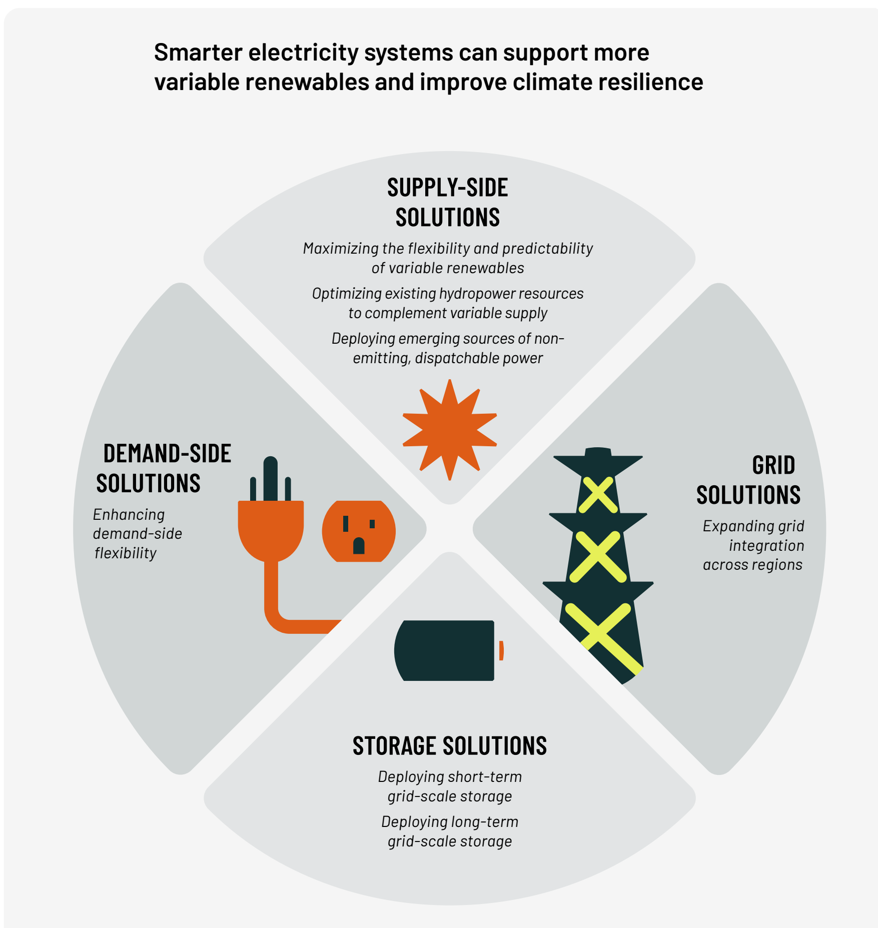
When the share of the electricity system's mix generated by renewables remains low (such as 10 per cent or lower), these challenges have only minor impacts on the system (IEA 2019). But when variable renewable energy's share becomes the majority of total generation at any given period, system flexibility becomes a significant need.

The challenge posed by variable renewable energy cuts to the core organizational principle of modern electricity systems, obliging them to evolve from meeting peak demand with baseload generation to supporting higher variable renewable energy shares and other transformative changes through system-wide flexibility. Thankfully, an array of technologies and practices now exist to improve the flexibility of electricity systems. Many measures to support integration of high variable renewable energy shares are well understood and widely in use around the world, including jurisdictions that already operate electricity systems with high shares of renewables such as Denmark, Ireland, and Germany. Our case study on Germany describes how one region within the country is already operating a grid with 60 per cent renewable capacity, targeting 100 per cent renewable generation by 2035 (Turner 2021).

We have summarized the most significant means of increasing electricity system flexibility in the figure below (Figure 10). Traditionally, supply-side solutions such as dispatchable electricity sources have provided the default means of enhancing electricity system flexibility. However, other options—including demand-side measures, grid-level measures, and storage—are becoming increasingly viable through innovation and expanded use around the world. A recent international study (IEA 2021c) reveals a major shift in sources of electricity system flexibility to achieve global net zero emissions by 2050. In G7 countries, fossil fuels currently provide two-thirds of hourly flexibility, but to achieve net zero by 2050, more than half of their flexibility needs would be met by demand-side flexibility and batteries, with the contributions from natural gas and coal supply significantly diminished.

Figure 10.

There are many ways to manage the variability of solar and wind



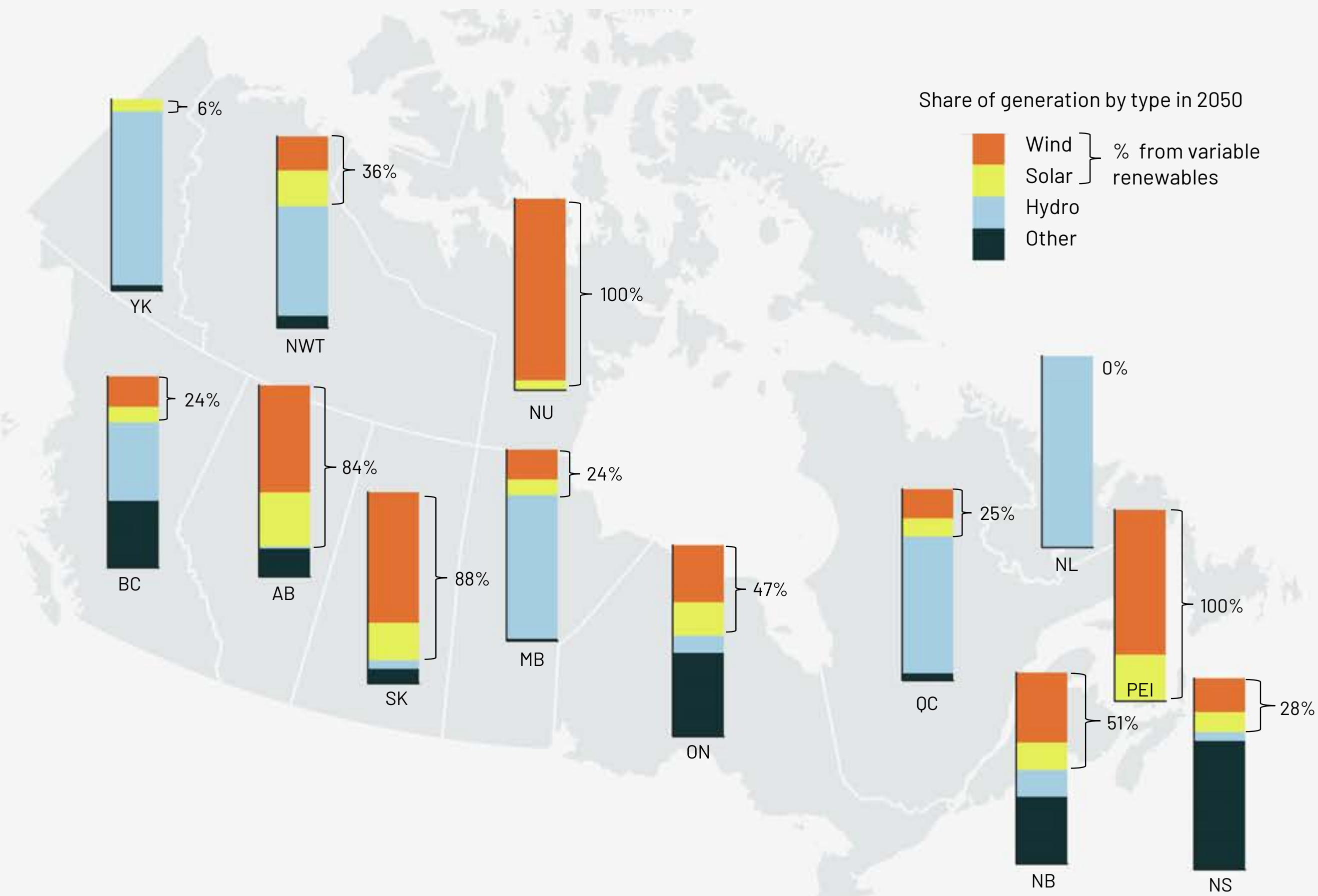
When variable renewable energy's share becomes the majority of total generation at any given period, system flexibility becomes a significant need.

In Canada, the flexibility needs of regions will differ depending on the shares of variable sources in their generation mixes (Figure 11). Regions that develop higher shares of solar and wind—those that tend to be more reliant on fossil generation today—will see greater needs for flexibility. They will also face additional challenges in that they cannot rely on abundant hydropower within their borders as their main source of flexibility. However, these regions will still have an array of other flexibility resources at their disposal (Figure 10)

Figure 11.

Regions that adopt larger shares of solar and wind will require more flexibility

Coordinating with neighbouring regions with dispatchable hydropower can help support more variable renewables



Source: IET (2021). Note: This figure displays electricity generation projections in 2050 from an illustrative net zero scenario. "Other" includes primarily nuclear, biomass, and fossil fuels paired with CCUS.

including enhanced interregional grid integration. As Figure 11 illustrates, all regions that see higher shares of solar and wind in a net zero world have a neighbour with dispatchable hydropower resources. Enhancing integration across hydro-rich regions and those with high shares of variable renewables, can serve to balance the variability of solar and wind.

4.1 Safe bet: *Maximizing the flexibility and predictability of variable renewables*

Variable renewable energy sources are crucial safe bets in the pursuit of net zero. Although they increase the amount of variability in electricity systems, additional measures can reduce their variability and improve their predictability. These include:

- diversifying both the location and type of variable renewable energy by developing both solar and wind power plants over diverse locations, to smooth overall variability (Figure 12);
- improving the accuracy of wind and solar forecasting, which allows system operators to better respond to variability; and
- introducing the right policy and operating rules to maximize the ability of variable renewable energy to contribute to flexibility (for example, connection codes can require variable renewable energy to provide frequency regulation [10]).

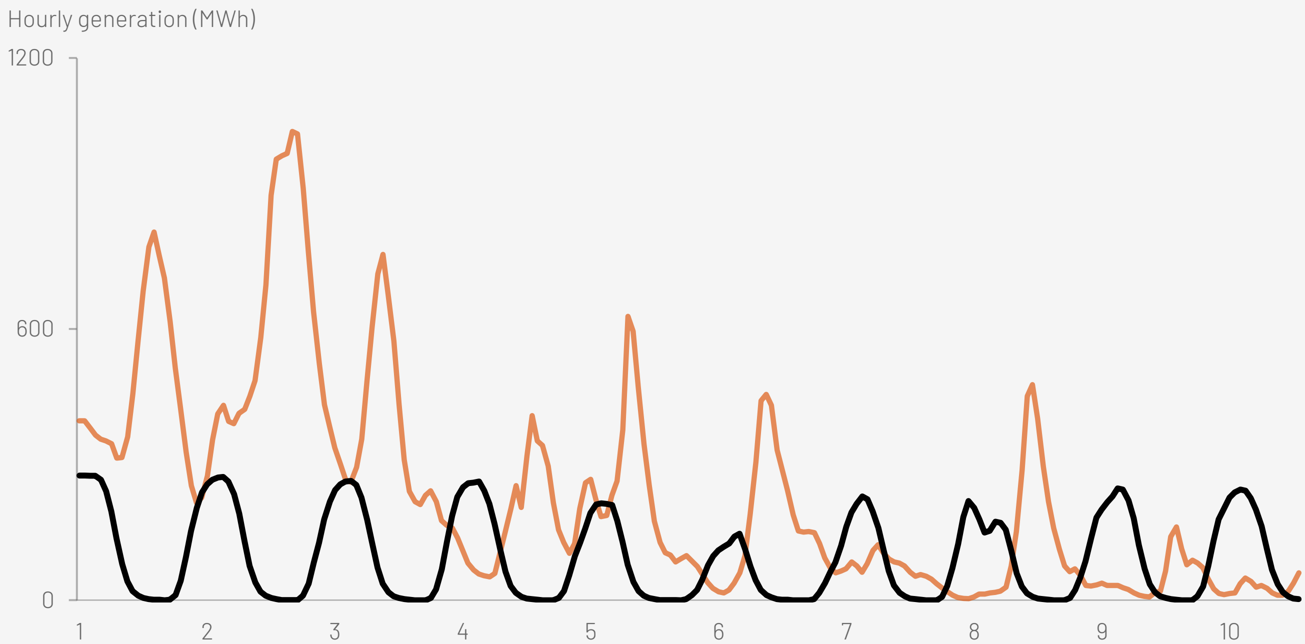
Measures to improve the flexibility and predictability of variable renewables are unlikely to be sufficient on their own, however, as they can reduce but not eliminate their inherent variability and intermittency. Other flexibility mechanisms will thus be essential to the net zero project, as we discuss below.

10. Frequency regulation refers to the act of adjusting electricity generation to ensure the maintenance of a certain frequency across the electricity system, in response to changes in demand. Imbalances in frequency can result in damage and overall system instability. Electricity generators typically respond in seconds to adjust their generation to correct frequency imbalances. Typically, rampable thermal generation sources provide frequency regulation.

Figure 12.

Wind and solar generation can complement each other

Diversifying both the type and location of solar and wind installations can smooth overall variability



Source: AESO (2021). Note: This figure shows wind and solar generation in Alberta in 2021 over a 10-day period in July, showing the complementarity of these sources: solar generation is highest mid-day while wind generation is highest at night.

4.2 Safe bet: *Optimizing existing hydropower resources to complement variable supply*

Optimizing existing hydropower resources, which are abundant in many Canadian jurisdictions, represents a safe bet for electricity systems transformation. Hydropower provides both non-emitting electricity and, as a readily dispatchable source of electricity, offers a reliable way to balance variable renewable energy as it increases in use. (Using interties to extend this use to provinces without abundant hydropower resources is a wild card which we discuss in section 4.7)

Hydropower resources can also be used for energy storage (see Box 6). In those provinces and territories that already have a strong base of reservoir hydro, including Quebec, Manitoba, British Columbia, Newfoundland and Labrador, and Yukon, these assets can be optimized for use as energy storage. Reservoirs can fill when solar and wind electricity is being generated, with this stored energy tapped to meet demand when needed. Another form of hydropower storage is pumped storage hydropower (discussed below), which entails pumping water to a different elevation for energy storage.

Hydropower's role in the energy transition, however, must take into account the impacts of climate change, which may include reduced or increased inflows and increased inflow variability (Clark and Kanduth 2022). Given the critical role for hydropower resources in Canada's current and future electricity systems, ensuring these resources remain resilient in a changing climate becomes all the more important.

4.3 Safe bet: *Enhancing demand-side flexibility*

Demand-side flexibility, which involves measures that shift the timing of electricity demand (particularly during peak demand times), is a safe bet for Canadian electricity systems transformation. Examples of demand-side flexibility include shifting electric vehicle charging or the operation of major appliances to off-peak hours or periods that better match wind and solar production. This can be achieved through consumer response to more dynamic pricing and utility control of loads.

Enhancing the flexibility of demand creates opportunities to adjust demand to better match with growing shares of variable supply, in contrast to the traditional approach of procuring supply to meet more or less fixed levels of demand. While the traditional forms of flexibility have been on the supply side, there is a growing role for demand-side measures to boost overall system flexibility. In fact, the (IEA 2021b) states that to achieve global net zero emissions by 2050, demand-side measures become the most important source of electricity system flexibility globally, contributing 30 per cent of flexibility needs in the sector.

While demand flexibility is already growing in Canada, expanding it to a much larger scale will face social and regulatory barriers. The implementation of dynamic retail pricing, for example, is likely to encounter political barriers, while consumers may resist large-scale utility control of demand (Wolinetz et al. 2018). Current market and regulatory structures also create barriers to expansion, due in large part to procurement and incentive structures that do not fully value the benefits that non-traditional sources of electricity supply such as demand-side management, distributed energy resources, storage, and transmission can bring (see our companion report, *Electric Federalism*). Overcoming these barriers, however, could create significant benefits. Several studies show that more flexible electricity systems reduce peak demand, which in turn reduce generation and capacity requirements (see Table 3). These studies also likely underestimate the full benefits of more flexible demand, since they do not consider benefits at the distribution level and for system resilience.

Table 3. **Enhancing demand-side flexibility has multiple benefits**

Benefit	Description
Generation	Reduces need for peaking generation, which tends to be higher in cost and/or come from emitting sources such as natural gas
Capacity	Reduces need for additional peaking capacity, commonly provided by fossil fuel sources
Transmission & distribution	Reduces or defers need to upgrade distribution infrastructure, which would be otherwise required to accommodate significant and simultaneous increases in load (such as EV charging) Reduces or defers need to upgrade transmission infrastructure
Resilience	Reduces vulnerability to disruptions if non-essential electricity uses can be temporarily reduced and/or shifted Provides frequency regulation

In Canada, policies to enhance demand-side flexibility have had limited uptake to date. Ontario is the only Canadian jurisdiction that has implemented time-of-use pricing, which varies consumer rates based on system-level generating costs to provide demand-side incentives to shift consumption away from peak demand times. (Lessem et al. 2017) estimated that time-of-use pricing has reduced summer peaks by a range of 1.1 to 3.6 per cent per year as of 2014. Deployment of remote load control measures and technologies has also been limited on Canadian grids, but it represents a significant opportunity. (Doluweera et al. 2020) have found that coordinating EV charging in Alberta could result in 1050 MW avoided capacity in 2031 (assuming a

30 per cent EV penetration rate). Another study (Wolinetz et al. 2018) determined that at the much higher penetration rate of 98 per cent by 2050, utility-controlled EV charging could result in 5100 MW avoided capacity in British Columbia and 4380 MW in Alberta.

4.4 Safe bet: *Deploying short-term grid-scale storage*

Short-term electricity storage is an important flexibility tool to balance the variability of solar and wind supply and a safe bet in Canadian electricity systems transformation. Short-term storage—for up to four hours—allows for electricity, especially from variable sources, to be stored and used at a later time to better match demand (see Table 4). It also reduces the amount of variable generation that is "wasted" or curtailed, which happens, for instance, when wind turbines produce more energy than demanded at a given time. The ability to store and dispatch electricity in this way—from peak times of wind production (late at night and early morning), for example, to peak demand times (before and after work hours)—will increase in value as the shares of wind and solar grow.

Table 4. **Deploying electricity storage has multiple benefits**

Type of benefit	Description
Supply-side	Reduces the need for capacity, if used to reduce peak loads and smooth demand peaks Reduces curtailment of variable generation Supports frequency balancing
Transmission and distribution	Eases congestion and strain within transmission and distribution systems, deferring costs of upgrading this infrastructure
Demand-side	Consumer-scale storage allows consumers to shift demand away from peak times when electricity rates are higher Consumer-scale storage supports the uptake of consumer-level "behind-the-meter" generation, such as rooftop solar PV
Resilience	Grid-scale storage can provide backup supply and resilience to disruptions "Behind-the-meter" storage can act as a backup power source for individual customers Long-term storage can support seasonal shifts in demand, such as higher space cooling demand in the summer

Grid-scale lithium-ion batteries are one of the main short-term storage technologies considered a safe bet, owing to their current commercial availability, declining costs, and increasing importance, especially in jurisdictions without strong hydropower resources.[11] Pumped storage hydropower can serve as both short- and long-term storage, which we discuss below. We don't formally consider reservoir hydropower without pumped storage capabilities as energy storage in this report, though recognize it has storage functions (Box 6).

BOX 6. *Hydropower reservoirs can play a role in storage*

Pumped-storage hydropower involves pumping water to a different elevation into a reservoir and releasing it through turbines when supply is needed. By doing this, pumped-storage hydropower serves as storage, absorbing and releasing energy on demand the same way a battery does. It is the typical form of energy storage for hydropower resources.

On the other hand, reservoir hydropower (i.e., hydropower dams without pumped storage) is mostly viewed as a form of electricity generation, and is not typically included in traditional definitions of storage. However, reservoir hydro can still act as storage. When other electricity sources are producing, reservoir energy can be held back (by stopping the turbines), then dispatched later as needed. It can be stored this way for hours, days, or even months. Quebec's reservoirs, for example, have over 170 TWh of storage capacity—equivalent to the province's annual electricity demand—and have been collectively referred to as a potential "battery" for the Northeast region of Canada and the United States (Dimanchev et al. 2021; Aubin 2021). This hydropower resource could be called upon to generate electricity as a balance for variable renewable energy or to meet demand fluctuations. Quebec could also "absorb" excess variable renewable generation from other regions when production exceeds local demand by importing and consuming some of this excess production and allowing reservoir levels to rise. The importing regions would also benefit from this arrangement by selling variable renewable generation into Quebec's market that would otherwise be curtailed.

One significant difference between hydro reservoirs and other forms of storage, including pumped hydro, is that the "charging" of reservoirs cannot occur on demand but rather relies on refilling through natural processes.

11. Because reservoir hydro can serve as storage, hydro-rich provinces such as Quebec, Manitoba, British Columbia, and Newfoundland and Labrador may have more limited needs for additional storage.

Studies indicate that short-term storage will play a growing role in achieving net zero, but the level of deployment depends in part on the uptake of other flexibility resources (Arjmand and McPherson 2022; CER 2021; EPRI 2021). For example, enhanced grid integration and increased electricity trade (see Section 4.7) could significantly reduce the need for short-term storage (Dolter and Rivers 2017), as could the availability of hydrogen as storage (CER 2021; see Section 4.5) and demand-side flexibility (Bistline 2021; see Section 4.3). In practice, however, it's unlikely that any of these measures will fully replace the need for short-term battery storage.

Despite their obvious benefits, short-term storage technologies face barriers to deployment because their full value in electricity systems—including their role in flexibility—isn't recognized by current regulatory and market structures (Hastings-Simon and Kanduth 2021). We discuss these and other barriers in our companion report, *Electric Federalism*.

4.5 Wild card: *Deploying long-term grid-scale storage*

Long-term storage—storing electricity for periods longer than four hours, often much longer—could play a valuable role in enhancing flexibility, since solar and wind generation vary not just from day to day but also season to season. But the leading long-term storage technologies all face significant challenges and we consider them wild cards in the transformation of Canadian electricity systems.

Long-term storage encompasses a diverse range of technologies, including pumped-storage hydropower, compressed air storage, flow batteries, and hydrogen. (Hydrogen is unique among these, able to use electricity as both an input and an output, as only one of these, or as neither; see Box 7.) The challenges vary for each technology, but all of them will encounter high costs as a critical barrier to their wide deployment.

Few Canadian studies to date have explicitly examined the role of long-term electricity storage, in part because the early-stage development of these technologies makes it difficult to represent them in model

BOX 7. *Hydrogen could play diverse roles in Canada's net zero future*

Like electricity, hydrogen is an energy carrier, not an energy source itself. It requires energy to be produced by another source, which can then be used directly or converted to other forms of energy, including electricity. Electricity and hydrogen can be highly complementary energy carriers, potentially operating as connected parts of a future net zero energy system, as we discuss in *Canada's Net Zero Future*.

Within the electricity system, the role of hydrogen can take several forms:

- as a means of diversifying the energy mix and enhancing system resilience by reducing vulnerabilities to disruptions to a given supply source;
- as a means of absorbing excess solar and wind generation, thereby reducing curtailment; and
- as electricity storage, when electricity, such as excess solar and wind power, is used to produce hydrogen (through electrolysis) and then later reconverted into electricity.

Hydrogen can also serve as a direct replacement for fossil fuels in sectors that are more difficult to electrify, such as heavy industry and heavy-duty transportation, providing an alternative (or complementary) path to electrification. Hydrogen's ability to fully or partially replace fossil fuels (the latter through blending) is aided by it being broadly compatible with existing fossil fuel infrastructure, though in many cases full compatibility would require retrofitting to support hydrogen production, use, and transportation.

We consider hydrogen to be a wild card due to its nascent stage of development and uptake. High costs both for production and for end-use technologies such as fuel cells represent significant current barriers. Hydrogen's compatibility with net zero goals also depends on how it is produced. At present, hydrogen production relies primarily on fossil fuels (producing "grey" hydrogen), but it could become a significant contributor to the transformation of Canada's electricity systems either by switching to renewable sources (producing "green" hydrogen) or being equipped with carbon capture utilization and storage (producing "blue" hydrogen).

frameworks. On pumped-storage hydropower, however, (Arjmand and McPherson 2022) and (Arjmand et al. 2019) identify numerous potential sites in Canada, though limited deployment is anticipated in low-carbon scenarios due to high costs. Only one pumped hydro project is currently operational in Canada (in Ontario), though several have been proposed, including one at a former coal mine in Tent Mountain in Alberta.

4.6 Wild card: *Deploying emerging sources of non-emitting, dispatchable power*

There are a number of emerging sources of firm, non-emitting power with the potential to provide flexibility in a net zero future (see Table 1). All of these technologies, however, still face significant barriers to large-scale deployment and are considered wild cards in Canada's electricity transformation.

Some of these firm sources are readily dispatchable (able to deliver electricity on demand), including natural gas equipped with CCUS, biomass, and hydrogen. These technologies likely offer the strongest support to grid flexibility. Nuclear energy—both large nuclear and small modular reactors—is technically dispatchable, though current technologies become less economical when they are regularly ramped up and down; some types of proposed small modular reactors are designed to overcome this limitation (see Box 8). The same is true of traditional geothermal energy, though advanced forms of geothermal energy may prove to be dispatchable and able to follow load.

4.7 Wild card: *Expanding grid integration across regions*

At present, Canada's electricity systems are planned and operated separately by each province and territory, in relative isolation from one another. Enhancing electricity integration across regional borders could play a major role in enhancing system flexibility and expanding access to other sources of non-emitting and dispatchable electricity, especially hydropower (see Table 5). In contrast to the other wild cards presented in this report, deploying this solution does not face any meaningful technical barriers (see Table 1): it relies on commercially available technology, and can be done at relatively low financial cost. We categorize this solution as a wild card because it faces significant political, social, and institutional barriers. These stem in large measure from electricity system planning and operation decisions being made primarily at the provincial and territorial levels, resulting in differing regulatory structures and regionally isolated, uncoordinated decision-making (Pineau 2021).

BOX 8. *Small modular reactors offer big potential but high uncertainty*

Small modular reactors are an emerging nuclear energy technology that has several potential benefits over large nuclear generation. Because they still face significant barriers to wider scale deployment, with most forms not expected to become commercially viable for at least another decade, they are considered wild cards in the transformation of Canada's electricity systems.

If small modular reactors can eventually be deployed at scale, they have the potential to contribute significant amounts of firm, non-emitting electricity in Canada. They could also be sized and sited based on demand, with much lower construction time and costs compared to large-scale nuclear plants. Depending on the technology, they may act as replacements to fossil fuel base load supply or small-scale diesel generation, or they may complement variable renewable generation.

Some kinds of small modular reactors (such as Natrium technology) can also act as energy storage (World Nuclear News 2020). Because these technologies can generate heat in addition to electricity, that heat can be stored and converted back to electricity at a time when the value of that supply is higher.

Small modular reactors are not yet commercially viable, however, and they may face social opposition similar to large nuclear plants, especially in jurisdictions where experience with nuclear power is limited. A commercial supply chain for certain fuels would also need to be established, and there are additional regulatory barriers to project approvals and deployment. And not all small modular reactor technologies are designed to be dispatchable, so their ability to enhance flexibility may vary compared to other non-emitting and dispatchable sources of electricity such as hydropower.

The benefits of grid integration are well understood. Numerous studies have highlighted these potentially significant benefits, which would accrue both between Canadian regions and between Canada and the United States. Deeper integration would enable emissions reduction targets to be met at significantly lower costs, enhance the resilience of electricity systems, and deliver benefits to all parties. Canada has significant potential to benefit from increased grid integration, which in particular would allow for non-emitting, dispatchable resources, such as hydropower, to be shared across regions. In fact, each region in Canada that will see high shares of solar and wind on the path to net zero, has a neighbouring region with strong hydropower resources (Figure 11).

Table 5. **Enhancing interregional grid integration has multiple benefits**

Benefit	Description
Lowering costs of reducing emissions	Reducing need to build additional capacity of dispatchable supply to support variable renewable energy, or to fulfill reserve margins for reliability
Supporting variable renewable energy integration	Facilitating access to sources of non-emitting, dispatchable electricity to balance variable renewable energy Diversifying the supply base by providing access to other electricity generation sources located at different sites and generating at different times (including variable renewable energy) Reducing variable renewable energy curtailment by providing access to a higher and more diverse set of demand sources
Supporting reliability and resilience	Expanding and diversifying the supply base to reduce vulnerability to disruptions of a single supply source Providing access to backup supply sources in case of disruption

What's more, most of these studies only assess the benefits of physical integration on emissions reductions (i.e., increasing the physical trade of electricity across regions through interties). Many tend to exclude the explicit consideration of institutional integration and enhanced resilience. (Institutional integration [12] refers to increased coordination in design and operation of electricity systems, including the dispatch of power plants and capacity planning across regions.) And benefits of grid integration are only compounded when measured as part of achieving net zero, which studies show could save billions of dollars annually in pursuit of deep reductions targets (see Table 6).

Despite these known benefits, enhanced grid integration faces major challenges. Expanding grid integration is somewhat unique as a wild card in our analysis given that the barriers it faces are almost exclusively political, social, and institutional in nature; technologically, this measure is deployable at relatively low costs today.

Among the main barriers, grid integration's progress is hampered by the prioritization of regional electricity self-sufficiency, the misalignment of electricity markets and institutions across regions, aversion to losses on incumbent plants, and concerns for ratepayer impacts (Pineau 2021; Martin 2018). Expanding physical transmission infrastructure may also face opposition from local communities. Indigenous communities experiencing the encroachment of physical

12. *Institutional integration could also mean coordinating the development of resource plans across regions, or sharing resources used as reserves in the case of supply disruptions.*

transmission infrastructure on their lands and territories may also oppose projects due to lack of mutual benefit stemming from the projects. This range of barriers explains why there has been such limited progress to date on enhanced interregional grid integration, even as its upside has only grown. Still, overcoming the barriers to expanding interregional integration could offer massive cost-savings to Canadian households, businesses, governments, and rate-payers as Canada seeks to align electricity systems with net zero. Our companion report, *Electric Federalism* and our scoping paper by (Pineau 2021) delve further into the barriers of enhanced grid integration in Canada and suggest ways to overcome them.

Table 6. **Grid integration makes economic sense**
Studies estimate large savings from increased interregional grid integration

Study	Dolter and Rivers (2017)	Sarasty et al. (2021)	Dimanchev et al. (2020)	Brinkman et al. (2021)	Doluweera et al. (2018)
Regions in scope	All Canadian provinces (no territories)	QC, ON, NE, NY, ATL	NE, NY, QC	All Canadian provinces (no territories), US	BC, AB, SK, MB
Scenario	100% reduction in electricity sector emissions by 2050	90% reduction in electricity sector emissions by 2050 (from 1990)	100% reduction in electricity sector emissions by 2050 (from 1990)	92% emissions reductions nationally by 2050 (from 2005)	80% emissions reduction by 2050 in the four provinces (from 2005)
Nature of enhanced integration	Increased (high-voltage direct current) transmission capacity and trade across regions	"Deep integration" through enhanced cross-border electricity trade, optimal transmission capacity expansion, pooled capacity for peak load requirements	Increased transmission capacity and increased trade between QC and NE and NY each	Increasing transmission infrastructure along with coordinated operation would help economics and reliability to cushion increased dependence on meteorological factors	Doubling of interregional intertie capacity Shared GHG target across the four provinces
Estimated savings	$4.2 billion/year 26% savings compared to current transmission	$1.4 billion/year	$3.4 billion/year 17-28% savings compared to current transmission	Up to $9.6 billion/year	$12 million/year

QC = Quebec; ON = Ontario; NE = US New England states; NY = New York State; ATL = Canadian Atlantic provinces; BC = British Columbia; AB = Alberta; SK = Saskatchewan; MB = Manitoba. Where required, cost savings were annualized and converted to CAD2022.

BOX 9. *Remaining gaps in the modelling of Canadian electricity systems*

A rich body of research and analysis on the low carbon transformation of Canadian electricity systems has already been amassed. There remain several crucial gaps in the modelling, however, and addressing them could improve our understanding of the implications of the transformation. These gaps include:

- Limited consideration of Canada's latest 2030 emissions reduction target (40–45 per cent reduction from 2005) and 2050 net zero target, owing to their relatively recent adoption (most studies consider less stringent mitigation targets).
- Coarse temporal resolution in the representation of electricity dispatch and load; only some studies represent these at the hourly resolution.
- Limited representation of physical climate impacts or broader resilience, including change in demand patterns, or impacts on electricity supply. Reliability or resilience are not represented beyond the adequacy of capacity or reserve margins.
- Limited representation of electricity demand response; electricity demand is often exogenously determined.
- Insufficient or coarse representation of "behind the meter" distributed energy resources and distribution systems in general.
- Limited representation of small- and community-scale generation, including Indigenous-owned projects.
- Limited representation of Canada's territories and of off-grid electricity systems.
- Limited integration between electricity and other fuel markets (e.g., using electricity to make hydrogen)
- Insufficient or coarse representation of storage, especially long-duration storage.
- Insufficient open-access data across regions (e.g., data on distribution systems), as noted in our 2020 study *11 Ways to Measure Clean Growth* (Arnold et al. 2020)

CONCLUSION

05 *Key takeaways for Canada in aligning electricity systems with net zero*

Transforming Canadian electricity systems is a crucial first step to meeting Canada's climate commitment of reaching net zero emissions by 2050. Our analysis indicates that there are enough safe-bet and wild-card solutions at hand that make the goal readily achievable, even if significant barriers must be overcome along the way. We have summarized six key takeaways from this analysis below.

This transformation will provide benefits and opportunities across the country and in many important sectors of the economy, but these can only be unlocked if policies are put in place to provide the necessary foundations for the project. We examine the policy implications of our analysis in full detail in the companion report, *Electric Federalism: Policy for aligning Canadian electricity systems with net zero.*

1. *Reaching economy-wide net zero requires three critical transformations in electricity systems*

To meet Canada's net zero goal, the country's electricity systems must undergo three transformational changes, becoming bigger, cleaner, and smarter:

1. They must grow bigger to support widespread electrification, and the growth in electricity demand that it entails.
2. They must become cleaner in order to reduce the emissions associated with how electricity is generated, by accelerating the growth of clean sources, phasing out of polluting ones, and maintaining existing non-emitting sources.
3. They must become smarter (or more flexible) to support growing shares of variable sources such as solar and wind, and enhance resilience to rising climate impacts.

In particular, this report shines a light on the need for the less obvious changes required for electricity systems to be compatible with net zero. It is not enough for electricity systems to get cleaner, strictly speaking. For electricity to become a backbone of Canada's net zero future, electricity systems must also grow bigger and become smarter and more flexible.

These broad changes are deeply interconnected and interdependent. Growing bigger, for example, without ensuring that new capacity is clean and/or supports system flexibility enhances the risks of building assets that will later be stranded.

2. *Aligning electricity systems with net zero is possible and the key to net zero by 2050*

Our analysis shows that transforming Canadian electricity systems to align with net zero goals is achievable, and doing so will require both safe-bet and wild-card solutions. Even though some of these solutions—especially wild cards—may never prove sufficiently viable or cost-effective to scale, there are a sufficient number of potential routes to building electricity systems for a net zero world that the transformation is well within reach.

The federal government has committed to making net zero electricity nationwide a reality by 2035. This goal is consistent with larger economy-wide net zero goals, but it is insufficient by itself to drive all the necessary changes to align electricity systems with net zero. Still, it is a necessary and technically achievable step in that process.

The technical viability of aligning electricity systems with net zero by making them bigger, cleaner, and smarter is an important finding, negating one of the most common arguments against the shift away from fossil fuel generation—that a system largely (or entirely) reliant on non-emitting, especially renewable, generation would be less reliable than current systems. Not only have we found that such systems could function reliably, these systems are already up and running in other jurisdictions with high variable renewable shares. Our case study on the next-generation grid project in the German state of Schleswig-Holstein, for example, discusses how the state operates with renewable sources currently comprising 60 per cent of capacity and was able to successfully operate at 100 per cent in a recent pilot project (Turner 2021).

3. *Many key barriers to electricity systems transformation are not technical, but social and institutional*

Technological readiness is an important challenge for the advancement of some net zero solutions, such as hydrogen and CCUS. But some of the most significant barriers impeding the broader electricity transformation are not technical but rather social and institutional in nature. We consider the deployment of variable renewable energy to be a safe bet from a technical point of view, for example, but current regulatory and market structures are not yet set up to value and reward the flexibility required to support higher shares of solar and wind (see the companion report, *Electric Federalism*). Local opposition is another barrier that could hinder the deployment of both safe-bet and wild-card solutions, and it has already done so for some renewable energy projects in Canada.

Enhancing interregional integration of grids is a textbook example of a solution where social and institutional barriers are the main impediment. Expanding integration including interties between provinces can be readily achieved at low cost using available technology. But this source of flexibility remains a wild card because the political and regulatory barriers it faces are so complex and deep-seated (we discuss how to address these barriers in *Electric Federalism*). The significant expansion of large reservoir hydro and large nuclear plants to new sites and the acceleration of energy efficiency and demand-side flexibility also face non-technical barriers.

4. *Regions without abundant hydroelectricity face different challenges to hydro-rich regions*

Canada's vast geography produces a diverse range of challenges on the path to net zero. Because the resource endowments of the provinces differ so greatly, each will need to take its own path to transform its electricity system. The presence or absence of significant hydroelectricity resources has a particularly strong impact on the challenges each region will face.

Hydro-rich regions will likely face relatively fewer challenges decarbonizing existing supply. They will, however, still need to sort out how to increase electricity supply and determine the role for measures like storage and enhanced integration with neighbouring regions (both as a means of enhancing system flexibility and as a way to reduce the costs of meeting emissions reduction targets).

Provinces without significant hydroelectric power, however, face different and arguably greater challenges—especially those that rely to a significant extent on fossil fuel generation. Achieving net zero will require these jurisdictions to transition away from emitting generation sources while simultaneously increasing overall capacity and generation. However, many of these regions possess renewable energy resources, which represent significant opportunities. To address flexibility challenges associated with higher shares of variable renewable energy these regions cannot rely on local hydropower. Other safe bets, such as demand-side flexibility and short-term battery storage, may be necessary to make important contributions to flexibility. But they likely will not be able to meet all flexibility needs, ensuring a greater reliance on wild card flexibility solutions such as natural gas with CCUS, small modular reactors, and expanded grid integration with other regions. Other than grid integration, these wild card solutions all face significant technical barriers to deployment.

Remote and off-grid communities, meanwhile, will face their own unique challenges (see Box 10).

BOX 10. *Remote and off-grid communities face unique challenges*

Approximately one in eight Canadians lives in a remote or less accessible region, characterized by low population density and inaccessible geography (Subedi et al. 2020). These communities, many of which are in northern Canada, tend to have higher energy consumption than the Canadian average due to lower building energy efficiency and colder climates. They also tend to be dependent on expensive diesel for electricity generation, translating to higher electricity bills than the Canadian average, even with bill subsidization (Lovekin and Hereema 2019) (Figure 13).

Indigenous Peoples are disproportionately represented in rural and remote communities, so electricity transformation presents an opportunity to advance the critical goals of Indigenous reconciliation and self-determination alongside the pursuit of net zero. Other opportunities are represented by the increasing viability of certain technologies such as solar and wind power, small hydropower and battery storage as their costs decline.

Remote communities are highly diverse, but many face shared challenges regarding the transformation of their electricity systems including:

- higher costs of delivering energy services to remote locations;
- entrenched reliance on existing fuels such as diesel, due in part to bill subsidization;
- reduced potential or higher costs for developing some sources of non-emitting electricity supply (climate variability and harsh conditions, for example, can make the adoption of renewables more technically challenging, and smaller-scale projects often do not benefit from economies of scale);
- regulatory barriers to the deployment of distributed energy resources, including small-scale renewable energy projects;
- lack of human capacity for the construction, operation, and maintenance of clean energy projects; and
- constraints in the adoption of certain end-use technologies (electric vehicle charging infrastructure may be less developed in these communities, for example, and the use of both electric vehicles and heat pumps can be more constrained in extremely cold climates).

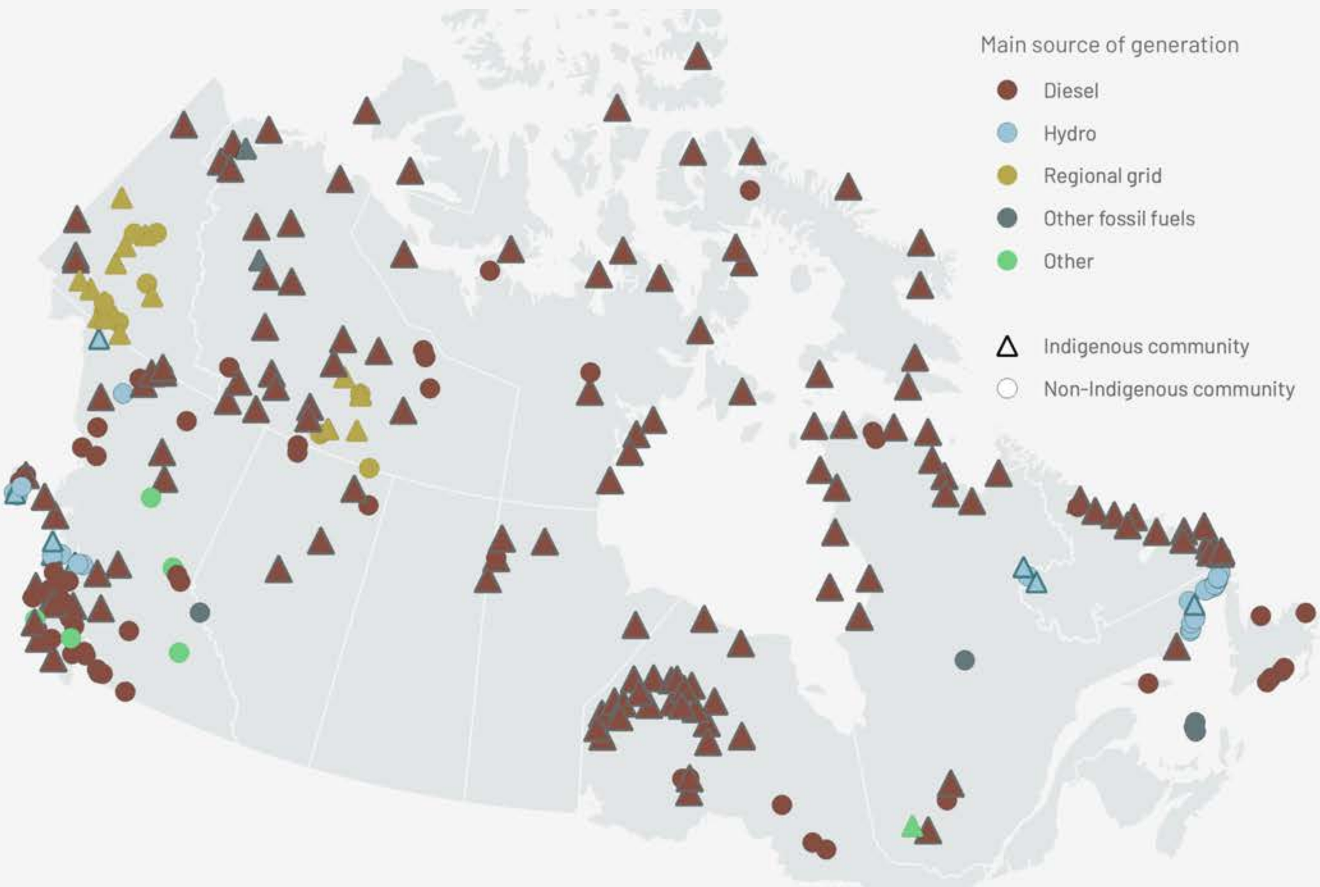
Overcoming these challenges will require targeted approaches. These include:

- Supporting Indigenous-led and Indigenous-owned projects that provide electricity for local grids (e.g., microgrids) through formal independent power producer policies.

- Expanding the valuation of project benefits to include local economic development, energy affordability, Indigenous sovereignty, air pollution benefits, and system flexibility and resilience (which may include rethinking rate design and project cost recovery).
- Building in required resources for capacity-building and operation and maintenance of projects from the start.
- Prioritizing energy efficiency to reduce energy needs, including in housing.

Figure 13.

Many off-grid communities rely on diesel as their main source of electricity generation
Indigenous communities are disproportionately represented in communities reliant on diesel



Source: Natural Resources Canada (2018). Notes: "Indigenous community" is used as a collective term for communities that identify as First Nations, Inuit, or Métis. "Regional grid" is an additional category for communities in Yukon and Northwest Territories that are connected to the territorial electricity grid. "Other fossil fuels" includes natural gas and heavy fuel oil. "Other" refers to generation sources categorized as unknown in the raw data.

5. *Successful transformation of electricity systems requires Indigenous leadership*

Indigenous governments, communities, and organizations are both leaders and participants in electricity systems transformation. The pursuit of net zero also takes place within the context of a crucial agenda to advance Indigenous reconciliation and self-determination, necessitating policies that advance both objectives, or at a minimum don't detract from either one. Advancing Indigenous reconciliation and self-determination requires forging new Indigenous-settler relationships in Canada, by ensuring meaningful involvement of Indigenous Peoples across the development of policies, measures, and decisions, that drive electricity systems transformation. Steps towards this include incorporating Indigenous perspectives into electricity planning, and proactively recruiting Indigenous candidates to utilities and other decision-making bodies. It also means ensuring Indigenous Peoples take a driving role in identifying and capturing clean energy opportunities, for example as owners of clean electricity projects (Indigenous Clean Energy 2022). Fundamentally, successful transformation of Canadian electricity systems in support of net zero requires real engagement and leadership of Indigenous Peoples along the way.

6. *Different orders of government must drive changes through policy*

The transformation of Canadian electricity systems in the three crucial ways we've identified—becoming bigger, cleaner, and smarter—will require substantial new public policies as drivers of these changes. This does not mean that every solution requires its own unique policy response, an approach that would risk being too binding and prescriptive. What is required instead is policies that can allow coherent outcomes to emerge across possible options. This will likely require both institutional and market reforms. But it will also require stringent, economy-wide climate policy.[13]

Canada has a strong foundation to build on. Economy-wide carbon pricing, as well as established provincial and federal standards and regulations for electricity all play a significant role. However, these climate policies alone will struggle to drive the broader changes in electricity systems that we've outlined in this report, and a range of new policy initiatives is urgently needed.

Governments at all orders each have important and complementary roles to play in filling the policy gap. Provincial and territorial governments are central, given that electricity systems are governed primarily under their jurisdiction. They have the power to establish regionally tailored policy frameworks to transform electricity systems and can also direct electricity regulators, who define the specific rules governing players in the electricity sector, to align their decisions with net zero. And they can pursue bilateral or multilateral projects with other provinces or territories to enhance electricity system integration and coordination. While the roles for provincial and territorial governments are preeminent, municipal governments also hold levers to transform local electricity generation and support end-use electrification.

13. In this report, we use a narrower definition of "climate policy," referring to policy targeting greenhouse gas emissions reductions. However, we recognize that in the broader sense, climate policy also encompasses climate change adaptation and clean growth policy.

The federal government sets the national framework for electricity transformation through foundational climate policies such as carbon pricing and most recently, a commitment to achieve net zero electricity across the country by 2035. It also has strong convening power, particularly on cross-jurisdictional issues such as expanding interregional grid integration and can wield its significant spending powers to incentivize actions by other orders of government.

We take up the need for policy more broadly, including the respective roles of different players in driving electricity systems transformation, in our companion report *Electric Federalism: Policy for aligning Canadian electricity systems with net zero*.

ANNEX

Overview table of modelling studies

	Canadian Climate Institute 2021	CER (Canada Energy Regulator) 2021	DSF (David Suzuki Foundation) forthcoming 2022	EPRI (Electric Power Research Institute) 2021	IET (Institut d l'Énergie Trottier) 2021	Jaccard and Griffin 2021
MODEL						
Model name	gTech	Energy Futures Net Zero Electricity (EFNZE)	Canadian Opportunities for Planning and Production of Electricity Resources (COPPER) and Strategic Integration of Large-capacity Variable Energy Resources (SILVER)	North America Regional Economy, Greenhouse Gas, and Energy (REGEN)	NATEM (North American TIMES Energy Model)	n/a
Modeler	Navius Research	CER	SESIT (Sustainable Energy Systems Integration & Transitions Group)	EPRI	ESMIA (Energy Super Modelers and International Analysts)	Jaccard and Griffin from the Energy and Materials Research Group at Simon Fraser University
Model type	Technologically rich computable general equilibrium model	Electricity capacity planning and dispatch model	COPPER: Capacity expansion model SILVER: Cost-optimization dispatch mode	Energy end use model linked with electricity capacity planning and dispatch model	Economy-wide optimization model	Spreadsheet model
Regional representation	All provinces, with territories aggregated	All provinces disaggregated, no territories	All provinces disaggregated, no territories	All provinces (with customizable aggregation); no territories	All provinces and territories disaggregated	All provinces disaggregated; territories aggregated
Demand	Fully endogenous demand for electricity consumption	Set exogenously	Demand in high electrification scenario determined by gTech and IESD (Integrated Electricity System Dispatch) models	Aggregate demand and hourly load shapes determined endogenously in the linked end-use model	Set exogenously, with some endogenous response	Set exogenously
Agent foresight	Limited foresight within each model timestep (recursive dynamic)	Perfect foresight	Perfect foresight	Perfect foresight	Perfect foresight	Perfect foresight
SCENARIO						
Name	Net zero by 2050	Net zero in electricity by 2050 (High Demand)	100% Clean + High Electrification by 2035	Net zero by 2050 (Base)	Net zero by 2050 (Base)	Net zero by 2035 (Environmentally Constrained)
Target	Net zero emissions (CO_2-eq) by 2050	Net zero emissions in electricity generation only by 2050	Zero gross emissions in electricity generation only by 2035	Net zero energy system CO_2 emissions (only) by 2050	Net zero emissions target (total CO_2-eq) by 2050	Net zero emissions in electricity generation only by 2035, with a 2030 deadline for hydro-rich provinces

	Canadian Climate Institute 2021	CER (Canada Energy Regulator) 2021	DSF (David Suzuki Foundation) forthcoming 2022	EPRI (Electric Power Research Institute) 2021	IET (Institut d l'Énergie Trottier) 2021	Jaccard and Griffin 2021
Key policy drivers	Declining emissions cap in line with net zero by 2050	Carbon price reaching \$300/t CO_2 by 2050 (2020CAD)	Emissions standard reaching 0gCO_2/kWh by 2035 Carbon price reaching \$370/t in 2050	Carbon price reaching >\$900/t by 2050 (2020CAD)	Declining emissions cap in line with net zero by 2050	Emissions standard reaching 0gCO_2/kWh by 2035; Rising carbon price coverage of electricity generators
TECHNOLOGY AND FUEL REPRESENTATION						
Distributed generation and other resources	Not represented	Not represented	Not represented	Distributed solar	Distributed solar, small-scale storage	Not represented
Large nuclear	New capacity constrained in some scenarios and available in others; existing capacity maintained	Existing capacity maintained	New capacity constrained; existing capacity maintained though no major refurbishments after 2026	New capacity constrained; some retirement in existing stock	New capacity constrained; existing capacity maintained to 2050	New capacity constrained; existing capacity maintained
Small modular reactors	Not represented	Yes, after 2030	Not represented	Yes, from 2035	Yes, from 2035	Not represented
Hydropower	New capacity constrained; existing capacity maintained	Existing capacity maintained	New capacity constrained; existing capacity maintained	New capacity constrained; existing capacity maintained	New capacity constrained; existing capacity maintained	New capacity constrained; existing capacity maintained
Storage	Not represented	Utility-scale lithium-ion batteries	Utility-scale lithium-ion batteries and pumped storage hydro	Utility-scale lithium-ion batteries; hydrogen; compressed air, existing pumped hydro	14 storage technologies, both long- and short-term and utility and consumer-scale, e.g. pumped hydro, lithium-ion, compressed air	Generic long- and short-term storage
Carbon capture utilisation and storage	Yes	Yes, NG-CCS in regions with CO_2 storage	NG-CCS significantly constrained	Yes, coal-CCS and NG-CCS	Yes, NG-CCS as well as in industrial applications	NG-CCS significantly constrained
Negative emissions technologies: Direct Air Capture (DAC) and Bioenergy Carbon Capture and Storage (BECCS)	Yes, DAC and BECCS, though DAC constrained in certain scenarios	No BECCS or DAC (BECCS is deployed in another scenario not considered in this analysis)	Significantly limited BECCS, no DAC	DAC primarily	BECCS and DAC	BECCS, no DAC
Hydrogen	Yes, hydrogen end-use, production, and hydrogen-fuelled electricity generation.	No (hydrogen-fuelled generation is deployed in another scenario)	Not represented	Yes, hydrogen-fuelled electricity generation. No hydrogen end use or hydrogen production	Yes, hydrogen end-use, production, and hydrogen-fuelled electricity generation	Yes, hydrogen-fuelled generation

	Canadian Climate Institute 2021	CER (Canada Energy Regulator) 2021	DSF (David Suzuki Foundation) forthcoming 2022	EPRI (Electric Power Research Institute) 2021	IET (Institut d l'Énergie Trottier) 2021	Jaccard and Griffin 2021
Energy efficiency and demand-side management	Accelerated efficiency improvements compared to reference	Accelerated efficiency improvements compared to reference	Accelerated efficiency improvements compared to Net Zero base scenario and reference; no significant demand response	Accelerated efficiency improvements compared to reference Deferred electric vehicle charging	Accelerated efficiency improvements compared to reference Demand response	Accelerated efficiency improvements compared to reference Demand response
ALIGNMENT WITH FEDERAL TARGETS						
40-45% emissions reduction target by 2030 from 2005	Yes (see notes)	Undetermined, electricity sector represented only	Undetermined, electricity sector represented only	Yes	Yes (40%)	Undetermined, electricity sector represented only
2035 net zero in electricity generation	Possibly 2035: 2-6 Mt depending on the scenario	Unlikely 2035 emissions not reported 2030: 28 Mt	Yes	No 2035: 32 Mt	Possibly 2035 emissions not reported 2030: 9Mt 2040: -25Mt	Yes
Level of negative emissions in 2050	-105 Mt CO_2	None	None	-114 Mt CO_2	-130 Mt CO_2e	None
OTHER ASSUMPTIONS						
Interregional transmission	Constrained	Unconstrained, endogenous expansion	Moderately constrained	Unconstrained, endogenous expansion	Unconstrained, endogenous expansion	Constrained
Physical impacts of climate change	Not represented	Not represented	Not represented	Not represented	Slight reduction in space heating demand, slight increase in space cooling demand over time	Not represented
Inclusion of electricity for export	Yes	No	Yes	Yes	Yes	Yes
Inclusion of cogeneration	Yes	Yes, though only electricity production tracked	No	Yes	Yes	Yes

	Canadian Climate Institute 2021	CER (Canada Energy Regulator) 2021	DSF (David Suzuki Foundation) forthcoming 2022	EPRI (Electric Power Research Institute) 2021	IET (Institut d l'Énergie Trottier) 2021	Jaccard and Griffin 2021
Costs for key technologies (CAD2020/kW)						**CAD2020/MWh**
Lithium-ion battery storage ($/kW)	n/a	2030: 425 2050: 190	2030: 995 2050: 746	2030: 776 2050: 582	2030: 1031 2050: 773	2030: 245 2050: 245
Utility-scale solar PV ($/kW)	2030: 1045 2050: 781	2030: 972 2050: 376	2030: 984 2050: 810	2030: 614 2050: 409	2030: 1082 2050: 858	2030: 44 2050: 44
Utility-scale onshore wind ($/kW)	2030: 1089 2050: 737	2030: 1115 2050: 676	2030: 1205 2050: 964	2030: 756 2050: 756	2030: 1422 2050: 1095	2030: 50 2050: 50
SMR ($/kW)	n/a	2030: 7000 2040: 6000 2050: 5000	n/a	2030: 6737 2050: 4926	2030: 7722 2050: 7119	n/a
Large reservoir hydro ($/kW)	2030: 11000-17600 2050: 11000-17600	2030: 4000 2050: 4000	project-specific values	n/a	2030: 7078 2050: 6725	2030: 98 2050: 98
Natural gas (combined cycle, $/kW)	2030: 1067 2050: 1067	2030: 1300 2050: 1300	2030: 1797 2050: 1797	2030: 1538 2050: 1538	2030: 1061 2050: 996	2030: 55 2050: 55
Natural gas (simple cycle, $/kW)	2030: 946 2050: 946	2030: 950 2050: 950	2030: 1265 2050: 1265	2030: 1087 2050: 1087	2030: 1060 2050: 996	2030: 188 2050: 188
BECCS ($/kW)	varying	n/a	n/a	2030: 7090 2050: 6678	2030: 6350 2050: 5545	2030: 70 2050: 70
DAC ($/t-$CO_2$)	2050: 138-405	n/a	n/a	2050: 133	varying	n/a
Geothermal ($/kW)	n/a	n/a	2030: 61140 2050: 61140	n/a	2030: 5188 to 39584 2050: 4693 to 35808	n/a
Natural Gas w/ CCUS ($/kW)	2030: 3190-3927 2050: 3190-3927	2030: 3000 2050: 2000	2030: 2757 2050: 2163	2030: 2900 2050: 2700	2030: 4243 2050: 3986	2030: 80 (Western Canada); 110 (Rest of Canada) 2050: 80 (Western Canada); 110 (Rest of Canada)

Notes: This table includes specific scenarios of key studies. These same studies may include different scenarios that are not listed here. Exogenous parameters are those determined outside of the model (e.g. external forecasts of economic growth). Endogenous parameters are those calculated by the model. Technology costs for (Jaccard and Griffin 2021) were specified as energy costs (levelized cost of electricity in $/MWh) due to the very aggregated level of the analysis. Results published in Canadian Climate Institute's 2021 report do not meet the 40-45 per cent reduction target, but updated (unpublished) results do. Where applicable, results are shown for a scenario with constrained deployment of direct air capture.

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