Canadian Energy Outlook

Infrastructure: operationalizing the net-zero transition

3rd edition

INSTITUT DE L'ÉNERGIE TROTTIER

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About the Trottier Energy Institute (TEI)

The Institut de l'énergie Trottier (IET) was created in 2013 thanks to an exceptional donation from the Trottier Family Foundation to Polytechnique Montréal. Since then, it has been involved in every energy debate in the country. At the source of major collective reflections, the team mobilizes knowledge, analyzes data, popularizes issues and recommends fair and effective plans, simultaneously contributing to academic research and training. Its independence gives it the neutrality essential to the collaborative approach it advocates, facilitating work with the players most likely to advance the energy transition, while allowing it to be freely critical when relevant.

As the initial 10-year mandate came to an end, the Trottier Family Foundation decided to renew its confidence in the IET and made a new donation. Given the scope of the IET's activities and its status as a key player, its mandate was extended. The team will thus be able to continue offering science-based advice and enriching societal dialogue in order to advance the way we produce, convert, distribute and use energy.

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Summary

As the modelling in the IET's latest *Canadian Energy Outlook* (CEO) shows,[1] Canada's climate objectives can only be achieved by adopting major technological changes that affect all energy sectors. These same modeling exercises do not, however, describe how new energy technologies will transform our daily lives in more profound ways than we might think.

Achieving carbon neutrality requires a massive electrification of services, making it possible to reduce total energy demand by 9% by 2050, despite the increase in population and gross domestic product. This transformation requires, however, a profound change in the technologies that support energy services in almost all economic sectors.

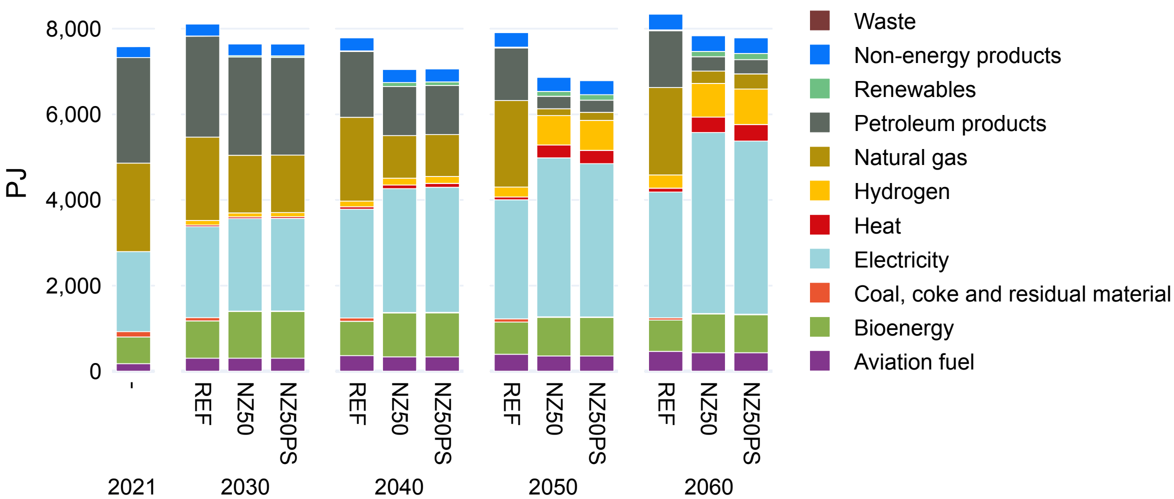
Understanding the scale of the operationalization challenge

These far-reaching transformations will require infrastructures capable of supplying electricity at the desired power level and at the desired time, the development of new technologies for decarbonizing industrial processes, and ultimately the mastery of major CO_2 capture and sequestration infrastructures to offset the unavoidable emissions of some sectors.

From an operational point of view, this transformation will involve the creation of new supply chains, and the disappearance of several existing ones. It will involve adapting various service sectors to meet new manufacturing, utilization, installation and repair needs.

In this report, we first assess the nature of the transformations required in the building and transport sectors, as well as emerging technologies related to CO_2 capture and sequestration. Secondly, this analysis enables us to take a more pertinent look at issues relating to the production, transport and distribution of the energy required for these energy services.

Figure R1 – Final energy consumption by source (excluding energy required for energy production) projected according to three scenarios: a reference scenario, which includes all measures in place in 2024, but does not impose a target on GHG emissions, and two scenarios which impose carbon neutrality in 2050 (NZ50 and NZ50PS).



Source: Langlois-Bertrand *et al.* 2024

The electrification of services as a cornerstone of transformation

Achieving carbon neutrality requires massive electrification of services, which will reduce total energy demand by 9% by 2050 (Figure R1), despite the increase in population and gross domestic product. This significant reduction in total energy consumption is based on two opposing trends. The first is a dramatic reduction in the role of fossil fuels in a carbon-neutral Canada. The second trend partially offsets the first, and consists of a doubling of electricity production up to 2050. The marked evolution of the Canadian energy mix is therefore accompanied by a profound transformation of all Canadian economic sectors, since it affects both energy production and consumption, in all forms.

[1] Langlois-Bertrand, S., Mousseau, N. Vaillancourt, K., Bourque, M. 2024.Pathways for a net-zero Canada – Horizon 2060. In Langlois-Bertrand, S., Mousseau, N., Beaumier, L. (Eds.), Canadian Energy Outlook 3rd edition, https://iet.polymtl.ca/en/publications/report/pathways-net-zero-canada

Fast action on residential and commercial buildings

Since heating systems have a lifespan of between 20 and 30 years, it is important to ensure that the heating technologies installed, whether at the time of construction or replacement, are carbon-neutral.

While these low-carbon technologies do exist, the biggest challenge is to ensure that the energy supply system is able to cope with the significant increase in demand associated with winter, and the even greater peaks generated by extreme cold.

The electrification of the heating sector is bringing about a profound change in the pattern of electrical demand, with a much more pronounced seasonal pattern. To meet winter demand, Canadian distributors will have to increase their maximum power by 50-70% compared with the summer peak, and even by more than 100% to meet the winter peak (Figure R2).

In order to reduce infrastructure requirements, it is essential to deploy strategies for shifting and reducing demand, particularly for heating, without affecting the quality of the energy service.

The uneven decarbonization of transport services

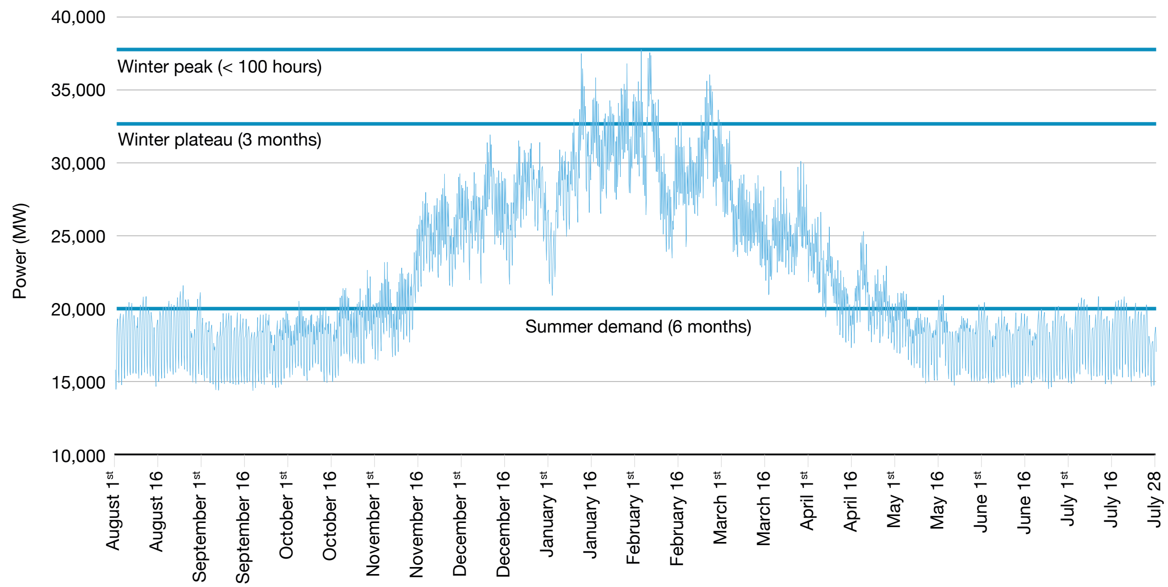
While public charging infrastructures are still inadequate in several provinces, the zero-emission vehicle sales mandate, which targets personal vehicles, should enable this sector to be decarbonized by 2050.

Strategies for decarbonizing heavy transport are still lacking, however. Several low-carbon alternatives are possible, including hydrogen, batteries and catenaries. However, each requires significant infrastructure, it is therefore essential that Canada quickly identifies the path it wants to push and deploys the pilot projects needed to validate it.

The decarbonization of the maritime and aviation sectors, which still presents many challenges, requires significant international coordination. With important potential resources in bio-energy and low-carbon electric power, as well as a first-rate aerospace industry, Canada would benefit from getting involved and leading efforts to decarbonize these sectors.

The same applies to the rail sector, where the solutions developed and deployed in Canada could be adopted in many countries where this sector is still powered by fossil fuels.

Figure R2 – Average hourly electricity demand over two years (2021-2022; 2022-2023) for the Hydro-Québec network. Maximum summer demand, winter plateau and peak demand during extreme cold are indicated.



Source: Hydro-Québec 2024a

The infrastructures to be developed and deployed to decarbonize the transportation sector are larger and more diverse than those required to decarbonize the building sector. On the one hand, this diversity enables Canada to position itself as a leader in various niches that are still under-exploited. To do so, Canada must act quickly, because every day that passes enables an industry elsewhere in the world to develop the intellectual property and know-how to fill them.

On the other hand, it also makes it possible to draw on a broader workforce from a wider range of sectors, ensuring the country's decarbonization without harming other economic sectors.

The crucial but uncertain role of carbon capture

All models indicate that Canada will need to capture and sequester between 100 and 200 million tonnes of CO_2 annually to achieve carbon neutrality. Canada has the opportunity to become a leader in this field, which is stagnating worldwide.

The challenges are many, but Canada has three significant advantages: a promising geology, large-scale low-carbon energy and a rich oil industry that will need to significantly reduce its GHG emissions if it is to remain globally competitive.

All that's missing is a real, credible strategy backed up by regulations capable of motivating investors.

> Creating a nationwide capture and sequestration infrastructure requires addressing at least three major challenges: (i) significantly increasing the rate of CO_2 capture; (ii) reducing the energy costs associated with capture and sequestration; and (iii) validating sequestration resources and techniques.

Transforming energy production

The CEO projections show that achieving carbon neutrality will require a massive increase in the use of electricity. The CEO scenario that achieves net-zero in 2050 indicates that, with a constant industrial structure, electricity production will more than double from 650TWh in 2021 to 1,281TWh by 2050.

Moreover, most models underestimate the rise in demand for electricity over the coming decades, driven not only by the electrification of heating and transport, but also by new economic sectors linked to the exploding digital economy. One thing is certain: Canada will need a lot of clean energy over the coming decades. We need to start building this capacity now.

As we aim for a complete decarbonization of electricity production, we cannot just add intermittent sources; we also need to deploy low-carbon infrastructures that align energy production with demand. With the exception of large hydroelectric reservoirs, no province yet has a strategy in this area. However, the significant variations in electricity demand over a year mean that purely nuclear, solar or wind power solutions will either be too costly, or unable to meet demand.

Canada needs to start exploring large-scale storage solutions now, whether chemical, physical or geological, in order to reduce the investment needed in infrastructure while providing the security of supply essential to a modern society.

Canada has two strategies for meeting the challenge of electrification. The first strategy is to multiply projects and technologies, enabling Canadian players to participate in their development and, potentially, become a supplier of these technologies to the rest of the planet. Following the model established for other renewable technologies, the second strategy is to wait for winning technologies to emerge, and to position ourselves as simple takers of new technologies, thereby reducing both the risks and the potential rewards.

In any case, it is probably best to avoid narrowing the choices by deciding too quickly on the technologies to be used up to 2050, as Ontario seems to want to do, with its heavy reliance on nuclear power for the bulk of its energy transition. A strategic approach would ensure that projects meet anticipated needs ten years in advance, no more.

The cost of the transition

Despite a real increase in electricity rates caused by major investments in the sector, the announced investments are not leading to an explosion in the cost of Canadians' energy portfolios, but rather to system savings. Without a specific effort on the part of governments, however, these savings will not be redistributed equitably among all energy consumers.

Whether we extrapolate projected costs or rely on more concrete investment plans from utility companies, the findings are the same: the massive electrification of our services will reduce the total cost of energy services.

Nevertheless, not everyone will benefit from the same savings, and some citizens, particularly those who use little fossil fuel today, are likely to bear the brunt of the energy transition.

Beyond system savings, we need to rethink tariff mechanisms to ensure a degree of fairness in the energy transition, a challenge that is not a matter of engineering, but of politics.

The traditional economic approach maintains that only by raising the price of carbon will Canada be able to decarbonize. However, modelling in recent years has shown that the costs of decarbonization are falling steadily in many (but not all) sectors.

Sectoral strategies can therefore be deployed to target the most appropriate tools (regulation, cost of pollution, support for technological development) for each service and sector.

Pace and timing

We need only look at the list of infrastructures built in Canada between 1960 and 1980, or those deployed by China between 2000 and 2020, to conclude that Canada has the means and capacity to successfully complete the transition to net-zero emissions by 2050.

To do this, Canada needs to tackle the barriers that are slowing investment today, and driving up costs far beyond those seen in Europe, for example. In addition to freeing up capital, such an overhaul would have immediate benefits across the Canadian economy.

Conclusions

Various techno-economic modeling exercises, such as the IET's Canadian Energy Outlook, have made it possible to study different decarbonization scenarios. These scenarios appear to impose extremely rapid structural transformations on the Canadian economy. However, an assessment of the challenges to be met in various energy consumption and production sectors shows that a sustained pace is both structurally and financially possible for those sectors where decarbonization technologies are already well identified. These include buildings, part of transport, CO_2 capture and sequestration (CCS) and power generation. Moreover, the cost of carbon-neutral technologies (excluding CCS) is falling rapidly, meaning that this transformation can already be achieved at zero total cost, or even at a profit, compared with upgrading fossil fuel-based technologies.

However, these benefits are not yet visible to all sectors, and special efforts should be made to develop competitive carbon-neutral solutions for the freight, air and sea transport sectors.

To remain competitive, Canada would do well to deploy strategies that will enable its citizens and companies to access existing technologies at prices similar to those observed abroad. It would also be in Canada's interest to identify technologies that support carbon neutrality and enable it to develop valuable intellectual property. This is the case for CCS technologies, including biochar, and for certain low-carbon technologies in niche sectors linked to aeronautics and heavy transport. The rest of the world is moving fast, however, so it is crucial for Canada not to delay any longer.

Whatever Canada decides, the remarkable progress seen in recent years in the development and deployment of low-carbon technologies underscores the much greater-than-expected agreement between productivity and decarbonization. It remains to be seen how far Canada will want to go in order to take advantage of this potential.

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1. Introduction

As modelling in the IET's most recent *Canadian Energy Outlook* (Langlois-Bertrand *et al.*, 2024) shows, Canada's climate objectives can only be achieved by adopting major technological changes that affect all energy sectors.

These same models do not, however, describe how new energy technologies will transform our daily lives in more profound ways than we might think. Indeed, the delivery and use of clean energy, dominated by electricity, opens the door to new ways of doing things that are not easy to imagine today. Just as it was difficult, at the beginning of the 20th century, to predict the impact of the use of this new form of energy that was oil, it is equally hazardous, today, to pretend to understand all the spin-offs and changes that will accompany the current transition. For example, while oil, a dense, easy-to-store form of energy, paved the way for affordable transport on a global scale, solar energy, coupled with low-cost energy storage solutions, promises energy independence at the individual level: a revolution, particularly where energy distribution infrastructure is still underdeveloped.

In order to better understand the operational issues involved in the transition of the Canadian economy to carbon neutrality, this report explores the nature of the transformations that Canada's infrastructures will have to undergo to enable us to achieve net-zero. Drawing on the most recent techno-economic modeling results, as well as the latest technological advances in the production and use of low-carbon energy, it describes the paths that will enable these infrastructures to be deployed. It thus seeks to make more concrete the structural challenges that will accompany the energy transition in an essentially Canadian context, while integrating the international context where appropriate.

2. Operationalizing the transition

Techno-economic models point to a profound transformation of the energy system. This will require infrastructures capable of supplying electricity at the desired power level and at the desired time, the development of new technologies for decarbonizing industrial and agricultural processes, and ultimately the mastery of major CO_2 capture and sequestration infrastructures to offset the unavoidable emissions of certain sectors.

From an operational point of view, this transformation will involve the creation of new supply chains and the disappearance of several existing ones. It will involve adapting various service channels to meet new manufacturing, utilization, installation and repair needs.

Although these transformations affect manufacturing processes and consumption choices, we will concentrate on the evolution of energy production and consumption technologies. Indeed, the question of processes requires in-depth analysis by sub-sector of activity, which is beyond the scope of this report.

First, we assess the nature of the transformations required in the building and transport sectors, as well as emerging technologies linked to CO_2 capture and sequestration. Second, this analysis enables us to take a more pertinent look at issues relating to the production, transport and distribution of the energy required for these energy services.

3. The expected scale of transformation

Achieving net-zero emissions requires a massive electrification of services, which will reduce total energy demand by 9% by 2050, despite the increase in population and gross domestic product.

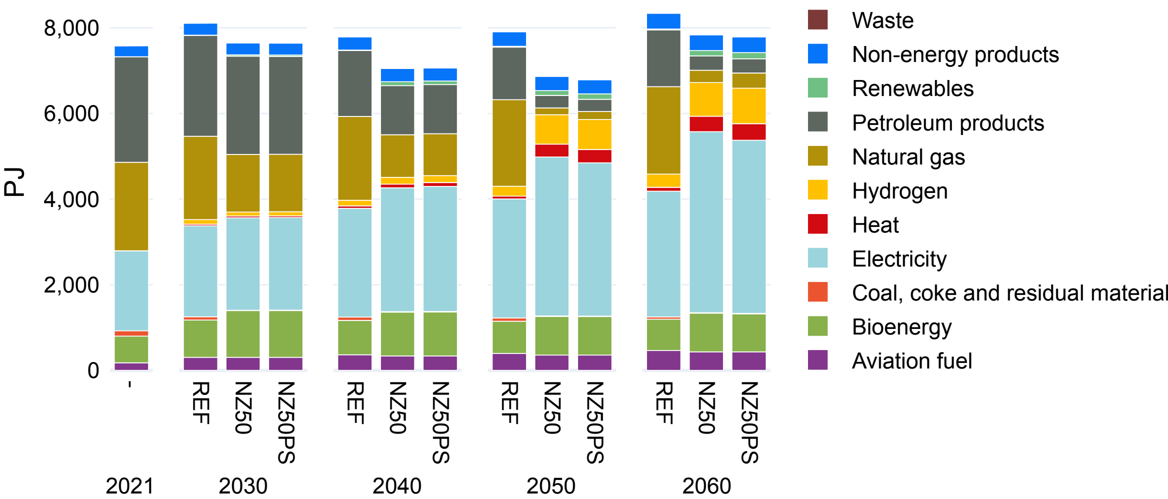
This transformation requires, however, a profound change in the technologies that support energy services in almost every economic sector.

The third edition of the IET's *Canadian Energy Outlook* (CEO) shows that meeting GHG emission reduction targets and making Canada net-zero by 2050 will require a profound transformation of the country's energy system, on both the production and consumption sides (Langlois-Bertrand *et al.*, 2024).

The epicenter of this transformation is illustrated in Figure 1, which shows the evolution of total energy demand for Canada, excluding energy used directly for its production. We can see that total energy demand for Canada falls by 9% between 2021 and 2050 in the NZ50 (net-zero by 2050) scenario, despite the country's demographic and economic growth over the previous thirty years. This significant reduction can be explained by the fact that the models favour massive electrification, which, to ensure the decarbonization of the various sectors, relies on energy-efficient technologies, enabling a significant increase in energy productivity, as we explain a little further on.

This significant reduction in total energy consumption is based on two opposing trends. The first trend is a dramatic reduction in the role of fossil fuels in a net-zero Canada, from 5,400 PJ in 2021 to 800 PJ in 2050. The second trend partially offsets the first, and consists of a doubling of electricity generation from 1,900 PJ in 2021 to 3,700 PJ in 2050. The marked evolution of the Canadian energy mix is thus accompanied by a profound transformation of all Canadian economic sectors, since it affects both energy production and consumption, in all forms, as we see in this section.

Figure 1 – Final energy consumption by source (excluding energy required for energy production) projected according to three scenarios: a reference scenario, which includes all measures in place in 2024, but does not impose a target on GHG emissions, and two scenarios which impose carbon neutrality 2050 (NZ50 and NZ50PS).



Source: Langlois-Bertrand *et al.* 2024

3.1. Buildings

Since heating systems have a lifespan of between 20 and 30 years, it is important to ensure that the heating technologies installed, at the time of building construction or heating system replacement, are net-zero.

While these low-carbon technologies do exist, the biggest challenge is to ensure that the energy supply system is able to cope with the significant increase in demand associated with their use in the winter, and the even greater peaks generated by extreme cold.

In the CEO's projections, achieving carbon neutrality by 2050 requires an almost complete decarbonization of the building sector. In this sector, the share of fossil fuels falls from 52% to 2% between 2021 and 2050. Fossil fuels are almost entirely replaced by electricity, whether this change is based on air-source or geothermal heat pumps, decarbonized heat networks or solar thermal energy. Only 3% of energy demand for buildings is still met by bio- or synfuels.

As Tables 1 and 2 show, such a transformation requires the replacement of more than half of all residential heating systems, and an even greater fraction of those in the industrial, commercial and institutional (ICI) sector. For the most part, this will involve replacing natural gas or oil furnaces with sophisticated appliances where electricity is used to transport heat rather than produce it.

Table 1 – Number of households by main energy source for heating in 2021 (in thousands)

Electricity	Natural gas	Oil/Coal/Propane	Firewood	Total
6 702	7 337	773	353	15 164
44 %	48 %	5 %	2 %	100 %

Source: Natural Resources Canada 2025

Table 2 – Secondary energy consumption for ICI space heating by energy source in 2021 (in PJ)

Electricity	Natural gas	Oil/Coal/Propane	Total	Total floor area
86	550	34	671	765 Mm^2
13 %	82 %	5 %	100 %	

Source: Natural Resources Canada 2025

3.1.1. Deployment

Since heating systems have a lifespan of 20 to 30 years, the pace of the transformations projected by the CEO to achieve net-zero is compatible with the natural replacement of these systems. It is therefore important to make it compulsory, right now, for fossil fuel units to be replaced by zero-emission technologies.

Although affordable low-carbon heating technologies already exist, the scale of their deployment calls for a strategic analysis of the challenges and opportunities involved.

From a technological standpoint, Canada has largely been treading water when it comes to heating technologies for several decades. As a result, it has not made any particular headway in the field of air-source or geothermal heat pumps, whether residential, commercial or industrial. While global markets are moving rapidly towards maturity, Canada has little time to develop a manufacturing industry for these advanced systems. Canada's added value will therefore lie in the adaptation of available systems to customer and building specifications, and in their installation, operation and maintenance, particularly for multi-residential, commercial and institutional (MCI) buildings. Indeed, the transition from a fossil fuel-fired heating technology to a more technically complex technology requires additional planning and design efforts, as well as different skills for the installation and commissioning of these new systems.

In practice, the advantage of heat pumps over natural gas is sometimes reduced, particularly for the MCI sector which, unlike smaller buildings, does not have access to standardized products. The barrier to heat pump installation for the MCI sector is often related to the additional risks, real or perceived, caused by customized systems, lack of skilled labor and standards that treat furnaces and heat pumps differently. To foster the installation of this equipment, governments need to support technical training for the workforce, impose equipment standardization and structure the market to remove barriers to installation and reduce the costs associated with acquisition and operation.

3.1.2. A necessary upgrade to the power grid

The electrification of heating systems is bringing about a profound change in the pattern of electrical demand, with a much more pronounced seasonal pattern. To meet winter demand, Canadian distributors will have to increase their maximum power output by 50-70% compared to the summer peak, and even by more than 100% to meet the winter peak.

In order to reduce infrastructure requirements, it is essential to deploy strategies for shifting and reducing demand, particularly for heating, without affecting the quality of the energy service.

The feasibility of decarbonizing the building sector depends on more than just the ability to install new heating equipment. Based on massive electrification of heating in a Nordic context, decarbonization will have marked effects on electricity demand, shifting peak electricity demand from summer to winter in most provinces.

First, it implies the creation of a new level of power and energy demand during the 3 or 4 winter months, whereas, apart from heating, the daily variation in electricity demand is relatively constant throughout the year. For example, in Quebec, whose building sector is the most electrified in Canada, heating demand drives average electricity demand up by about 65%, from less than 20 GW to almost 33 GW.

In addition to this seasonal increase, there are also small peaks in demand, correlated with periods of extreme cold and typically representing a total of less than a hundred hours per year. In Quebec, these peaks can boost average winter demand by 20%, to 42 GW. If this demand is not properly managed, these peaks could impose a major additional overinvestment.

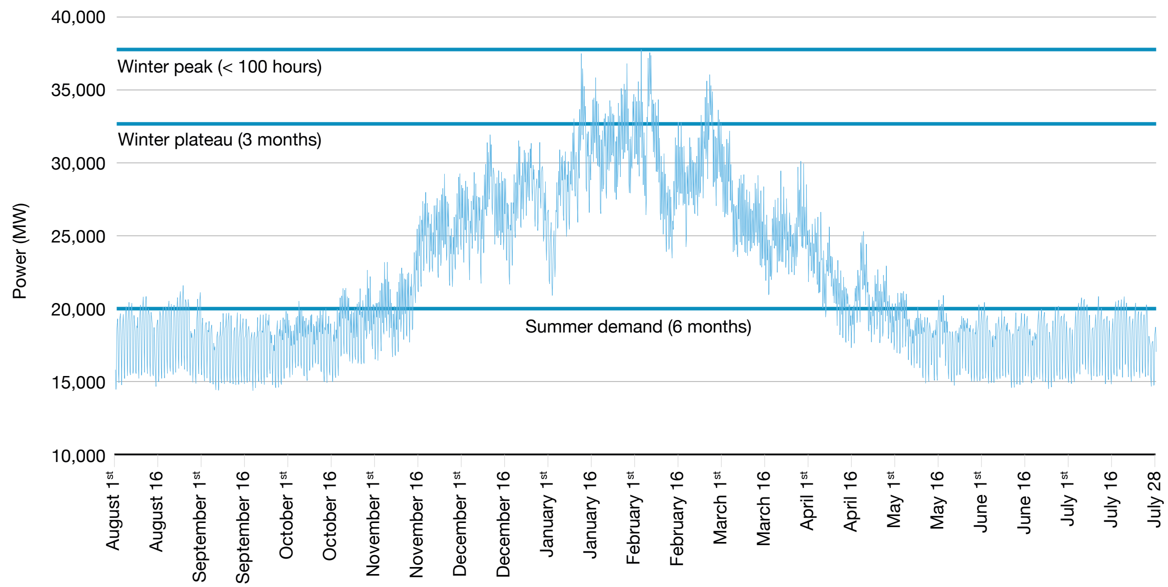
To support the decarbonization of heating, it is still essential to significantly increase the level of electricity generation and the capacity of the transmission and distribution network. This is necessary to be able to meet basic winter demand, while deploying measures that will control the fine peak in electrical demand associated with periods of extreme cold (for more details, see Edom and Mousseau, 2025). It should be noted that since most of northern North America will experience a similar demand pattern, it will not be possible to simply rely on exchanges with neighboring provinces and states to meet winter demand, let alone the fine peaks lasting a few hours. Each jurisdiction will therefore need to ensure that it has access to major electrical infrastructures that will only be used for a third to a quarter of the year and even, for the extreme peak, for a few hours each year.

Responding to these seasonal variations in demand means that we cannot simply ensure that we produce enough energy on an annual basis. Networks must be able to supply additional power to meet new seasonal peak demands and those linked to periods of extreme cold. In Quebec, for example, Hydro-Québec has been refusing to allow customers to fully electrify their heating systems for several years now, due to a lack of available power to meet the fine peaks in demand on the distribution networks (Pedroli and Mousseau, 2022). It is more than likely that similar situations are occurring elsewhere in the country. Each refusal by a distributor delays the decarbonization of a building by 20 to 25 years, as it encourages the renewal of fossil-fuel-powered equipment rather than the development and implementation of net-zero peak demand management solutions.

In short, replacing fossil-fuel heating systems with electrified solutions does not, in itself, pose any fundamental labor or scheduling problems. Of course, the low price of natural gas, even including carbon pricing, does not encourage the installation of alternative technologies. They are often more expensive to buy and, in some cases, more expensive over the lifetime of the equipment, particularly outside the residential market. These barriers could be considerably lowered, however, with the introduction of strategic government programs that encourage learning, standardization and market creation, which will lead to cost reductions. Such programs could replicate approaches that have made low-carbon power generation and electric vehicles highly competitive with fossil fuel-based solutions.

The main structural challenge of eliminating fossil fuels lies rather more on the side of electricity distributors. Indeed, it is the upgrading of distribution networks, necessary for the electrification of heating, and the deployment of strategies to reduce winter peak demand that pose the greatest challenges in planning and deploying energy resources to support the decarbonization of this sector. We come back to these issues later in this report.

Figure 2 – Average hourly electricity demand over two years (2021-2022; 2022-2023) for the Hydro-Québec network. Maximum summer demand, winter plateau and peak demand during extreme cold are indicated.



Source: Hydro-Québec 2024a

3.2. Transport

As the models show, decarbonizing the transport sector is more complex than decarbonizing the building sector, due to the diversity of modes, uses and levels of maturity of the low-carbon solutions available to this sector. This is why it is necessary to discuss the various segments that make up the transport sector separately. These are presented below, with the exception of off-road transport, which is dealt with exhaustively in a separate report (Langlois-Bertrand and Mousseau, 2025).

3.2.1. Road transport

While public charging infrastructures are still inadequate in several provinces, the Zero-Emission Vehicle sales mandate, which targets personal vehicles, should make it possible to decarbonize this sector by 2050.

Strategies for decarbonizing heavy transport are still lacking, however. As several low-carbon alternatives are possible, including hydrogen, batteries and catenaries, but that each requires significant infrastructure, it is essential that Canada quickly identifies the path it wants to push and deploys the pilot projects needed to validate it.

In the CEO projections, the personal vehicle sector is almost totally electrified by 2050, thanks to zero-emission vehicle mandates both at the federal level and in some provinces, but also in line with the global evolution of the sector. We are more uncertain about the decarbonization technologies that will be adopted for other types of road vehicles. For example, while it is likely that local goods distribution will take place in battery-powered trucks, thanks to ever more efficient and less expensive batteries, the potential options appear more diverse for long-distance goods transport, complicating infrastructure planning.

These uncertainties are well captured by the CEO, which projects that the fleet of passenger vehicles will be over 99% electrified and battery-powered in all scenarios, including the reference scenario. On the other hand, the CEO projections point to the fact that decarbonized road freight transport would use a variety of solutions, split between hydrogen (47%), batteries (29%) and catenaries (24%). However, this diversity is unlikely to be observed, as each of these technologies requires its own infrastructure, which is both cumbersome and costly. Instead, the results suggest a lack of field experience that would enable us to better identify the benefits and disadvantages of each of these solutions.

For example, rapid battery recharging for heavy-duty vehicles could be achieved by swapping batteries or, more likely, using high-power chargers. This technology is likely to become dominant in Europe, thanks to regulations designed to secure the industry. For example, the European Union imposes a maximum speed limit of 90 km/h on heavy goods vehicles, in addition to a 45-minute break every 4.5 hours for truck drivers (European Union). In this context, a battery capable of covering 500 km and rechargeable in 20 minutes - which is possible today - is sufficient.

In the absence of such regulation, the advantage of batteries for long-distance freight transport is less clear-cut in North America, which explains the diversity of options apparent in the models. However, deploying catenaries or a hydrogen distribution network and powerful chargers on a large scale is costly, so it is likely that these two technologies won't be able to coexist everywhere on the continent. In the absence of a clear direction, the choice of energy carriers is, in many cases, linked to leverage effects still uncertain. For example, the net costs of deploying a low-carbon hydrogen production and distribution network, whether blue or green, will depend on its overall use in society. If low-carbon hydrogen finds its place on a large scale, as an energy carrier or chemical input in the industrial and construction sectors, the deployment of a hydrogen offer at service stations will be much easier; indeed, this deployment will be able to draw on both the know-how and the private and public investments developed for other sectors. The installation of catenaries over freeways, on its part, is likely to require a much more proactive role on the part of governments, even if studies show that reasonable user charges would enable these sums to be recouped over time (Kayser-Bril *et al.*, 2021).

The choice of energy carriers will affect investment in power grids. Both battery recharging and catenary systems require more electricity to be generated, and the power offered must be more closely aligned with the needs of the transport sector, thus increasing the need for power grid reliability. For its part, hydrogen produced by electrolysis would generate an even greater demand for electricity, to compensate for the significant losses that occur in the production, transport and use of this gas. Nevertheless, this solution offers greater flexibility in terms of electricity demand, thanks to hydrogen's storage capacity. Moreover, hydrogen adds an element of resilience by temporally decoupling the production of this energy carrier from the instantaneous state of the power grid: therefore, a regional power cut would not mean the complete paralysis of transport services in that area.

The role of governments and public bodies in deploying charging infrastructure for short-distance passenger and freight transport should not be overlooked. The more distributed nature of service in these segments, with smaller batteries on vehicles, is compatible with aggressive electricity demand management and a combination of small-scale private and public investment. This compatibility is conditional, however, on electricity distributors upgrading their supply and part of their network to ensure that power and energy are available to support the electrification of the sector.

The decarbonization of long-distance freight transport, on its part, requires more consistent planning due to the fundamental nature of this sub-sector. Trucks cross many jurisdictions, need to be able to travel for long hours and rely on a reliable energy supply. To reduce costs and risks, infrastructure will therefore need to be standardized, planned and supported by players capable of working on a regional or even continental basis.

By projecting parallel solutions for road haulage, the models clearly show the extent of the technical and economic uncertainties that remain – and the limits of modelling. Reducing the risks implies that certain players must rapidly deploy large-scale pilot projects to demonstrate and compare technologies, in order to facilitate technological choices. To these sums must be added the investment needed to deploy vehicles using these technologies.

Unless Canada takes a leadership position in the decarbonization of heavy-duty transportation, it runs the risk of having the technological choices made by neighboring states south of its border imposed on it. In so doing, it also runs the risk of not being able to take advantage of this change to foster the emergence of Canadian companies capable of positioning themselves as leaders in the sector. Without a strategic vision, Canada won't be able to identify quickly enough the technologies or services that could be successfully developed in Canada and become established on the rest of the continent or the planet.

In conclusion, beyond the decarbonization of vehicles, the energy transition offers an opportunity to rethink the role of transport modes used for goods. While road transport has gained in interest, for reasons of speed and flexibility, automation, which can accompany electrification, makes it possible to rethink the balance between road, sea and rail transport. Here again, Canada would benefit from developing a strategic approach to take full advantage of its various transport infrastructures.

3.2.2. Rail, sea and air transport

The decarbonization of the maritime and aviation sectors, which still presents many challenges, requires significant international coordination. With significant potential resources for bioenergy and low-carbon electric power, as well as a first-rate aerospace industry, Canada would benefit from getting involved and leading efforts to decarbonize these sectors.

The same applies to the rail sector, where the solutions developed and deployed in Canada could be adopted in many countries where this sector is still powered by fossil fuels.

The models show the same diversity in energy carriers for the **rail sector** as for road haulage. By 2050, the latter is equally decarbonized thanks to electricity and hydrogen, while the maritime and aviation sectors remain predominantly dependent on fossil fuels (liquefied natural gas for maritime transport and kerosene for aviation).

Ground-based, dominated by a few private players, the rail sector should be able to converge towards regional or even continental solutions that will avoid duplication of infrastructure. Already, consortia are at work distributing pilot projects and testing various technologies (Transport Canada, 2023). While modelling highlights the uncertainties regarding the comparative advantages of the various technologies, a little additional regulatory pressure should speed up testing and pilot projects. Indeed, the sector has no shortage of financial resources to support a transition that should be economically profitable over the long term. Although railway companies are already reluctant to make the investments needed to maintain their infrastructures (Latragna, 2023), the record profits of recent years show that they have sufficient revenues to successfully complete the transition to carbon neutrality without relying on taxpayer support. That said, a government contribution would tie choices regarding the rail sector with other infrastructures, facilitating efforts to structure the best overall solutions.

The technical and economic models presented in the CEO show that there are no viable decarbonized solutions for the **aviation sector**. The NZ50 scenario therefore maintains the use of kerosene for this sector, adding, to compensate, negative emissions generated by the use of biomass and the direct extraction of CO_2 from the air. Of course, the models do not offer predictions; rather, they provide a better understanding of the state of our knowledge of today's technologies. The results of the NZ50 scenario therefore underline the importance of supporting research and development into clean energy carriers suitable for the aviation sector. The recent history of wind turbines, solar panels and electric cars shows that effective industrial policy coupled with predictable and ambitious regulations can lead to transformations of surprising scale and speed.

The CEO projections suggest that the **maritime sector** is technologically somewhere between rail and aviation. If techno-economic solutions exist to reduce emissions from this sector, they involve a change of fossil fuel and a switch from bunker fuel to natural gas, combined with the purchase of negative emissions. The absence of credible solutions, even in the long term, is partly due to the fact that the shipping industry operates on the margins of existing regulations. Shipowners prefer to use flags of convenience to keep costs to a minimum, with little regard for the environment. Without strong regulations from the countries that host these ships in their ports, it is highly unlikely that this industry will make the investments needed to develop carbon-neutral solutions by 2050.

3.2.3. Deployment

The infrastructures to be developed and deployed to decarbonize the transport sector are larger and more diverse than those needed to decarbonize the building sector.

On the one hand, this diversity enables Canada to position itself as a leader in various niches that are still under-exploited. To do this, Canada must act quickly, because every day that passes enables an industry elsewhere in the world to develop the intellectual property and know-how to fill these niches.

On the other hand, it also makes it possible to draw on a broader workforce from a wider range of sectors, ensuring the country's decarbonization without harming other economic sectors.

The infrastructures to be developed to decarbonize the transport sector are more considerable than those required to decarbonize the building sector. These infrastructures require deployment on multiple scales and, for several sub-segments of the sector, present sufficient uncertainties to allow for parallel but potentially incompatible deployment trajectories. Because of the nature of the service, some of the investment will have to come from the private sector, but there is no doubt that public leadership, including funding and regulation, would reduce risk and accelerate the transition. Given that several sub-sectors underpin cross-border movements, certain technological choices will need to be made in a concerted fashion.

The example of Quebec in deploying charging stations for electric vehicles shows that it is possible to act effectively and early while respecting these constraints. Indeed, back in 2012, when Quebec had just 600 electric vehicles, Hydro-Québec created the Circuit électrique with the support of four partners: the Agence métropolitaine de transport, a network of hardware stores and two restaurant and supermarket chains. The Circuit électrique then made available to the public some thirty Level 2 charging stations installed in locations where motorists can store, eat or even leave their cars to take public transport while recharging. Hydro-Québec, which owns the Circuit électrique, is continuing its efforts to offer an ever more powerful and accessible network of public charging stations throughout the province and eastern Ontario. This reliable network contributes significantly to reassuring Quebec motorists when they switch to all-electricity. They know they can always count on the presence of an appropriate charging station on their travels, whether along major highways, in the city or in the regions. With its proactive approach, the Circuit électrique has also fostered the emergence of an ecosystem for the production and management of electric charging stations, whose equipment and know-how can be exported.

Whatever technologies are chosen, electricity remains at the heart of the decarbonization and modernization of transport. It is by far the preferred solution for personal transport, of course, but also for some road and rail freight transport. Whether the energy is supplied on demand, via catenaries, or stored in the vehicle in chemical form (hydrogen) or in a battery, the electrification of transport improves the control and performance of the various services, while increasing their productivity.

However, the choice of technologies can affect the power grid. For example, battery storage and, even more so, storage in the form of chemical compounds enable better use to be made of electricity demand or production cycles than catenaries, thereby reducing the investment required in the power grid. The choice of vectors will also influence the nature and amount of investment, as well as the manpower required. Depending on whether hydrogen, batteries or catenary systems are chosen, the jobs required will demand different skills. In some cases, it will be possible to make direct transfers of manpower from the fossil fuel industry, for example for hydrogen, while other sectors, such as electricity, are already in high demand.

While it is possible to change the heating system of an existing building, decarbonizing transportation generally requires a revised design of traction equipment, whether it is the entire truck, tractor-trailer or locomotive. Depending on the technology, the decarbonization of aircraft and ships may also require an adapted design. This requirement opens the way to additional productivity gains, as seen with the electric car, which is already cheaper and more reliable than the gasoline-powered car[2]. We can therefore expect the net cost of upgrading to be zero or even negative for series production.

[2] Without the 100 percent tariff on Chinese cars, Canadian motorists would be able to buy electric vehicles available at much lower prices than equivalent internal combustion engine vehicles.

3. THE EXPECTED SCALE OF TRANSFORMATION

As in the automotive sector, we can expect upheavals to affect the various ecosystems associated with the transportation sub-sectors. New manufacturers will emerge, offering innovative products that have been thoroughly redesigned to compete with the established players on new foundations. These upheavals will largely be achieved with a constant or reduced workforce, as manufacturers take the opportunity to adopt the most modern manufacturing methods. To position itself at the forefront, Canada will need to develop specific, effective and integrated sector strategies to attract significant investment in product development and production infrastructure. As the federal and provincial governments have understood with the battery sector, this transformation represents an ideal opportunity for Canada to position itself for certain crucial products, thanks to innovation strategies combined with aggressive market development approaches. These strategies of course entail risks, but these can be mitigated by implementing market creation strategies in parallel.

3.3. CO_2 capture and sequestration

All models indicate that Canada will need to capture and sequester between 100 and 200 million tonnes of CO_2 annually to achieve carbon neutrality.

By building on its petroleum industry as well as others, Canada has the opportunity to become a leader in this field, which is stagnating worldwide.

The challenges are numerous, but Canada has three significant advantages: a promising geology, large-scale low-carbon energy and a rich oil industry that will need to significantly reduce its GHG emissions if it is to remain globally competitive.

All that is missing is a real, credible strategy backed up by regulations capable of motivating investors.

According to the CEO projections, large-scale CO_2 capture and sequestration (CCS), including biochar, is essential if we are to achieve carbon neutrality. By 2050, the CEO projects that we will need to capture and sequester up to 160 $MtCO_2e$ annually, which represents 23% of Canada's current emissions or twice Quebec's total emissions for 2022. These quantities are significant: they are equivalent, in mass, to the annual production of oil from the tar sands (187 Mm^3 or around 170Mt in 2023) (Statistics Canada, 2024). In 2023, CCS projects in Canada captured only about 1.5 $MtCO_2e$ and sequestered perhaps 1.2Mt. To reach model projections, current efforts would have to be multiplied by around 130. By comparison, oil production from tar sands has increased by a factor of just under 8 between 1995 and 2023.

The models identify three dominant sources of carbon that can be captured and sequestered: CO_2 from combustion and industrial processes, CO_2 extracted directly from the air, and carbon stored in biomass. While each of these sources requires different capture infrastructures, capture technologies as well as transport and sequestration infrastructures can be shared, at least for the first two cases.

3.3.1 Models highlight missing technologies

It should be remembered that these projections are not predictions. The importance of CCS in the models underlines the many unknowns in decarbonized technologies, particularly in heavy industry, transport and agriculture. However, many solutions aimed at eliminating emissions at source are currently under development, such as Stegra's pilot plant in Sweden, which will produce ultra-low-emission steel using green hydrogen and decarbonized electricity. Although the costs of these technologies are too high for them to be included in techno-economic optimization models, significant advances in electrolysers, for example, or the creation of new markets for green products could rapidly change the situation.

However, even with these breakthroughs, there is no doubt that to reach net-zero, CCS will have to be deployed on a large scale, all over the planet (Taylor *et al.*, 2025). In Canada alone, we can therefore estimate that several tens of millions of tonnes of CO_2 will need to be sequestered annually in the best-case scenario to achieve and maintain carbon neutrality.

3.3.2. Three challenges for CCS

The creation of such an infrastructure on a national scale calls for tackling at least three major challenges: (i) significantly increasing the rate of CO_2 capture; (ii) reducing the energy costs associated with capture and sequestration; and (iii) validating sequestration resources and techniques.

Capture rates. While, on paper, CCS technologies could capture up to 95% of concentrated CO_2 emissions from fossil fuel combustion or chemical processes, the reality shows that there is still a lot of work to be done to reach these levels in industrial facilities.

Today, there are few examples of large-scale technological capture with a significant capture rate, but they already point to significant progress. A number of CCS installations have already been set up in Canada. Among these, two pilot projects have been in operation for several years - the Boundary Dam and Quest projects - and others are more recent, such as the NWR Sturgeon refinery and the Glacier natural gas-fired power plant. A comparison of the two generations of projects shows the progress that has been made, as well as the efforts that still need to be made in this area. Each of these plants captures highly concentrated CO_2 produced by industrial processes or during combustion. We are not talking here about direct extraction of CO_2 from the air.

According to SaskPower, the Boundary Dam project, which was to capture up to 1 million tonnes of CO_2 per year (1,000 kt CO_2/year), with a capture rate of 90%, had reached 730 kt/year by 2021 (SaskPower, 2021), meaning that only 66% of the CO_2 produced is captured. Shell's Quest project, meanwhile, reported sequestering a total of 770 kt of CO_2 by 2023, with a net capture rate of around 75% (Limited, 2024).

New infrastructures show similar or higher capture rates. For example, according to NWR (2022), the NWR Sturgeon refinery captures around 1,400 kt of CO_2 annually, representing 70% of its total emissions, thanks to a process that enables it to produce hydrogen and very pure CO_2 from petroleum residues. In contrast, the Glacier plant would capture around 47 kt of CO_2 per year, with a CO_2 recovery rate of over 90% and a net capture of 89% of emissions (Advantage Energy Ltd., 2022; Entropy, 2022).

In many of these projects, the captured CO_2 is reinjected into oil wells to facilitate its recovery, thus reducing the real environmental benefit of these projects. This use, however, allows us to finance part of the development and research, which helps to reduce the costs and risks associated with this technology. These projects also enable us to better identify the advances and challenges that still need to be overcome before CCS technology can be deployed on a large scale.

However, this alliance reduces the importance attached to the overall efficiency of net CO_2 emission reduction. For many of these infrastructures, the primary interest is in harvesting enough CO_2 for oil extraction operations, and not necessarily in maximizing the overall capture rate. So, while over 90% of the CO_2 produced during combustion or processing is captured, the figures show that, in many cases, leakage occurs along the pathway from extraction to use of fossil fuels. These leakages mean that the net reduction in total emissions by CCS is much lower, often between 50 and 70 percent, which is not compatible with a carbon-neutral society. Even at the stack, the 10 percent of CO_2 that escapes will have to be captured by direct air extraction activities to achieve carbon neutrality, increasing the real costs of these installations in a net zero society (Langlois-Bertrand *et al.*, 2021).

Energy costs. The second issue is the energy cost of CO_2 capture and sequestration. Firstly, the energy required for capture increases as the concentration of CO_2 decreases. There is therefore an advantage in capturing as much greenhouse gas as possible at source, rather than repairing the damage by extracting it directly from the air, especially as today's technologies are still a long way from their theoretical limits. For example, the latest figures provided by Entropy for its Glacier project suggest that the advanced technologies used limit energy demand to around 2 GJ (560 kWh)/tonne of CO_2 captured at the stack, at a concentration of 5%, for a net cost of $32/tonne (Entropy, 2022). While energy consumption compares favorably with other installations, it is almost five times higher than the theoretical minimum of 120 kWh required to extract one tonne of CO_2 directly from the air, at a concentration of 420 ppm. Capturing 100 million tonnes of CO_2 at concentrations of over 5% would therefore require 56 TWh annually, at a cost of around $3.2 billion.

Adding compression and sequestration, and taking into account that a significant part of this capture will be carried out at concentrations closer to 0.04%, we can therefore estimate the energy demand for CCS at a few hundred TWh per year, which increases the cost of capture accordingly. Even at 250 TWh and $20 billion per year, these costs would be only slightly less than the combined investment in upgrading the electricity grid in Quebec and Ontario, while representing around one percent of Canadian GDP.

Where to bury this carbon? Sequestering these large quantities of CO_2 also represents a major geological challenge. Canada has major potential reservoirs, in large sedimentary basins and saline aquifers located within them. Theoretically, these reservoirs could store over 100 billion tonnes of CO_2, particularly in western Canada (Natural Resources Canada, 2023). However, these studies are not yet based on scale tests that would enable us to better understand the real constraints of long-term geological storage of CO_2. There is therefore a major need to validate these figures and the real effectiveness of CO_2 storage, while assessing the risks associated with these operations.

3.3.3. Biochar

The CEO modelling projects that biochar could play an important role in CO_2 capture and sequestration. Through pyrolysis, this technology transforms biomass residues into a product with a high concentration of low-reactivity forms of carbon. Relatively porous, this material can be used to store carbon over the long term, while stabilizing and enhancing soil quality. Although CO_2 is captured naturally, transporting the residues and certain pyrolysis processes are energy-intensive (Campion *et al.* 2023). It is therefore important, in this field too, to support the large-scale deployment of these solutions to facilitate learning and reduce costs.

3.3.4. Deployment

The multiple forms of CCS make it possible to envisage the creation of new industrial sectors. These range from the large-scale production of the chemical compounds needed to fix GHGs and transform biomass, to geological storage, the construction of capture facilities on industrial sites and direct extraction from the air, including the compression and transport of CO_2. To be carbon-neutral, these industries will need to rely on clean energy, mainly electricity, which requires additional investment on top of that mentioned above for the generation and transmission of electricity to the sites of interest.

In Canada, the structuring of this industry is limited today by the lack of certainty about the price of carbon and how the financing of independent infrastructures could be secured. Technological advances in recent years clearly demonstrate the need for a broad approach that supports innovation. For example, biochar, which was absent from the models just three years ago, now appears to be a very promising sector, although several aspects of it have yet to be scientifically validated. For many high-GHG-emitting industries, such as concrete, steel and aluminum, the question today is whether it is better to aim directly at zero-carbon solutions or invest in CCS. In other sectors, such as forestry and even the oil industry, CCS represents an interesting opportunity to diversify uses and revenues.

Thanks to its biomass resources, its geology that facilitates storage and its industrial skills, Canada has particularly attractive conditions for positioning itself as a leader in the field of CCS. To consolidate its role, it must both support the deployment of large-scale CCS infrastructures and actively contribute to the emergence of the offset market now enshrined in the Paris Agreement. To do this, it can build on the industry structure offered by the oil and gas sector, while rapidly extending the application of these technologies to other high-emission sectors.

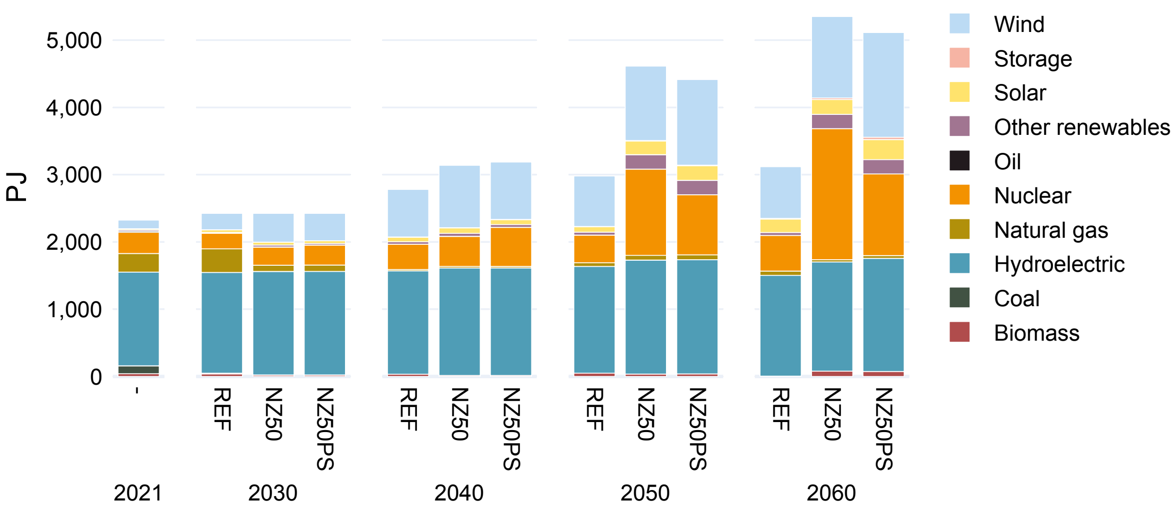
4. Energy production

As we have seen when analyzing the transformation of energy services in the various sectors, the CEO projections show that achieving carbon neutrality requires a massive increase in the use of electricity. The scenario for achieving carbon neutrality in 2050 indicates that, with a constant industrial structure, electricity production, which stood at 2,317 PJ (or 650 TWh) in 2021, is set to increase by 5% between 2021 and 2030, and then double in the following 20 years to 4,612 PJ (1,281 TWh).

According to CEO projections, hydropower generation will rise from 1,400 to 1,700 PJ (470 TWh), representing an increase of around 20% (see Figure 3). These projections suggest that, in addition to hydropower, Canada will mostly add nuclear generation, quadrupling its contribution from 310 to 1,280 PJ (360 TWh). It will also increase wind generation, from 130 PJ today to 1,100 PJ (310 TWh) in 2050. Solar power, on the other hand, will only account for around 5% of the total, with 202 PJ (56 TWh).

We need to take the time to analyze these figures to fully understand what they reflect. In this section, we consider a few aspects, namely the size of the demand forecasted and the relative value of the various sources of electricity, as well as their potential evolution between now and 2050. We continue our analysis by examining deployment strategies, both in general terms and in their operationalization.

Figure 3 – Evolution of total electricity generation according to the scenarios discussed above



Source: Langlois-Bertrand *et al.* 2024

4.1. Underestimating demand

Most models underestimate the rise in demand for electricity over the coming decades, driven not only by the electrification of heating and transport, but also by new economic sectors linked to an exploding digital economy. One thing is certain: Canada is going to need a lot of clean energy over the next few decades. We need to start building now.

While these projections are in line with other decarbonization models for Canada and developed countries in general, two systematic biases inherent in these modeling exercises suggest that electricity requirements will be much higher than projected by the models. These two biases are the conservative approach to the development of new sectors, and the strong optimization of energy use that is assumed.

The first bias comes from the fact that to avoid multiplying assumptions, the authors assume economic growth on a constant industrial base. The models therefore do not include emerging sectors, such as artificial intelligence or greenhouse production, whose strong growth could significantly increase electricity demand over the next few years. For example, Quebec's Minister of the Economy, Innovation and Energy has on her desk industrial projects representing a demand of over 13 GW (Gerbet, 2024), representing 100 TWh of energy, with demand at 75% of the time. Due to a lack of available electricity, the Minister is unable to accept these projects at present, and they are therefore not included in the data on which the modeling exercises are based.

The underestimation of demand also results from the optimization approach used in the model. At all stages, the model systematically selects the least costly technology over the equipment's life cycle, which generally amounts to choosing the most energy-efficient technology. However, experience shows that equipment is not always chosen or used optimally, and actual energy demand is systematically higher than that projected by forward-looking models.

The underestimation of demand, for example, helps to explain the various forecasts made for Quebec. For example, although electricity already accounts for 40% of Quebec's domestic energy consumption - twice the national average - Hydro-Québec forecasts that electricity production will potentially have to double by 2050 (Hydro-Québec, 2024), whereas the CEO projects an increase of only 32% over 2021 levels for the Quebec grid.

4.2. Understanding the value of different electricity sources

As we aim for a complete decarbonization of electricity production, we cannot just add intermittent sources; we also need to deploy low-carbon infrastructures that align energy production with demand. With the exception of large hydroelectric reservoirs, no province yet has a strategy in this area. However, the significant variations in electricity demand over a year mean that purely nuclear, solar or wind solutions will either be too costly, or unable to meet demand.

Canada needs to start exploring large-scale storage solutions now, whether chemical, physical or geological, in order to reduce the investment needed in infrastructure while providing the security of supply essential to a modern society.

The modeling of power generation technologies is based not only on the construction and operating costs of the various technologies, but also on the match between production and demand. To fully understand the results of the various forecasting exercises, it is therefore essential to link the deployment projections for the various technologies to an analysis of the specific features of each one. Indeed, in a world where electricity plays an ever-increasing role, the attractiveness of the various modes of power generation depends on factors that go well beyond the average cost per kWh, and include flexibility, suitability to demand and resilience. Yet, as we see in this section, technological advances have the potential to transform these assessments over the next few years.

Natural gas-fired power plants and hydroelectric turbines at the head of a large retention basin offer a flexible and instantaneous response, or almost instantaneous response, to demand, giving them great strategic value in power generation. Nuclear power plants, on the other hand, offer little flexibility, since they produce at constant capacity, but in a totally predictable way. Other facilities, such as run-of-river hydroelectric plants, provide a base for electricity production, but cannot be adjusted to meet peak demand. Finally, photovoltaic and wind power sources are said to be "intermittent", producing when it is sunny or windy, with no way of controlling the match between production and demand.

For these last two families of electricity generation technologies, maximizing capacity to meet demand requires production overcapacity, which increases the net cost of electricity. Thus, building a nuclear power plant to meet 100 hours of annual peak demand means selling electricity the rest of the time at prices well below its production cost. The same applies to intermittent energy sources, whose production is out of step with demand, and must therefore be lost or sold at a loss, with no guarantee that increased production will enable production to match demand.

This situation is well understood by the electricity industry players. For them, it is clear that, with these energy sources, solutions to better match production and demand will necessarily involve large-scale energy storage or the additional integration of flexible sources. Some storage technologies are well mastered, such as hydraulic pumping, which involves using surplus electricity to pump water into reservoirs high above the ground, and then turbining the water when additional electricity is needed. On the other hand, other storage technologies are under development or are limited to specific uses. This is particularly true of lithium-ion batteries, whose use is largely limited to storage for a few hours or days at most. As for flexible sources, the ability to build large hydraulic reservoirs is limited for environmental reasons, while the cost of natural gas or coal-fired power plants rises rapidly when carbon capture and sequestration is imposed.

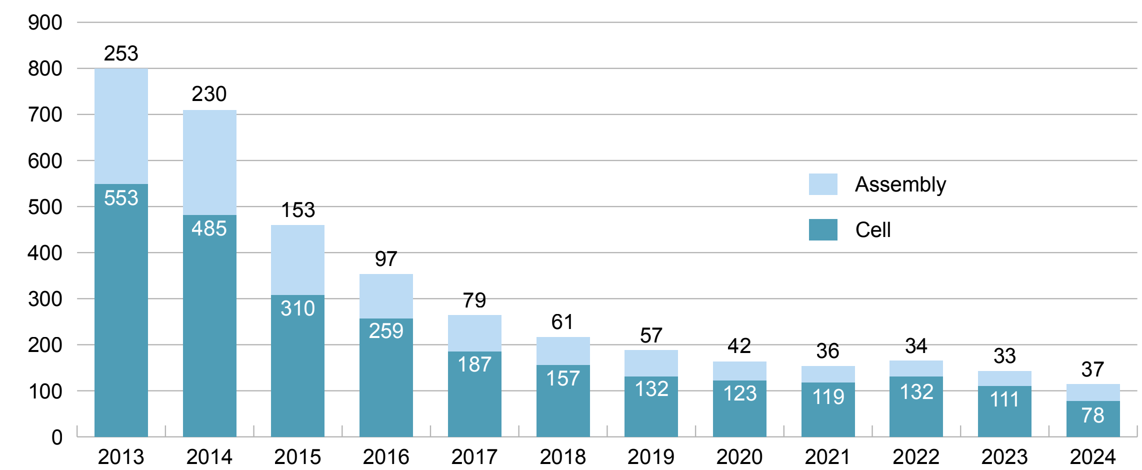
However, technologies are evolving rapidly. Today, for example, hydrogen is seen as an interesting energy carrier. Produced by methane reforming or electrolysis, it could be stored for long periods to be either burned or used in fuel cells. Other solutions are based on metal-air battery technologies using oxidation and reduction mechanisms for base metals such as iron (Form Energy). These solutions are also being tested on a large scale, with the advantage of being 5 to 10 times cheaper than lithium-ion batteries, offering a price as low as $20/kWh (Agatie, 2023).

The emergence of low-cost, large-scale energy storage solutions can transform the strategic and operational balance between different power generation technologies, in particular by reducing the barriers posed by intermittency and winter demand.

Of all the new sources of supply, photovoltaic and onshore wind generation offer the cheapest electricity by far (see figure 5). However, while wind power is favored by the NATEM model used in the CEO and by other Canadian models, solar power is not. This preference is explained by electricity demand, which are much higher in the winter than in the summer in a cold climate, even with heat pumps, when heating is electrified. With fewer hours of sunshine in the winter, photovoltaic generation is unable to respond directly to peak winter demand in the morning or evening, reducing its relevance. Wind generation, on the other hand, is better synchronized with Canadian demand: it is windier in winter, and cooling is directly correlated with the presence of wind and greater air density.

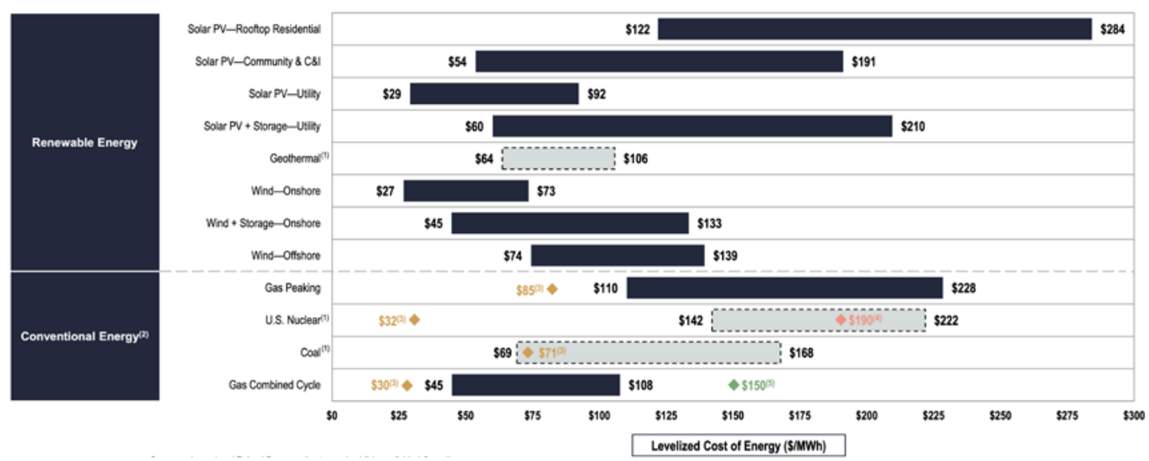
Inexpensive, high-performance mass storage solutions could therefore provide an ideal complement to intermittent sources. They would promote a better balance between wind and solar power, at the expense of nuclear power and fossil-fuel power plants with CCS. In fact, intermittent generation infrastructures are modular, which means they can be deployed more quickly and more closely to demand. This advantage, which is particularly marked in relation to nuclear power and large-scale hydroelectricity, ensures a more precise adjustment between production and demand.

Figure 4 – Lithium battery price trends in US dollars (2024).



Source: BloombergNEF 2024

Figure 5 – Discounted energy costs for various types of production. In orange: production costs once infrastructure costs have been amortized



Source: Lazard 2024

4.3. How should investments be planned?

To meet the expected increase in demand, electricity producers and distributors will have to make major investments. Since the time required to deploy these heavy infrastructures often exceeds a decade, it is essential to start building ahead of demand, following the model adopted between the 1960s and 1980s. As far as distribution is concerned, the investments to be made may seem conventional. The aim is to increase network capacity at all levels to cope with rising demand at every customer site, and to meet the need to improve service resilience. This is necessary because electricity will become an essential element in all aspects of civil security, including heating, communications and transportation. Yet, the addition of intelligent, two-way management capability requires a modular design capable of adapting to future transformations. Yet, both utilities and regulators across the country are showing widely varying degrees of openness and readiness to address these issues (Edom, Langlois-Bertrand and Mousseau, 2022).

As far as production is concerned, the way forward is less uncertain, as the technological advances of recent years transform the comparative evaluation of the various energy sources (see figure 5). Indeed, while many economists have long maintained that only high carbon prices could justify abandoning fossil fuels, the reality on the ground shows that they were wrong. Today, electricity from renewable sources is cheaper to produce than electricity from fossil fuels. Moreover, renewable sources offer far superior quality, since they deliver work directly, in the form of electricity, rather than heat. In addition, while fossil-fuel-based technologies are mature and show little room for improvement, those based on electricity still show interesting learning curves. Betting on fossil energies today therefore represents a major risk, which is growing rapidly as the speed of return on investment increases. This race is also largely lost for the nuclear industry, whose only advantage today lies in the reliability of its production, while its cost is ever-increasing and often uncertain. While nuclear generation can be expected to maintain its market share in Canada, thanks mainly to Ontario, it seems unlikely to increase it significantly.

Evolving technologies call for careful planning of electricity generation over the next 25 years. The deployment of wind farms presents few risks, since costs remain competitive and production is more in line with demand in Canada. However, the intermittency of this energy source means that the various producers need to plan low-carbon balancing solutions in parallel. These include both an increase in inter-regional transmission lines to smooth production and demand, and the implementation of large-scale energy storage solutions, including solutions lasting several weeks or even months. Here again, the strategies chosen across Canada are diverse and at very different stages of preparation.

Quebec, for example, is able to draw on its huge hydraulic reservoirs, by encouraging turbine and power plant capacity increases to boost the total available capacity of hydroelectric power plants with reservoirs. This enables the province to benefit from the multi-year storage provided by its immense reservoirs.

Ontario, meanwhile, has also opted for hydraulic storage, with two pumped storage projects that could generate 1,400MW, and various battery storage projects that would provide the equivalent, or around 1,600MW[3]. In both cases, we are talking about storage for short-term use, often two hours for batteries and half a day for pumped storage. Ontario is therefore still a long way from being able to plan for inter-seasonal demand variations and heating peaks during cold winters.

In the other provinces, existing or planned systems are even smaller, underlining their lack of preparedness for a marked acceleration in the electrification of the economy.

[3] https://www.jdsupra.com/legalnews/plan-de-l-ontario-pour-un-avenir-8730360

4.4 Operationalization

Canada has two strategies for meeting the challenge of electrification. The first strategy is to multiply projects and technologies, enabling Canadian players to participate in their development and, potentially, become a supplier of these technologies to the rest of the planet. Following the model established for other renewable technologies, the second strategy is to wait for winning technologies to emerge, and to position ourselves as simple takers of new technologies, thereby reducing both the risks and the potential rewards.

In any case, it is probably best to avoid narrowing the choices by deciding too quickly on the technologies to be used up to 2050, as Ontario seems intent on doing, with its heavy reliance on nuclear power for the bulk of its energy transition. A strategic approach would ensure that projects meet anticipated needs ten years in advance, no more.

5. Can we afford the energy transition?

Numerous studies analyze the cost of the transition from various angles: changes in the cost of electricity and the cost of the energy mix, or a comparison of the price of low-carbon technologies versus those based on fossil fuels, the size of investments, the price of carbon, etc. (Langlois-Bertrand *et al.*, 2021; Dion and Harland, 2023; Canadian Electricity Advisory Council, 2024; Haig, 2024).

In this section, we consider two ways of approaching the problem, based on analyses drawn from the CEO and specific investment projections in the electricity sector.

5.1. Electrical system upgrade costs

Whether we extrapolate projected costs or rely on more concrete investment plans from utility companies, the findings are the same: the massive electrification of our services will reduce the total cost of energy services.

Nevertheless, not everyone will benefit from the same savings, and some citizens, particularly those who use little fossil fuels today, are likely to bear the brunt of the energy transition.

Beyond system savings, we need to rethink tariff mechanisms to ensure a degree of fairness in the energy transition, a challenge that is not a matter of engineering, but of politics.

Chapter 14 of the second edition of the IET's Canadian Energy Outlook assesses the investments required in electricity generation and transmission to meet the projected increase in demand to 2050. According to the CEO, these investments would represent around $1,100 billion, or around $48 billion/year between 2030 and 2050 (Baggio, Joannis and Stringer, 2021). While this amount may seem remarkably high, it must be compared with the cost of fossil fuels saved by massive electrification. Thus, the analysis shows that once the system is deployed, from 2050 onwards, oil and gas savings of around $75 billion/year would be more than sufficient to offset the capital and interest on these new infrastructures, helping to lower the net cost of average Canadian energy expenditure.

Table 3 – Annual investment costs for electrification and fossil fuel expenditure according to the different scenarios in the CEO 2021 ($ billion)

		REF	CP30	NZ60	NZ50	NZ45
Electrification investment costs	2016-2030	4.0	8.0	6.1	9.8	13.5
	2030-2050	4.8	7.2	37.6	47.7	46.0
	2050-2060	-4.8	1.1	41.6	14.7	14.4
Change in fossil fuel expenditures	2030-2050	10.3	4.9	-3.1	-13.5	-17.1
	2050-2060	29.2	20.6	-54.3	-75.5	-74.4
	2060+	43.3	34.3	-77.7	-76.8	-73.6

Source: Baggio, Joanis et Stringer, 2021

This estimate corresponds closely to Hydro-Québec's investment forecasts for the period 2023-2035. This plan outlines a first phase of network expansion and reinforcement that is in line with the Legault government's objectives and the achievement of carbon neutrality by 2050, a requirement imposed by the federal government in compliance with the Paris Agreement. To achieve this, Hydro-Québec is announcing that it will invest up to $185 billion, tripling and even quadrupling the annual investments of recent years. These major investments will increase service reliability and quality, as well as power generation. With these investments, Hydro-Québec expects to add some 7GW of power and 50TWh of energy, in addition to reducing demand by 10TWh and peak power by 1.7GW through energy efficiency measures (Hydro-Québec, 2023).

More specifically, the investments announced for the next 10 years represent between three and four times Hydro-Québec's annual expenditure over the past few years. These expenditures will rise from around $5 billion/year to $15 billion/year. Subtracting the historical investment of $60 billion over 12 years, which is simply intended to maintain the network, the additional investments planned between now and 2035 represent some $125 billion.

Using the approach of Baggio and colleagues (Table 3), we can compare these investments with the sums saved by purchasing other energy sources. Indeed, by 2035, the vast majority of Quebec's vehicle fleet will have to be electrified. In 2023, Quebec purchased 9.2 billion liters of gasoline (Whitmore and Pineau, 2025). For the equivalent service (vehicle size and mileage), this fuel can be replaced by 21 TWh of electricity (Lavictoire *et al.*, 2025), adding a maximum capacity of around 3 GW. Excluding taxes, this purchase corresponds to an energy expenditure of around $10.1 billion, or 48¢/kWh, for the same service. An electrification of the vehicle fleet would therefore generate savings on fuel purchases sufficient to pay for all the interest and debt on Hydro-Québec's additional investments, while generating almost 30 TWh of surplus electricity at zero cost.

While Quebec as a whole stands to gain from the increased electrification of society, these benefits will not necessarily be distributed equitably. No political party on the Quebec scene, for example, is proposing to adopt a differentiated rate for vehicle recharging to better distribute costs and gains.

In short, both the analysis of Hydro-Québec's investment plans to meet the province's decarbonization objectives and the pan-Canadian analyses published by various organizations come to the same conclusion. They show that, despite a real increase in electricity rates caused by major investments in the sector, the announced investments are not leading to an explosion in the cost of Canadians' energy portfolios, but rather to system savings. Without a specific effort on the part of governments, however, these savings will not be redistributed equitably among all electricity consumers (Martin *et al.* 2024).

5.2. Marginal carbon price

The traditional economic approach maintains that only by raising the price of carbon will Canada be able to decarbonize. However, modelling in recent years has shown that the costs of decarbonization are falling steadily in many (but not all) sectors.

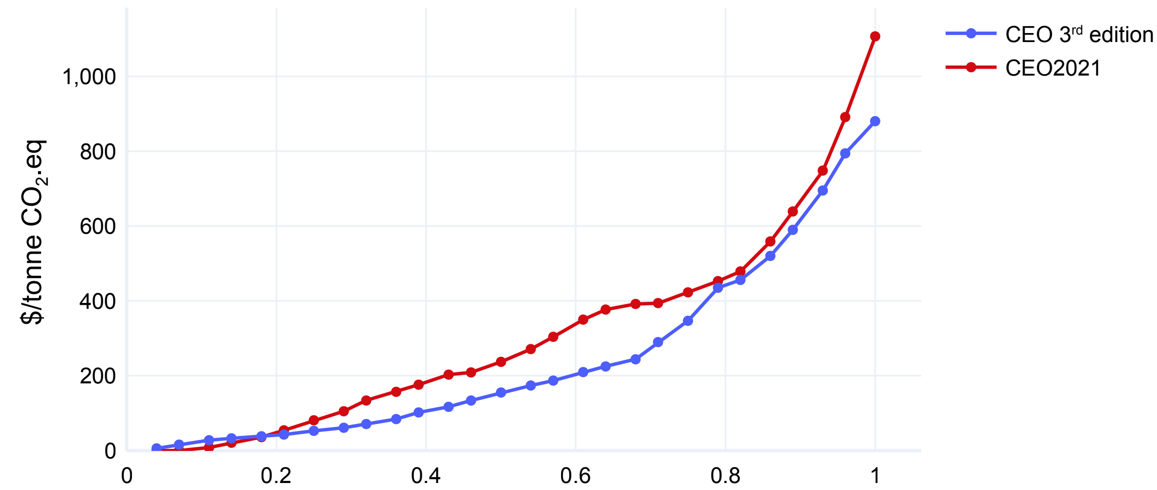
Sectoral strategies can therefore be deployed to target the most appropriate tool (regulation, cost of pollution, support for technological development) for each service and sector.

These analyses enable us to shed a different, rather optimistic light on the evolution of the marginal cost of carbon derived from the ESMIA Consultants model used in the CEO. Figure 6 shows that between 2021 and 2024, the marginal price of reducing GHG emissions by 70% by 2050 compared with today has fallen by almost half (from $400/t$CO_2$e) to just over $200/t$CO_2$e). However, after a 80% reduction, the two curves overlap almost perfectly, with the exception of the end point, which is defined by the estimated cost of last-resort solutions, which are highly uncertain.

These results show a marked reduction in the estimated price of low-carbon technologies by 2050 between the 2021 and 2024 projections. This means that the prices projected in 2021 were overestimated in relation to actual market trends. As a result, the price of several low-carbon technologies has fallen sufficiently in recent years for them to be cheaper today than their fossil fuel-based equivalents, even without the inclusion of carbon pricing. As we have seen, this is already the case for electricity generation and electric passenger vehicles (when including Chinese production).

These advances are continuing across sectors at uneven rates, of course, which explains why eliminating the last 20% of GHG emissions is still as costly in the 2024 projections as in those for 2021. These emissions mainly come from industrial processes, agriculture and certain modes of transport - sea and air - for which alternatives remain limited or very costly. To achieve carbon neutrality, the model must offset these emissions with CO_2 capture and sequestration technologies. Since these technologies are added to traditional infrastructures, rather than replacing them, the total cost of carbon neutrality can only be higher than that of the current system, which does not have to include the real cost of carbon pollution.

Figure 6 – Evolution of the marginal price to eliminate one equivalent tonne of CO_2 in 2050.



Source : Langlois-Bertrand *et al.* 2024

5.3. System costs vs. individual costs

The models therefore show that the innovation sparked by the energy transition has rapidly reduced the cost of several low-carbon technologies linked to the production or consumption of electricity. These reductions can continue with effective deployment strategies aimed at maintaining price pressure for individual and commercial consumers, be they electric vehicles, heat pumps or other appliances. So, by building on these technological advances and better structuring supply, distribution and service chains, decarbonized solutions could have a negative cost compared to current technologies, both in terms of production and energy services.

That leaves the sectors for which these approaches do not work, and which will have to bear the brunt of the transition costs, since CO_2 capture and sequestration processes will have to be added to existing production infrastructures. That said, as we have seen, the NWR Sturgeon refinery project in Alberta suggests that it is possible to capture and sequester carbon at extremely low prices – just over $30/t$CO_2$e – in industrial contexts. Once mastered, this approach could therefore be competitive for several high-emission sectors.

Although the impact of this decarbonization spending is largely positive at the systemic level, it is certain that the gains and losses arising from the energy transition will not be evenly distributed. For governments, the objective should therefore not be to offset the costs of the transition, but rather to ensure that the gains are equitably shared. This requires strategic analyses and programs, which are currently lacking. Without fairness, there is a risk of opposition rising, which would be a loss for society as a whole, given the overall net benefit of the transition.

6. Is it possible to keep to the schedule?

We need only look at the list of infrastructures built in Canada between 1960 and 1980, or those deployed by China between 2000 and 2020, to conclude that Canada has the means and capacity to complete the transition to carbon neutrality by 2050.

To do this, Canada needs to tackle the barriers that are slowing investment today, and driving up costs far beyond those seen in Europe, for example. In addition to freeing up capital, such an overhaul would have immediate benefits across the Canadian economy.

According to McKinsey (Dussud *et al.*, 2023), between $350 and $400 billion have been invested in infrastructure in Canada in 2021. Although significant, this sum represents only two-thirds of the investment required to meet all the needs of Canadians in terms of population growth, economic development and infrastructure maintenance and renewal, to which we must add industrial growth and the necessary adaptation to climate change. Compared to these figures, what do efforts to support the transition to carbon neutrality represent?

Taking Hydro-Québec's plan as a reference, upgrading the Canadian power grid, from generation to distribution, would require an investment of around $45 billion more per year than is being made today. This is similar to the investment estimated by Baggio *et al.* (Baggio, Joanis and Stringer, 2021) and represents around 10% of current investment in Canada. In the same plan, Hydro-Québec forecasts that it will need around 35,000 construction workers to roll out its infrastructures, or 11% of workers in this field in Quebec; this proportion would probably be similar in most provinces.

Replacing fossil-fuel technologies with electric ones requires staff training and some reallocation of human resources. Overall, however, the demand for technical staff is not expected to increase significantly. For example, electric cars require much less maintenance than gasoline-powered cars, while heat pumps may require slightly more maintenance than a natural gas furnace, while still offering the advantage of air conditioning. Yet Canada has far more auto mechanics than air-conditioning specialists. In Quebec, for example, there are 35,000 mechanics, but only 5,000 heating technicians[4]. Retraining one-third of auto mechanics would triple the number of heating technicians.

As we can see, both the investment and the number of technical staff required to successfully complete the energy transition are substantial. However, they represent sufficiently small fractions that they do not threaten the rest of the economy, provided, however, that the necessary support is implemented to redeploy human resources while respecting everyone's aspirations.

[4] Québec 2025; Métiers Québec 2025.

7. Conclusions

Various techno-economic modeling exercises, such as the IET's *Canadian Energy Outlook*, have made it possible to study different decarbonization scenarios. These scenarios appear to impose extremely rapid structural transformations on the Canadian economy. However, an assessment of the challenges to be met in various energy consumption and production sectors shows that a sustained pace is both structurally and financially possible for those sectors where decarbonization technologies are already well identified. These include buildings, part of transport, CO_2 capture and sequestration (CCS) and power generation. Moreover, the cost of carbon-neutral technologies (excluding CCS) is falling rapidly, which means that this transformation can already be achieved at zero total cost, or even at a profit compared with upgrading fossil fuel-based technologies.

However, these benefits are not yet visible to all sectors, and special efforts should be made to develop competitive carbon-neutral solutions for the freight, air and sea transport sectors.

To remain competitive, Canada would do well to deploy strategies that will enable its citizens and companies to access existing technologies at prices similar to those observed abroad. It would also be in Canada's interest to identify technologies that support carbon neutrality and enable it to develop valuable intellectual property. This is the case for CCS technologies, including biochar, and certain low-carbon technologies in niche sectors linked to aeronautics and heavy transport. The rest of the world is moving fast, however, so it is crucial for Canada not to delay any longer.

Whatever Canada decides, the remarkable progress seen in recent years in the development and deployment of low-carbon technologies underscores the much greater-than-expected agreement between productivity and decarbonization. It remains to be seen how far Canada will want to go in order to take advantage of this potential.

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