gTech-IESD: A fully integrated energy-economy-electricity model

Model documentation

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SUBMITTED BY

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About Us

Navius Research Inc. is an independent and non-partisan consultancy based in Vancouver. We operate proprietary energy-economy modeling software designed to quantify the impacts of climate change mitigation policy on greenhouse gas emissions and the economy. We have been active in this field since 2008 and have become one of Canada's leading experts in modeling the impacts of energy and climate policy. Our analytical framework is used by clients across the country to inform energy and greenhouse gas abatement strategy.

We are proud to have worked with:

- Most provincial and territorial governments, as well as the federal government.
- Utilities, industry associations and energy companies.
- Non-profit and research organizations with an interest in energy, climate change and economics.

Thank you to Natural Resources Canada for sponsoring development of the Canada Energy Dashboard through the Energy Innovation Program.

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1. Introduction

The **Canada Energy Dashboard** is a publicly available tool that enables the user to explore pathways for Canada's energy-economy-electricity system from now until 2050[1]. The user can examine two levels of policy and vary six uncertain assumptions, resulting in 216 future trajectories of how Canada's system could evolve to 2050. The user can then examine how changing policy or uncertainty will affect a broad set of metrics for environmental and economic performance.

Underlying the dashboard is an extensive modeling project, in which Navius Research fully integrated two of their models: (1) the gTech model, which is a computable general equilibrium model of North America's energy-economy; and (2) the IESD model, which is a capacity addition and dispatch model of North America's electricity system. The integrated model provides an internally consistent framework with which to examine how the electricity system affects the general economy, and vice versa. The integrated model was used to simulate 324 individual scenarios for the evolution of Canada's energy economy. These results are summarized in the Canada Energy Dashboard.

This documentation summarizes our method and key assumptions to help with interpretation of the results. The following section describes the criteria typically used to assess greenhouse gas (GHG) policy models. The combination of gTech and IESD was designed to perform well against these criteria, subject to computing and complexity constraints. Section 3 documents the gTech model, while Section 4 documents IESD. Section 5 describes the methodology for integrating the two models. The final two sections of the report address scenario design. Section 6 provides details on the legislated and net zero policy scenarios that were simulated and are presented on the Canada Energy Dashboard. This is followed in Section 7 by a discussion of uncertainty in energy-economy modeling and the sensitivity analysis that was carried out to address uncertainty for this project.

[1] Visit: https://canadaenergydashboard.com/

2. Why are models useful?

Models that are used to estimate the energy consumption, emissions, and/or economic impacts of policies designed for GHG reduction are typically assessed according to a series of well-established criteria[2]. Computing requirements generally prevent any one model from performing well against all the criteria described in this section. There are also limits to the desired complexity of models. Trade-offs between the criteria are therefore necessary, depending on the characteristics of the policy or policy package that is being tested.

Explicit representation of technological change: Since the process of technological change is fundamental to long-term GHG abatement, all models used to estimate the emissions impacts of GHG policies should be capable of representing (either explicitly or implicitly) the evolution of technology stocks within the energy system. However, while some GHG policy models explicitly represent thousands of technologies across all economic sectors, others represent technologies implicitly through model calibration[3]. A technologically explicit model is necessary for estimating the GHG impacts of technology-focused policies such as technology- and building-specific tax credits, subsidies, penalties, and regulations. Furthermore, the explicit representation of technologies ensures that the simulated outcomes of the model are technologically feasible (this is not guaranteed by the standard production functions of CGE models that represent technologies implicitly).

Realistic representation of technological choice: Methodologies that consider important non-financial influences on human decision-making can be described as behaviorally realistic. These non-financial decision factors include human preferences related to convenience, comfort, and status, as well as risks and our attitudes toward them. Another component of behavioral realism is the ability to capture market heterogeneity – different decision-makers may perceive different non-financial influences and may also face different financial costs. A behaviorally realistic model is

[2] Rhodes, E., Hoyle, A., McPherson, M., & Craig, K. (2022). Understanding climate policy projections: A scoping review of energy-economy models in Canada. *Renewable and Sustainable Energy Reviews, 153*, 111739. https://doi.org/10.1016/j.rser.2021.111739

[3] Rhodes, E., Hoyle, A., McPherson, M., & Craig, K. (2022).

necessary for forecasting the outcome of a policy when that outcome is meaningfully influenced by human decisions.

Capture of policy interactions: All levels of government in Canada and the United States have implemented policies designed to abate GHG emissions. Achieving Canada's net zero target by mid-century will require strengthening existing policies and/or implementing new policies. In many cases, more than one policy directly or indirectly targets the same source of emissions. For example, a patchwork of federal and provincial vehicle regulations, fuel regulations, and carbon pricing efforts all act to reduce GHG emissions from passenger vehicles.

Given the multitude of policies that exist, interactions between them can have a significant impact on energy consumption and GHG emissions. For example, a policy that improves building shell efficiency would be expected to reduce the need for temperature regulation, thereby mitigating the potential energy savings from policies that encourage or mandate more efficient heating, ventilation, and air conditioning technologies. Given that such interdependencies exist, it is not appropriate to simply estimate the GHG impacts of actions[4] and/or policies in isolation and then add them together. Energy-economy models that treat all actions as happening simultaneously have been developed to address this problem.

Capture of macroeconomic feedbacks: According to economic theory, supply and demand in all markets, including commodities, services, and factors of production, are balanced through responses to prices. Similarly, price changes are absorbed by the economy through supply and demand adjustments. For example, compliance with GHG regulation may result in an increase in the cost of producing electricity that is passed on to households in the form of a higher price. In turn, households would be expected to reduce their consumption of electricity through a variety of possible responses. These include switching to technologies that are more energy-efficient, switching to technologies that consume other forms of energy, and reducing consumption of services that use electricity, such as heating and lighting.

Models capture these types of feedbacks to various degrees. Models that represent all economic activity and link all the major macroeconomic feedbacks in a full equilibrium framework are referred to as computable general equilibrium models. In these multi-

[4] An action is the technology or behavioral change that reduces GHG emissions through energy conservation, an energy efficiency improvement, and/or fuel switching in response to a policy or policies.

sector models, equilibrium is reached when a specific set of prices results in supply being equal to demand in every market. Policies that are expected to induce significant energy supply-demand and/or other macroeconomic impacts should be simulated using a model that represents those impacts. For example, federal and provincial carbon pricing efforts affect fuel prices across multiple sectors and have knock-on effects on the prices of diverse goods and services.

High resolution representation of time and space: Some applications require a higher resolution approach to modeling than others. For example, in order to simulate policies that encourage or mandate a significant shift to intermittent renewables (such as solar and wind) for electricity generation, a methodology may be required that represents time in terms hours instead of years[5]. Likewise, interest by city governments in developing strategies to reduce urban GHG emissions has resulted in the need for methodologies that represent space in terms of cities or neighborhoods, rather than countries or regions. Modeling at high resolution in either dimension is associated with a significant computational burden, resulting in a trade-off between the two[6].

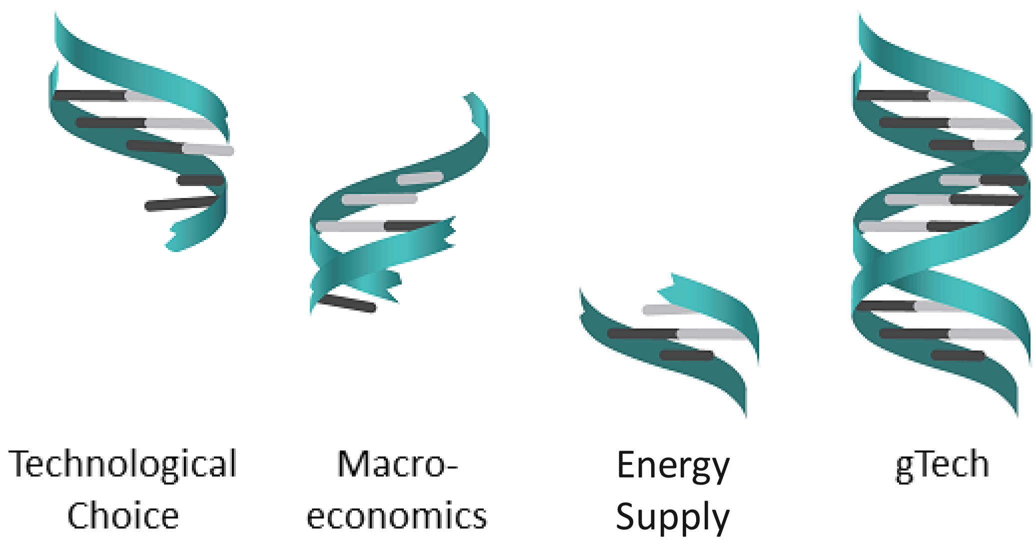
[5] Lopion, P., Markewitz, P., Robinius, M., & Stolten, D. (2018). A review of current challenges and trends in energy systems modeling. *Renewable and Sustainable Energy Reviews, 96*, 156-166. https://doi.org/10.1016/j.rser.2018.07.045

[6] Lopion, P., Markewitz, P., Robinius, M., & Stolten, D. (2018).

3. The gTech model

Navius maintains and operates an in-house computable general equilibrium (CGE) model of Canada and the United States called gTech. The model was designed to perform well against the first four criteria outlined above in Section 2. By virtue of being an energy-economy model that treats all actions as happening simultaneously, gTech performs well at capturing policy interactions. However, unlike other energy-economy models, gTech incorporates a sophisticated representation of technological change and technological choice (Section 3.3) within a full equilibrium framework that links all major macroeconomic feedbacks (Section 3.2). The three key elements that were brought together to create gTech are illustrated in Figure 1.

Figure 1: Origin of the gTech model



3.1. Why is gTech useful?

By incorporating an explicit and realistic representation of technological change into an equilibrium framework that links all the major macroeconomic feedbacks, gTech can provide extensive insight into the effects of climate and energy policy.

Because gTech explicitly represents technological change, the model can respond to questions such as:

- What is the impact of a technology-focused policy, such as a vehicle emissions standard?
- How do policies affect the adoption of a particular technology?
- How does adoption of a technology affect GHG emissions and energy consumption?

In addition to being a technologically explicit model, gTech considers important non-financial influences on the technological choices of consumers and businesses. Therefore, it provides realistic insights, rather than insights into illustrative, hypothetical, or optimal situations.

Because gTech captures macroeconomic feedbacks in a CGE framework, the model can respond to questions such as:

- What is the impact of an economy-wide policy, such as a carbon price, at the federal or provincial level?
- How do policies affect national and/or provincial gross domestic product (GDP)?
- How do policies affect individual sectors of the economy?
- How are households affected by policies?
- Do policies affect energy prices or any other price in the model, such as food prices?

Because gTech combines these features – incorporating an explicit representation of technological change within a CGE model – it can respond to questions such as:

- What are the effects of investing carbon tax revenue into low- and zero-carbon technologies?
- What are the macroeconomic impacts of technology-focused policies?

3.2. Macroeconomic feedbacks

CGE models are widely used by economists investigating the impact of GHG policy. Therefore, a general description of the CGE approach, its strengths, and its limitations is provided in Section 3.2.1 below. The specific attributes of gTech as a CGE model are documented in Section 3.2.2.

3.2.1. Introduction to CGE models

CGE models represent the economy through a series of simultaneous equations linking economic inputs with outputs. Their parameters capture aggregate relationships between the relative costs and market shares of energy and other inputs to the economy, and may be estimated econometrically from time-series data. CGE models represent all economic activity and capture all the major macroeconomic feedbacks that balance supply and demand through price signals. They do so in a full equilibrium framework, solving for a set of prices that results in supply being equal to demand in every market.

In addition to parameter values, CGE models require data in the form of a social accounting matrix (SAM). The SAM describes all income and spending in an economy over a specified period, typically one year. It includes income and spending by households, firms, and governments. The matrix also records savings and investment spending and international trade. The SAM is normally based on information from official national accounts. Researchers must decide to what degree data are aggregated (or disaggregated) within the SAM, trading off the benefits of disaggregation for analysis of specific industries, for example, against the benefits of an aggregated database, which include ease of use and understanding[7].

CGE models are used to simulate the economy's response to a financial signal or "shock." When these models are applied to the problem of GHG emissions abatement, this signal would normally be in the form of an emissions tax or an emissions permit price that increases the relative cost of emissions-intensive technologies and energy forms. The magnitude of the financial signal necessary to achieve a given emissions reduction target indicates its implicit cost.

When an external shock such as a carbon tax is simulated, the model describes changes in the prices of and demand for different energy forms, impacts on prices and demand for other goods and services, and effects on employment and wages. CGE

[7] Loschel, A. (2002). Technological change in economic models of environmental policy: A survey. Ecological Economics, 43, 105-126. https://doi.org/10.1016/S0921-8009(02)00209-4

models can address not only demand from producers and households but also from government, investors, and foreign markets. These models are used to calculate macroeconomic indicators such as gross domestic product (GDP), aggregate savings and investment, the balance of trade, and (in some cases) the fiscal position of government[8].

CGE models generally lack an explicit representation of technologies, including those that can potentially improve energy efficiency and/or reduce GHG emissions. Technological change tends to be represented as an abstract, aggregate phenomenon. Conventional CGE models are therefore only able to help policy makers assess economy-wide policy instruments, such as taxes and tradable permits. Likewise, these models are unable to identify the specific changes that comprise the response of the economy to a shock.

When the parameters of a CGE model are based on historical data, the model can be said to provide a realistic representation of technological choice because it captures how people have responded to price changes in the past. This is the case even though the technologies themselves are not explicit. However, there is no guarantee that the values of the statistically estimated parameters will remain valid into the future under substantially different policies, energy prices, and technological options for GHG abatement[9,10,11].

These challenges in the field of CGE modeling motivated the developers of gTech to incorporate an explicit representation of technological change into the model. The treatment of technology stock turnover and technology choice in gTech is described in Section 3.3.

[8] Burfisher, M. (2021). Introduction to computable general equilibrium models. In *Introduction to computable general equilibrium models* (pp. 9-24). Cambridge University Press. https://doi.org/doi:10.1017/9781108780063.002

[9] DeCanio, S. J. (2003). *Economic models of climate change: A critique.* Palgrave Macmillan.

[10] Grubb, M., Kohler, J., & Anderson, D. (2002). Induced technical change in energy and environmental modeling: Analytic approaches and policy implications. *Annual Review of Energy and the Environment, 27*, 271-308. https://doi.org/10.1146/annurev.energy.27.122001.083408

[11] Laitner, J. A., DeCanio, S. J., Koomey, J. G., & Sanstad, A.H. (2003). Room for improvement: Increasing the value of energy modeling for policy analysis. *Utilities Policy, 11*, 87-94. https://doi.org/10.1016/S0957-1787(03)00020-1

3.2.2. Specific attributes of gTech

gTech accounts for all economic activity in Canada and the United States, as measured by national accounts. Specifically, it captures all sector activity, all GDP, all trade of goods and services, and the transactions that occur among households, firms, and government. As such, the model provides a forecast of how government policy affects many different economic indicators including GDP, investment, trade, household income, and employment. The key macroeconomic feedbacks captured by gTech are summarised in Table 1.

The key macroeconomic inputs to gTech are: (1) a social accounting matrix (SAM) used to characterize the structure of the economy in the model base year (currently 2015) and (2) forecasts of growth in labour supply and productivity. The SAM is based on Statistics Canada supply and use tables[12] and IMPLAN supply and use tables[13] for the United States. The expected rates of growth in labour supply and labour productivity are based on the Parliamentary Budget Office's Fiscal Sustainability Report[14] for Canada and the U.S. Energy Information Administration's Annual Energy Outlook[15]. gTech generates an internal forecast of economic growth from these growth rates, subject to policy and other conditions, such as the price of oil.

gTech is customizable in terms of the way North America is divided into regions. The version used for this analysis represents all the Canadian provinces separately, except for the Maritimes, which are aggregated together with the territories as a single region. In the United States, California is represented separately, and the rest of the country is modeled as a single region.

The model has a high degree of sectoral disaggregation, representing over 80 economic sectors. Each sector represented by gTech produces a unique good or service (e.g., the mining sector produces ore, while the trucking sector produces

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[12] Statistics Canada (annual). *Supply and Use Tables*. Available from: www150.statcan.gc.ca/n1/en/catalogue/15-602-X

[13] IMPLAN, 2021, Customized supply-use tables.

[14] Parliamentary Budget Office, 2020 Fiscal Sustainability Report. Available from: https://www.pbo-dpb.gc.ca/en/blog/news/RP-1920-029-S-fiscal-sustainability-report-2020-rapport-viabilite-financiere-2020

[15] U.S. Energy Information Administration, 2021, Annual Energy Outlook 2021. Available from: https://www.eia.gov/outlooks/archive/aeo21

transportation services) and requires specific inputs to production. Of these inputs, some are not directly related to energy consumption or GHG emissions (e.g., the demand by a sector for services or labour), while other inputs are classified as "energy end-uses". The sectors, fuels, and energy end-uses covered by gTech in this analysis are listed in Appendix B. To categorize the low-carbon economy in gTech, we assign economic activity to one of three categories: low-carbon energy, rest of energy, and non-energy. Appendix C defines these categories and details which sectors are considered part of the low-carbon energy category.

gTech normally solves in 5-year increments. While Navius has developed versions that solve in smaller time increments, 5-years is the default because the model simulates full equilibrium in all markets and is intended to capture long-term trends, as opposed to the short-term effects of business-cycles in which markets may be out of equilibrium. Solving in 5-year increments also reduces the amount of time required to complete analyses (relative to annual or biannual increments).

To characterize the energy-economy of Canada and the United States, gTech is calibrated to a variety of data sources, as documented in Appendix A. GHG emissions are calibrated in the model base year (currently 2015) to align with historical emissions. Between the base year and the most recent year for which data are available, modeled emissions are also calibrated to align with historical trends. The ability of gTech to replicate these trends improves confidence in its projections.

Table 1: Macroeconomic feedbacks captured by gTech

Model feature	Description
Full equilibrium	gTech ensures that all markets in the model return to equilibrium (i.e., that the supply of each good or service is equal to its demand). This means a shift that occurs in one sector is likely to have ripple effects throughout the entire economy. For example, greater demand for electricity due to GHG policy initiatives will require greater electricity production. In turn, greater production is expected to necessitate greater investment in and consumption of goods and services by the electricity sector. An increase in demand for labour in construction services could ultimately lead to higher wages. The model also accounts for price responses. In the above example, the price of electricity may increase, as more expensive generation resources are brought online to meet the increased demand. Households can adjust to this price increase by making changes that reduce their electricity consumption, such as switching to technologies that are more energy efficient, switching to technologies that use alternative forms of energy, and reducing their consumption of services that use electricity. They may even reduce their demand for unrelated goods and services.

Energy supply markets	gTech accounts for all the major energy supply markets, such as electricity, refined petroleum products, and natural gas. Each market is characterized by resource availability and production costs by region, as well as costs and constraints related to transporting energy between regions (e.g., pipeline capacity). Low carbon energy sources can be introduced within each market in response to policy, including renewable electricity and bioenergy. The model accounts for the availability and cost of bioenergy feedstocks, allowing it to provide insight about the economic effects of emissions reduction policy, biofuels policy, and the approval of pipelines. Oil price is an exogenous input to the model (i.e., based on an assumed global price). The price for other energy commodities is determined by the model based on demand and the cost of production.
Labour and capital markets	Like other markets, labour and capital markets must achieve equilibrium in the model. The availability of labour can change with the real wage rate (i.e., the wage rate relative to the price for consumption). If the real wage increases, the availability of labour increases. The model also accounts for "equilibrium unemployment".
Interactions between regions	Economic activity in each region represented in gTech is highly influenced by interactions with other modeled regions. These interactions are based on: (1) the trade of goods and services, (2) capital movements, (3) government taxation, and (4) various types of "transfers" between regions (e.g., the federal government provides transfers to provincial and territorial governments).
Representation of households	Households receive income from businesses in exchange for their labour and investment of savings. They use this income to consume various goods and services. gTech accounts for these interactions. Households are disaggregated into 5 different income groups within the model to provide greater insight into how policies might affect different households.

3.3. Technological change

gTech contains detailed information describing the key technologies and processes that influence energy consumption and GHG emissions. The model currently includes over 300 technologies across more than 70 energy end-uses (e.g., light-duty vehicle travel, residential space heating, industrial process heat, management of agricultural manure). The energy end-uses covered by gTech in this analysis are listed in Appendix B. Key technologies and the quantitative assumptions used to describe them are provided in Appendix D. The technologies that are represented in gTech are either currently available or are likely to become available in the coming decades[16].

gTech keeps track of how stocks of technologies change over time. As older technologies reach the end of their lifespans, they are retired. Technology stock retirement follows a logistical function as in Equation 1.

Equation 1: Technology stock retirement in gTech

$$STOCK_{t,y} = STOCK_{t,0} \times \frac{1}{\left(1 - e^{\left(-7.5 \times (1 - y/life_t)\right)}\right)}$$

Where:

- $STOCK_{t,y}$ is the stock of technology *t* in year *y* that was installed in year 0;
- $STOCK_{t,0}$ is the stock of technology *t* in its installation year;
- $life_t$ is the lifespan for technology *t.*

As new technologies are needed to replace retiring stocks and meet any growth in service demand, gTech simulates how households and businesses choose between the available options (Section 3.3.1). The explicit representation of stock turnover in gTech allows technology stocks to improve in terms of their energy and emissions performance over time. If an emerging technology is included in the model database that is more energy efficient and/or uses an energy source with lower emissions than the conventional existing technology, and if this technology is attractive to households and businesses, then it will gain market share as stocks of the conventional technology retire. However, stock turnover is also a source of inertia with respect to meeting emissions targets, both in gTech and in the real world, because some technologies, such as electric power plants and pipelines, have long lifespans, and a cost is incurred when a technology is retired before the end of its economic life.

[16] gTech excludes undefined technologies, such as backstop technologies. Backstop technologies are used in some models to represent future technology development that could limit abatement costs.

3.3.1. Technological choice

If demand for an energy end-use exceeds the availability of technologies from previous years, new technologies must be added to fill that demand. The process of technological choice, whereby households and businesses select the technologies that best meet their needs, has a profound influence on energy consumption and GHG emissions in a market economy. Table 2 summarizes key factors that influence technological choice and describes how each of these are addressed in gTech.

The factors addressed in Table 2 include financial costs, non-financial influences, and policy. Accounting for non-financial influences such as time preference, technology-specific preferences, and diversity of choice allows gTech to represent human behavior in a realistic way. Policies can influence technological choice indirectly by affecting the other factors (e.g., a subsidy that reduces the capital cost of a technology) or by directly imposing requirements or restrictions on the technological options available to households and businesses through regulation (e.g., a standard that requires a minimum level of energy efficiency). Additional factors (not addressed in Table 2) that influence technological choice in gTech include technology operating costs, technology lifespans, and constraints on technology adoption.

Several of the technology cost components taken into account by gTech are dynamically represented, meaning they can change over time based on the model simulation. gTech includes functions that allow capital costs, as well as the non-financial (intangible) costs representing technology-specific preferences, to decline over the course of a simulation. Energy costs are also dynamic in gTech because they are influenced by energy prices, which are determined by the model (except for the global price of oil).

Table 2: Key factors that influence technological choice in gTech

Influencing factor	Description
Capital cost	The capital cost is simply the upfront cost of purchasing a technology. For emerging technologies, the capital cost can decline as more units are produced, reflecting economies of scale and economies of learning (as manufacturers gain experience). The literature confirms that this dynamic is important[17]. It has been observed in a wide variety of contexts, such as aircraft

[17] Löschel, A. (2002). “Technological Change in Economic Models of Environmental Policy: A Survey”. *Ecological Economics*, 43 (2-3), 105-126.

	manufacturing, chemical processing, agricultural technology, shipbuilding, and automobile manufacturing[18]. The cost of electric vehicles has come down significantly in recent years and this trend is expected to continue[19]. A declining capital cost function has been incorporated into gTech to allow costs to decline over time as a function of cumulative production, until a technology reaches maturity (defined by a prespecified minimum cost). Capital costs can be broken down into components in gTech, with the declining capital cost function applied to each one independently. Therefore, increased adoption of one technology can affect the cost of another technology that uses similar components. For example, increased battery electric vehicle adoption reduces battery, motor and electronics costs for fuel cell vehicles.
Energy cost	The energy cost associated with a technology is a function of: (1) the price of energy (e.g., cents per litre of gasoline) and (2) its energy requirements (e.g., a vehicle's fuel economy, measured in litres per 100 km). In gTech, the energy requirements of a given technology are fixed, but the price of energy is determined by the model.
Time preference	Some technologies offer energy cost savings in exchange for a higher capital cost, relative to the conventional option. Because households and businesses generally incur the capital cost of a technology before they incur its energy costs, a trade-off exists between the higher upfront costs and future energy savings in these cases. Energy-economy modelers represent the higher priority placed by households and businesses on upfront costs using a "discount rate" (analogous to the interest rate applied to a loan). Many energy modelers employ a "financial" discount rate (commonly between 5% and 10%) to represent time preference. However, research has consistently shown that the decisions of households and firms indicate rates significantly higher than a financial discount rate[20]. This implies that using a financial discount rate would overvalue future savings relative to revealed behavior and provide a poor forecast of household and firm decisions. Given the objective of forecasting how households and firms are likely to respond to climate policy, gTech employs behaviorally realistic discount rates of between 8% and 25%[21] to simulate technological choice.
Technology-specific preferences	Households and businesses also exhibit preferences for specific technologies and technology attributes. For example, when it comes to electric passenger vehicles, some potential buyers may be concerned about driving range and available charging infrastructure or the risk associated with an emerging

[18] Bollinger, B., & Gillingham, K. (2014). Learning-by-doing in solar photovoltaic installations. Available at SSRN 2342406.

[19] Nykvist, B., Sprei, F., & Nilsson, M. (2019). "Assessing the Progress Toward Lower Priced Long-Range Battery-Electric Vehicles". *Energy Policy*, 124, 144-155.

[20] Rivers, N., & Jaccard, M. (2006). "Useful Models for Simulating Policies to Induce Technological Change". *Energy Policy*, 34 (15), 2038-2047.

[21] Axsen, J., Mountain, D.C., Jaccard, M. (2009). "Combining Stated and Revealed Choice Research to Simulate the Neighbor Effect: The Case of Hybrid-Electric Vehicles". *Resource and Energy Economics*, 31, 221-238.

	technology, while others may see a zero-emission vehicle as a status symbol[22]. Technology-specific preferences can be quantified as non-financial or "intangible" costs, which are included in the technology choice algorithm of gTech. As emerging technologies penetrate the market, improved availability of information and decreased perceptions of risk can make people even more likely to buy them[23]. The literature indicates that this dynamic is important[24]. To represent it in gTech, a function is available that allows the intangible cost of an emerging technology to decline as its share of the market for new purchases increases.
Diversity of choice	As suggested by the example regarding electric vehicle preferences above, individuals are unique and may weigh factors differently when choosing what type of technology to purchase. Different people may come to different decisions, even when faced with the same financial costs. Financial costs and the availability of technologies and fuels can also vary across individuals within a given region. According to the gTech market share equation, the technology with the lowest net cost (including all the cost factors described above) will capture the greatest market share, but technologies with higher net costs may still capture some market share[25]. The more costly a technology is relative to its alternatives, the less market share it will earn.
Policy	One of the most important drivers of technological choice is government policy. Governments have a variety of policy options available to influence technological choice in order to mitigate GHG emissions: (1) subsidy or incentive programs, which pay for a portion of the capital cost of a preferred technology or technologies; (2) regulations, which impose requirements or restrictions on the technological options available to households and businesses; (3) carbon pricing, which increases energy prices in proportion to their carbon content; (4) adjustments to other taxes (e.g., not charging GST on a preferred technology); and (5) flexible regulations, like the federal Clean Fuel Regulations, which create a market for compliance credits. gTech can be used to simulate the impact of virtually any substantive GHG abatement policy on technological choice, as well as the combined impact of multiple policies implemented together.

[22] Kormos, C., Axsen, J., Long, Z., Goldberg, S., 2019. Latent demand for zero-emissions vehicles in Canada (Part 2): Insights from a stated choice experiment. Transportation Research Part D: Transport and Environment 67, 685-702.

[23] Mau, P., Eyzaguirre, J., Jaccard, M., Collins-Dodd, C., & Tiedemann, K. (2008). "The Neighbour Effect: Simulating Dynamics in Consumer Preferences for New Vehicle Technologies". *Ecological Economics*, 68, 504–516.

[24] Axsen, J., Mountain, D. C., & Jaccard, M. (2009).

[25] Rivers, N., & Jaccard, M. (2006). "Useful Models for Simulating Policies to Induce Technological Change". *Energy Policy*, 34 (15), 2038-2047.

Each component of the cost for a technology is incorporated into its life-cycle cost, which is then used to calculate its market share. A “typical" technology’s life-cycle cost is calculated as in Equation 2.

Equation 2: Technology life cycle cost in gTech

$$LCC_t = \frac{PK \times CC_{t,y}}{ou_t} \times crf_{eu} + \frac{PK \times oc_t}{ou_t} + \sum_f \left(PF_f \times fuel_{t,f}\right) + \sum_{eu} \left(PEU_{eu} \times sereu_{t,eu}\right) + \sum_{pol} \left(PP_{pol} \times preq_{pol,t}\right)$$

Where:

- $CC_{t,y}$ is the capital cost for technology *t* in year *y*. Capital costs for many technologies are dynamic and can decline over time;
- PK is the price for capital determined by the model;
- ou_t is the output for technology *t*;
- crf_{eu} is the capital recovery factor for all technologies that compete in the same end-use *eu* as technology *t*;
- oc_t is the operating cost for the technology;
- PF_f is the price for fuel *f* (e.g., $ per gj) determined by the model;
- $fuel_{t,f}$ is the requirement of fuel *f* per unit of output (e.g., gj of diesel per tonnes kilometers traveled);
- PEU_{eu} is the price for end-use *eu* (e.g., $ per gj of heat load) determined by the model;
- $sereu_{t,eu}$ is the service requirement of end-use *eu* per unit of output (e.g., gj of heat load per m2 of floorspace);
- PP_{pol} is the policy price of policy *pol*. A policy price could either be explicit (e.g., carbon pricing) or implicit (e.g., shadow price for a ZEV mandate).

- $preq_{pol,t}$ is the policy requirement for technology *t* under policy *pol*. For carbon pricing, this value would be set to the covered emissions under the policy.

Please note that the technology life-cycle cost equation provided above is a simplification and excludes some costs or benefits for some technologies.

4. The IESD model

The IESD model is a linear programming model that simulates how the electricity sector makes capacity and dispatch decisions based on the hourly load curve, energy prices, and the cost of installing and operating different resources. The model endogenously adds and dispatches electricity generation and storage such that the total costs of the electricity system are minimized, system revenues are maximized, and load in each hour is met. The value provided by storage technologies and their possible revenue streams are reflected by the extent to which they can minimize system costs relative to generation technologies. The model can be adjusted to represent how specific electricity markets may or may not value the grid services provided by storage. Table 3 summarizes the key electricity sector dynamics taken into account by IESD.

Table 3: Electricity sector dynamics captured by IESD

Model feature	Description
Hourly electricity consumption	The supply of electricity must match the demand at all times. This poses a challenge because electricity consumption is not consistent or entirely predictable throughout the day or year. Data on annual electricity consumption by end-use are received from gTech and then converted into an hourly load curve for each of the modeled regions.
Hourly generation profiles	Some generation resources can be made available upon demand, whereas others cannot. For example, generation from wind resources is available when the wind is blowing and generation from solar photovoltaics is available when the sun is up. IESD includes a detailed representation of the options available to generate electricity in each region, including the hourly availability of intermittent resources. Quantitative assumptions used to describe generation resources in IESD for this analysis are provided in Appendix E.
Electricity trade	IESD explicitly simulates the hourly interprovincial and cross-border trade of electricity. (Within any given province, electricity is assumed to be transmitted free of constraints and losses.)
Electricity storage	Electricity storage is a promising option for balancing electricity supply and electricity demand, given an increasing share of intermittent renewables in generation. IESD represents both shorter duration storage and seasonal storage options. Quantitative assumptions used to describe storage resources in IESD for this analysis are provided in Appendix E.
Hydrogen production	Hydrogen can be produced via electrolysis, either as a dispatchable electricity storage technology or for use in other sectors, such as transportation. The capacity of intermittent renewables has expanded rapidly on many systems in recent years. At times when generation is relatively high and demand is relatively low, a surplus of power may result. At times of surplus power, hydrogen production from electrolysis becomes economically attractive. IESD simulates the

	potential for this type of hydrogen production, accounting for the intermittency of renewables and the impact of this intermittency on the production cost.
Dispatchable load	Dispatchable load provides an opportunity to “shift” electricity consumption from periods of peak load or low capacity factors for renewables to periods of lower load or higher renewables. One such example is utility-controlled charging, which refers to utilities scheduling power delivery to a chargeable device. IESD simulates dispatchable load for the following end-uses: electric space heating, electric space cooling, and light and medium/heavy-duty battery-electric transportation. Details on how dispatchable load was modeled for this analysis are forthcoming.

IESD is customizable with respect to how North America is broken up into regions. The version used in this analysis represents all ten Canadian provinces separately[26] and divides the United States into three regions (California, U.S. East, and U.S. West).

The model is calibrated to historical data on installed capacity, generation by fuel type, and trade in the model base year (currently 2015), using sources as described in Appendix A. Simulation outputs are also calibrated to reflect historical trends, based on the most recent year after the base year for which data are available.

4.1. Characterization of electricity load

Data on annual electricity consumption by end-use are received from gTech and then converted into an hourly load curve for each of the modeled regions. For example, if a policy increases electricity demand for space heating, it will affect consumption at specific times of the year when the weather is colder, altering the shape of the load curve.

In order to develop a regional load curve for a given simulation year, annual electricity consumption for each end-use is combined with an approximation of how consumption is distributed throughout the hours of the year for that end-use. To generate the required distributions, we started with hourly load data for all jurisdictions in North America (over 200 utilities) in 2015, the base year of the current model. We then disaggregated the hourly load curves into end-use categories based on annual electricity consumption, hourly temperature, and other assumed load profiles for end-uses such as lighting and hot water.

[26] Hourly modeling of electricity generation in the territories was not conducted as part of this analysis.

4.2. Capacity additions

Part of the solution to minimizing costs in the electricity system is the addition of new electricity generation capacity (i.e., the amount of generation that can be produced by a unit at a given moment). Each type of electricity generation resource is characterized by its cost profile (i.e., capital costs, fixed operating costs, and variable operating costs), heat rate (i.e., energy efficiency), and maximum capacity utilization. Capacity additions in IESD are tracked as the total capacity of a given generation type (e.g., combined-cycle gas turbine vs. wind power) rather than as individual generation units. This framework for electricity generation capacity additions also applies to electricity storage. Quantitative assumptions used to describe generation and storage resources in IESD for this analysis are provided in Appendix E. The model can simulate specific policy decisions that may promote or constrain the use of a given technology (e.g., a performance standard that constrains coal power, or a portfolio standard that requires renewable energy).

IESD has some of the same advantages as gTech when it comes to simulating the process of technological improvement. As with gTech, an explicit representation of stock turnover provides opportunities for the sector to evolve. The same declining capital cost function used in gTech is also available in IESD to represent cost declines as a function of cumulative production.

4.3. Dispatch and capacity utilization

Thermal electricity generation (i.e., fossil fuel or biomass combustion) can be dispatched at any time when it will minimize total system costs subject to any existing policy constraints. However, we assume that cogenerated electricity is not dispatchable and is produced when heat is required by the thermal host. Like thermal generation, electricity storage can be dispatched. However, this dispatch is constrained by the installed storage generation capacity, the amount of energy already stored, and any relevant technical constraints represented in the model. Hydroelectric resources with reservoirs are unique because they can store energy in order to generate electricity in the future, such that revenue from the system is maximized.

Electricity from intermittent resources can be dispatched up to the maximum hourly availability of the resource and is either consumed, exported, or stored. Hourly wind avilability is based on the installed capacity and the hourly capacity utilization. Run-of-river capacity availability varies for each month of the year (lowest in winter and highest in spring) and IESD assumes it is constant during each hour of a given month. Solar capacity availability varies for each month of the year (lowest in winter and highest in summer) but changes each hour according to the movement of the sun through the sky (zero at night, low the morning, and highest at noon).

As with capacity additions, a given type of generation resource is dispatched rather than individual generation units. Therefore, while IESD does have constraints that determine what fraction of unused capacity can provide short-term power reserves, it does not represent the specific constraints and costs associated with starting or ramping individual units as a function of their current electricity output or how long they have been offline. For example, in the real world, dispatching a spinning unit is faster and less costly than dispatching a “warm” unit that has been offline for several hours. In turn, the “warm” unit is less costly and faster to dispatch than a “cold” unit that has been offline for days.

4.4. Implications of not modeling individual generation units

This approach to modeling the electricity sector has limitations, which generally favour thermal generation. These limitations relate to the inability of IESD to represent individual power plants or generation units within a power plant. Specifically, IESD does not represent:

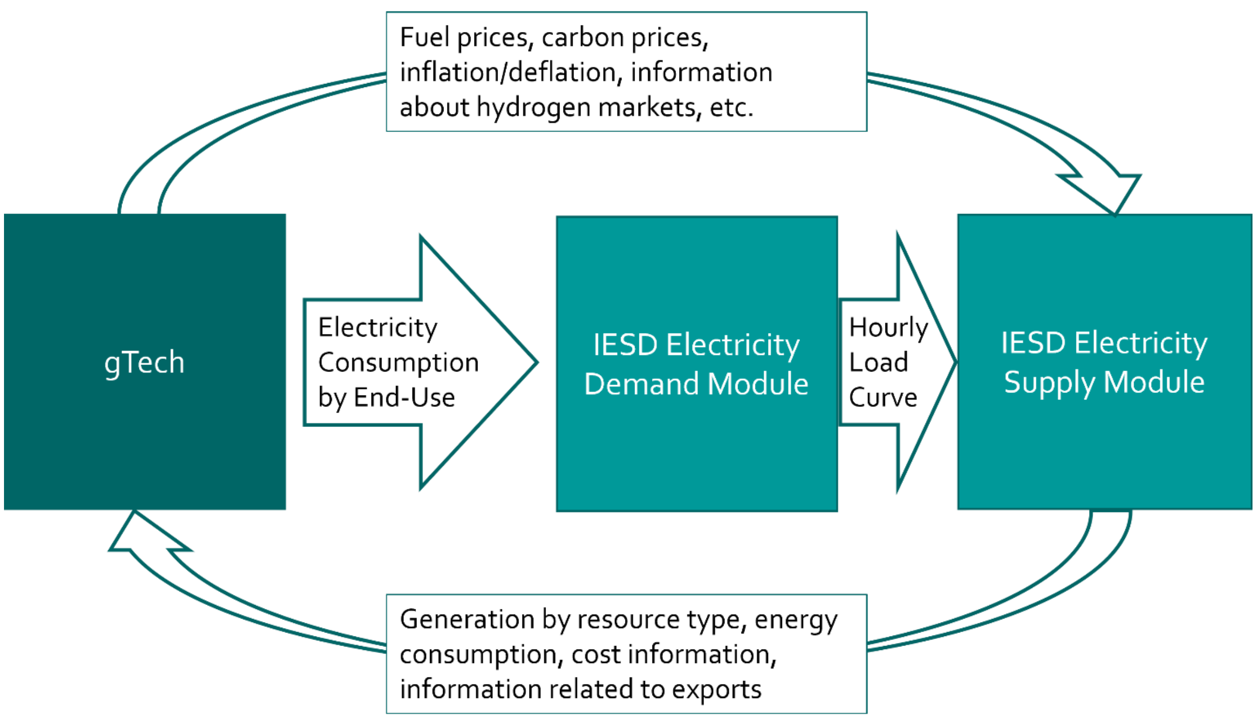
- **Ramping costs** that would increase the cost of providing reserves with technologies that use steam turbines (e.g., coal, biomass, but also including combined heat and power). To a lesser extent, these would also increase the cost of supplying reserves with gas turbines and reciprocating engines.
- **Ramping limitations** that apply to both thermal and hydroelectric generators are not included in IESD.
- **Start-up costs** that would increase the cost of providing power from a unit of generation capacity that has not been used in the previous hour. As with ramping costs, this is most noticeable for technologies that use steam turbines but would also affect the levelized cost of electricity from gas turbines and reciprocating engines.

- **Start-up constraints** that would limit the availability of generation units that have been off-line for a significant amount of time (e.g., several days). These units would require a “cold start” and would not be able to provide power as quickly as assumed.
- **Reductions in energy efficiency from part-load operation**, which would increase the cost of using this strategy (i.e., running a unit at less than 90-100% of its nameplate capacity) to preserve some available capacity for supplying reserves.

5. Integration of gTech and IESD

The full integration of gTech and IESD allows for information to be passed back and forth between the models. In the integrated model, gTech completes a simulation for a given year, then passes key information to IESD. IESD then completes its simulation for the same year and passes key information back to gTech. This process is referred to as an iteration. The linked models continue to iterate until convergence is achieved and then advance to the next simulation year. In this section, we describe the integration methodology in more detail. Section 5.1 describes the information passed from gTech to IESD, Section 5.2 describes the information passed from IESD to gTech, and Section 5.3 explains the convergence procedure. Finally, Section 5.4 covers how declining capital costs are linked across the two models so that they are consistent in an integrated run. Figure 2 provides a visual representation of the integrated system.

Figure 2: The integrated gTech-IESD energy-economy-electricity modeling system



5.1. Information gTech passes to IESD

- **Electricity consumption by end-use.** gTech generates an estimate for electricity consumption by end-use. This electricity consumption is used to generate hourly electricity profiles which are ultimately used in IESD (this process was discussed previously in Section 2).
- **Fuel prices and carbon prices.** gTech estimates the price for fuels that are used by the electricity sector. For example, the price for natural gas paid in the electricity sector is endogenously calculated by gTech, and this price is then passed into IESD. Carbon prices provided to IESD include prices that are set explicitly and prices that are simulated in gTech as the result of other GHG policies (e.g., a cap and trade system).
- **Capital cost inflation or deflation.** Information on overall capital cost inflation or deflation is taken into account by the electricity supply simulation in IESD. Capital cost inflation could, for example, be the result of increased labour costs in gTech leading to increased construction costs, while deflation could be the result of corporate income tax cuts.
- **Costs and prices related to captured CO_2.** The cost of CO_2 pipeline transport, the cost of CO_2 storage, and the price of CO_2 for use in Enhanced Oil Recovery (EOR) are provided by region and influence how much carbon capture and storage occurs in IESD.
- **Renewable natural gas (RNG) availability.** The maximum amount of RNG available for use in electricity generation acts as a resource constraint in IESD. Please note that the price for RNG is also passed into IESD from gTech.
- **Hydrogen consumption.** IESD can endogenously simulate electrolysis-based hydrogen production. To do this, it requires a load curve for hydrogen. The shape of the hydrogen consumption load curve influences the amount of hydrogen storage that must be built in IESD to accompany hydrogen production from electrolysis. The amount of storage required, in turn, influences the cost of hydrogen production. We currently assume that the shape of the hydrogen consumption load curve is the same as the shape of the electricity consumption load curve. Estimating a load curve specific to hydrogen is an area for future work.
- **Hydrogen produced using electrolysis.** This information establishes a lower bound on hydrogen production in IESD. The model must supply this quantity of hydrogen,

regardless of the cost. Total demand for hydrogen (regardless of the production method) is also estimated by gTech and establishes an upper bound on hydrogen production in IESD. The model supplies up to this quantity of hydrogen from electrolysis, as long as the cost is less than the price of hydrogen.

5.2. Information IESD passes to gTech

Once the simulation in IESD is complete, information is compiled and passed back to gTech. Information from IESD is used to build an aggregated electricity sector within gTech that comprises all the dynamics included in IESD. These include:

- **Electricity generation by resource type.**
- **Energy consumed by electricity generation.**
- **Total capital cost and fixed operating cost of generating electricity.** This information includes the cost for storage technology and hydrogen production.
- **Any dispatchable hydrogen produced by IESD.**
- **Origin and destination of exported electricity.**

Other information is used to adjust end-use electricity prices in gTech.

- **Cost of any transmission system upgrades required.** Transmission system costs are calculated based on peak load and an average cost per unit of capacity.
- **Cost of any distribution system upgrades required.** Distribution system costs are calculated by sector (industry, residential, and commercial) based on peak load and an average cost per unit of capacity. If growth in peak load outpaces growth in annual electricity consumption, the distribution system cost per unit of electricity consumed could increase significantly. This has been raised as a potential concern for scenarios involving the rapid electrification of residential buildings (with heat pumps and other electric heating appliances) and personal transportation (with electric vehicles). However, under electrification scenarios, it is expected that total electricity consumption will increase as well, mitigating the impact on per unit distribution system costs.

5.3. Convergence

In each simulation year, after passing information to and receiving information from IESD, the gTech model then runs again, and the entire process is repeated until convergence is achieved. In every iteration, the dollar values of all physical inputs to and outputs from electricity generation across all regions (including the United States) are summed together. The total is compared across iterations, and once the difference falls below a threshold value, the model is considered to have achieved convergence for that simulation year and moves on to the next.

5.4. Declining capital costs

When the declining capital cost function applies to a technology or technology component that appears in both gTech and IESD, the function considers cumulative production across the two models. The sharing of information around declining capital costs ensures that, as experience with the technology increases over time, the capital cost declines consistently in both models. This dynamic is important for the batteries used in both electric vehicles (gTech) and for storage by the electricity sector (IESD), the electrolysis technology used by both industry (gTech) and the electricity sector (IESD) to produce hydrogen, and other technologies such as fuel cells and carbon capture and storage.

6. Policy scenarios

6.1. Legislated policy

This scenario includes federal (Table 4) and provincial (Table 5) policies legislated in Canada as of January 2023. Note that we don't include provincial policies in the list below if there is an equally or more stringent federal policy. At the federal level, the Clean Fuel Regulations are now considered to be current policy, as are changes to the Federal Fuel Charge and the Output-Based Pricing System (carbon price scheduled to rise to $170/tCO_2e in 2030, previously $50 in 2022). Many additional policies have been announced, including policies that are part of Canada's 2030 Emissions Reduction Plan; however, there is significant uncertainty regarding the coverage, design, stringency, and timelines for policies that are not yet legislated. Therefore, we do not include these policies in the legislated policy scenario.

Table 4: Federal policies included in the legislated policy scenario

Policy	Description
Federal Fuel Charge[27]	Backstop policy that applies a tax on fossil fuels in provinces that don't have an equally stringent carbon pricing system. The federal fuel charge reached $50/tCO2e in 2022 and will be annually increased by $15/tCO2e starting in 2023 until it reaches $170/tCO2e in 2030, after which it is scheduled to remain constant in nominal terms. Large industrial emitters are excluded from the fuel charge.

[27] Government of Canada. (2022). The Federal Carbon Pollution Pricing Benchmark. Available from: https://www.canada.ca/en/environment-climate-change/services/climate-change/pricing-pollution-how-it-will-work/carbon-pollution-pricing-federal-benchmark-information.html

Output-Based Pricing System (OBPS)[28]	Tradable emissions performance standard that applies to large industrial emitters. The OBPS puts a price on industrial emissions if a facility's emissions intensity exceeds the sectoral benchmark. Like the Federal Fuel Charge, the OBPS carbon price applies in provinces that don't have an equally stringent OBPS system and will be annually increased by $15/tCO2e until it reaches $170/tCO2e in 2030. The sectoral OBPS benchmarks will be annually increased in stringency by 2 percentage points starting in 2023.
Clean Fuel Regulations (CFR)[29]	Require liquid fossil fuel suppliers to reduce the lifecycle greenhouse gas intensity of their fuels. The Canada Gazette Part II requires a carbon intensity reduction of 3.5 g CO2e/MJ in 2023, increasing to 14 g CO2e/MJ in 2030. The regulations create a credit-based compliance market which allows regulated liquid fuel suppliers and voluntary credit generators to trade compliance credits. At the end of each compliance period, regulated suppliers must present sufficient credits to comply with the reduction requirement. Credits can be produced by reducing upstream emissions associated with liquid fossil fuel production, blending low carbon fuels such as ethanol into the liquid stream, or end-use fuel switching in transport.
Energy efficiency regulations[30]	Federal standards exist for space conditioning equipment, water heaters, household appliances, and lighting products. Major standards include a minimum annual fuel utilization efficiency of 90% for natural gas furnaces, a minimum energy factor of 0.61 for gas water heaters and ban of incandescent light bulbs.

[28] Environment and Climate Change Canada. (2021). Review of the OBPS Regulations: Consultation Paper. Available from: https://www.canada.ca/en/environment-climate-change/services/climate-change/pricing-pollution-how-it-will-work/output-based-pricing-system/2022-review-consultation.html

[29] Government of Canada. (2022). Clean Fuel Regulations: SOR/2022-140. Canada Gazette, Part II, Volume 156, Number 14. Available from: https://www.gazette.gc.ca/rp-pr/p2/2022/2022-07-06/html/sor-dors140-eng.html.

[30] Natural Resources Canada. (n.d.). Canada's Energy Efficiency Act and Energy Efficiency Regulations. Available from: www.nrcan.gc.ca/energy/regulations-codes-standards/6861

Green Freight Assessment Program[31]	Four-year funding program launched in 2018 with a budget of $3.4 million available for medium and heavy-duty fleet performance reviews, implementing operational best practices, installing fuel saving technologies, and purchasing alternative fuel vehicles.
Hydrofluorocarbon Controls[32]	The Canadian government was one of the signatories of the 2016 Montreal Protocol-amending Kigali Agreement on ozone-depleting substances. Canada has pledged to reduce its HFC-related GHG emissions by 15% by 2036 relative to 2011/2013 levels by revising the Regulations Amending the Ozone-depleting Substances and Halocarbon Alternatives Regulations.
Light-Duty ZEV Subsidy[33]	Light-duty vehicle subsidy available at $2,500 for short-range plug-in hybrids and $5,000 for long-range plug-in hybrids, hydrogen vehicles, and battery electric vehicles.
Regulations Amending the Heavy-duty Vehicle and Engine Greenhouse Gas Emission Regulations[34]	The federal government has amended the Heavy-Duty Vehicle Emissions Standard to increase the vehicle emission stringency for vehicles manufactured in model years 2018 to 2027.

31 Government of Canada. (2020). Green Freight Assessment Program. Available from: https://www.nrcan.gc.ca/energy-efficiency/energy-efficiency-transportation/greening-freight-programs/green-freight-assessment-program/20893.

32 Government of Canada. (2018). Canada agrees to control hydrofluorocarbons under the Montreal Protocol. www.canada.ca/en/environment-climate-change/services/sustainable-development/strategic-environmental-assessment/public-statements/canada-agree-control-hydrofluorocarbons.html

33 Government of Canada. (n.d.) Zero-emission vehicles. Available from: https://tc.canada.ca/en/road-transportation/innovative-technologies/zero-emission-vehicles

34 Government of Canada. (2018). Regulations Amending the Heavy-duty Vehicle and Engine Greenhouse Gas Emission Regulations and Other Regulations Made Under the Canadian Environmental Protection Act, 1999: SOR/2018-98. http://gazette.gc.ca/rp-pr/p2/2018/2018-05-30/html/sor-dors98-eng.html

Regulations Amending the Passenger Automobile and Light Truck Greenhouse Gas Emission Regulations[35]	New passenger vehicles and light-commercial vehicles/light trucks sold in Canada must meet fleet-wide GHG emission standards between 2012 and 2016, and between 2017 and 2025. Fleet targets for passenger cars are aligned with U.S. regulation.
Regulations Amending the Reduction of Carbon Dioxide Emissions from Coal-fired Generation of Electricity Regulations[36]	This policy closes coal-fired power plants by 2030 unless they emit less than 420 tonnes CO_2e/GWh.
Regulations Limiting Carbon Dioxide Emissions from Natural Gas-fired Generation of Electricity[37]	This policy limits the emissions intensity of natural gas-fired electricity generation to 420 tonnes CO_2e/GWh.
Regulations Respecting Reduction in the Release of Methane and Certain Volatile Organic Compounds[38]	Oil and gas facilities must adopt methane control technologies and practices that lead to a 45% reduction in methane emissions relative to 2012 levels by 2025.
Zero Emission Vehicle Tax Write-Off[39]	Businesses that purchase light-, medium-, or heavy-duty ZEV vehicles (including plug-in hybrids with a battery capacity of at least 7kWh, fully electric vehicles, and hydrogen vehicles) are eligible for a 100% tax write-off. Vehicles that qualify for the federal Incentive for Zero-Emission Vehicles Program are ineligible for the tax write-off.

[35] Government of Canada. (2018). Regulations Amending the Passenger Automobile and Light Truck Greenhouse Gas Emission Regulations. http://www.gazette.gc.ca/rp-pr/p2/2014/2014-10-08/html/sor-dors207-eng.html

[36] Government of Canada. (2018). Regulations Amending the Reduction of Carbon Dioxide Emissions from Coal-fired Generation of Electricity Regulations: SOR/2018-263. Available from: https://laws-lois.justice.gc.ca/eng/regulations/SOR-2012-167/page-2.html#h-4

[37] Government of Canada. (2018). Regulations Limiting Carbon Dioxide Emissions from Natural Gas-fired Generation of Electricity: SOR/2018-261. Available from: https://laws-lois.justice.gc.ca/eng/regulations/SOR-2018-261/index.html

[38] Government of Canada. (2020). Regulations Respecting Reduction in the Release of Methane and Certain Volatile Organic Compounds (Upstream Oil and Gas Sector): SOR/2018-66. Available from: https://laws-lois.justice.gc.ca/eng/regulations/SOR-2018-66/index.htm

[39] Government of Canada. (2020). Zero Emission Vehicles. Tax Write-Off. Available from: https://tc.canada.ca/en/road-transportation/innovative-technologies/zero-emission-vehicles

Zero Emission Vehicle Infrastructure Program[40]	Federal funding available (total budget of $130 million over five years from 2019 to 2024) to partially pay for various types of charging and re-fueling stations, including medium- and heavy-duty vehicle charging and re-fueling stations.

Table 5: Provincial policies included in the legislated policy scenario

Province	Policy	Description
Alberta	Capping oil sands emissions[41]	Limits emissions from the oil sands to 100 Mt CO_2e annually.
British Columbia	Low carbon Energy Act[42]	A minimum of 93% of provincial electricity generation must be provided by low carbon or renewable sources.
British Columbia	Light-Duty ZEV subsidies[43]	Provides incentives at $1,500 for short-range plug-in hybrids and $3,000 for long-range plug-in hybrids, battery electric vehicles, and hydrogen vehicles. It is unclear how long the incentives will be available; the province has extended funding multiple times since the policy's introduction.
British Columbia	Low Carbon Fuel Requirement Regulation (part of the Low Carbon Fuel Standard)[44]	British Columbia introduced this policy in 2008. The regulation requires a decrease in average carbon intensity of transportation fuels by 10% by 2020 and by 30% by 2030 relative to 2010.

[40] Government of Canada. (2020). Zero Emission Vehicle Infrastructure Program. Available from: https://www.nrcan.gc.ca/energy-efficiency/energy-efficiency-transportation/zero-emission-vehicle-infrastructure-program/21876

[41] Government of Alberta (2020). Capping oil sands emissions. Available from: https://www.alberta.ca/climate-oilsands-emissions.aspx#:~:text=Alberta%20will%20transition%20to%20an,to%20oil%20sands%20GHG%20emissions.&text=A%20legislated%20emissions%20limit%20on,cogeneration%20and%20new%20upgrading%20capacity

[42] Government of British Columbia. (2010). Clean Energy Act. Available from: http://www.bclaws.ca/civix/document/id/lc/statreg/10022_01

[43] Government of British Columbia. (2020). Go Electric Passenger Vehicle Rebates. Available from: https://www2.gov.bc.ca/gov/content/industry/electricity-alternative-energy/transportation-energies/clean-transportation-policies-programs/clean-energy-vehicle-program/passenger-vehicles

[44] Government of British Columbia. (2020). Greenhouse Gas Reduction (Renewable and Low Carbon Fuel Requirements) Act, SBC 2008, c. 16. Available from: https://www.bclaws.ca/civix/document/id/complete/statreg/08016_01

Province	Policy	Description
		Fuel suppliers can meet the second requirement by acquiring credits generated from fueling electric vehicles.
British Columbia	PST Exemption[45]	Use of electricity in residential and industrial buildings is exempt from provincial sales tax.
British Columbia	Specialty Use Vehicle Incentive[46]	Rebates of up to $50,000 for plug-in hybrid, electric, and hydrogen on-road medium- and heavy-duty freight vehicles.
British Columbia	Zero Emission Vehicle Standard[47]	Requires a minimum share of light-duty vehicles sold in BC to be zero-emission. This policy mandates 10% electric vehicle sales by 2025, 30% by 2030 and 100% by 2040.
Manitoba	Biofuels Mandate Amendment[48]	Renewable fuel content requirement set at 10% for gasoline and 5% for diesel by volume.
Manitoba	Coal phase-out[49]	Manitoba Hydro phased out its last coal-fired generating unit in 2018.
Manitoba	Efficient Trucking Program (ETP)[50]	Provincial and federal joint fund of $11.8 million for heavy-duty vehicle efficiency retrofits. Applications closed April 2020.
Manitoba	Keeyask Hydro-electricity Project[51]	695-megawatt (MW) hydro generating station with assumed completion in 2021.

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[45] Government of British Columbia. (2017). Provincial Sales Tax (PST). Tax Rate. Available from: https://www2.gov.bc.ca/gov/content/taxes/sales-taxes/pst

[46] Plug In BC. (n.d.). Specialty Use Vehicle Incentive. Available from: http://pluginbc.ca/suvi/

[47] Government of British Columbia. (2019). Zero-Emission Vehicle Act. SBC 2019, Chapter 29. Available from: https://www.bclaws.ca/civix/document/id/complete/statreg/19029

[48] Government of Manitoba. (2020). Biofuels Mandate and Renewable Fuels in Manitoba. Available from: https://reg.gov.mb.ca/detail/3340256

[49] Manitoba Hydro. (n.d.). Generation Stations. Available from: https://www.hydro.mb.ca/corporate/facilities/generating_stations/

[50] Red River College. (2020). Vehicle Technology & Energy Centre. Efficient Trucking Program. Driving sustainability forward in Manitoba. Available from: https://www.rrc.ca/vtec/efficient-trucking-program/

[51] Manitoba Hydro. (n.d.). Keeyask Generating Station. Available from: https://www.hydro.mb.ca/projects/keeyask/

Province	Policy	Description
New Brunswick	Renewable Portfolio Standard[52]	The renewable portfolio standard requires NB Power to ensure that 40% of in-province electricity sales are from renewable energy by 2020. Imports of renewable energy from other jurisdictions qualify for compliance, as do energy efficiency improvements.
Newfoundland and Labrador	Muskrat Falls Hydro Project[53]	A hydro project with a capacity of 824 MW.
Nova Scotia	Cap-and-Trade Program[54]	Annual caps on certain activities in Nova Scotia, including fuel suppliers, electricity importers and large final emitters.
Nova Scotia	Cap on GHG emissions from electricity generation[55]	This policy requires emissions from the electricity sector to decline to 4.5 Mt by 2030.
Nova Scotia	Renewable Portfolio Standard[56]	This renewable portfolio standard requires that 25% of electricity consumption be provided from renewable resources in 2015, increasing to 40% by 2020.
Nova Scotia	Maritime Link[57]	This transmission line connects Nova Scotia to hydroelectric generation from Newfoundland and Labrador.

52 Government of New Brunswick. (2015). New Brunswick Regulation 2015-60 under the Electricity Act (O.C. 2016-263). Available from: www.gnb.ca/0062/acts/BBR-2015/2015-60.pdf

53 Naclor Energy. (2019). Muskrat Falls Project: Project Overview. https://muskratfalls.nalcorenergy.com/project-overview/

54 Government of Nova Scotia. (n.d.). Nova Scotia's Cap-and-Trade Program. Available from: https://climatechange.novascotia.ca/nova-scotias-cap-trade-program.

55 Government of Nova Scotia. (2013). Greenhouse Gas Emissions Regulations made under subsection 28(6) and Section 112 of the Environment Act. Available from: www.novascotia.ca/JUST/REGULATIONS/regs/envgreenhouse.htm

56 Government of Nova Scotia. (2020). Renewable Electricity Regulations made under Section 5 of the Electricity Act. Available from: https://novascotia.ca/just/regulations/regs/elecrenew.htm

57 Emera Newfoundland & Labrador. (2014). Maritime Link. Available from: http://www.emeranl.com/en/home/themaritimelink/overview.aspx

Province	Policy	Description
Ontario	Coal Phase-out[58]	Ontario phased out its last coal-fired generating unit in 2014. In 2019, about 94% of Ontario's electricity generation was emissions free.
Ontario	Greener Diesel Regulation[59]	Specifies a minimum renewable fuel content of 4% for diesel, by volume. Renewable diesel life cycle GHG emissions are required to be at least 70% lower than standard petroleum diesel.
Ontario	Greener Gasoline Regulation[60]	Specifies a minimum renewable fuel content of 10% for gasoline, by volume. Renewable gasoline must have an average of 45% less life cycle GHG emissions than standard petroleum gasoline.
Ontario	Nuclear Power Plant Refurbishment[61]	Ontario will refurbish 10 nuclear power plants which together will provide more than 9,800 MW emissions-free capacity.
Ontario	Steel Plant Upgrades[62,63]	Two major steel companies in Ontario, ArcelorMittal and Algoma, announced that they will upgrade their steel plants, which will result in GHG reductions of about 3 Mt in each plant. This is simulated as a switch to less carbon intensive forms of steel production, such as direct reduced iron steel production, and achieves a 6 Mt reduction in GHG emissions in 2030 relative to 2020.

[58] Government of Ontario. (2020). The End of Coal. Available from: https://www.ontario.ca/page/end-coal#:~:text=Ontario%20enshrined%20its%20commitment%20in,to%20generate%20electricity%20in%20Ontario

[59] Government of Ontario. (2020). Greener Diesel. Available from: https://www.ontario.ca/page/greener-diesel-regulation

[60] Government of Ontario. (2020). Greener Gasoline. Available from: https://www.ontario.ca/page/greener-gasoline

[61] Government of Ontario. (2018). Chapter 2. Ensuring a Flexible Energy System. Available from: https://www.ontario.ca/document/ontarios-long-term-energy-plan-2017-order-council-21202017/chapter-2-ensuring-flexible-energy-system#section-8

[62] https://www.globenewswire.com/news-release/2021/11/11/2332532/0/en/Algoma-Steel-Announces-Final-Investment-Decision-for-Electric-Arc-Steelmaking.html

[63] https://corporate.arcelormittal.com/media/press-releases/arcelormittal-and-the-government-of-canada-announce-investment-of-cad-1-765-billion-in-decarbonization-technologies-in-canada

Province	Policy	Description
Québec	Biofuels mandate[64]	In 2019, Québec released a draft regulation that would require a minimum blend of 10% renewable fuel in gasoline and 2% in diesel by volume starting in 2021 and rising to 15% for gasoline and 4% for diesel by 2025.
Québec	Cap and Trade System for Greenhouse Gas Emissions Allowances[65]	Cap and trade for industrial and electricity sectors as well as fossil fuel distributors. Revenue raised by the policy is invested in low carbon technologies.
Québec	Electric Vehicle Incentives[66]	Provides incentives between $4,000 and $8,000 for the purchase of a zero-emission vehicle.
Québec	Renewable Natural Gas Regulation[67]	This regulation requires a minimum renewable fuel content of 1% in distributed natural gas in Québec as of 2020, rising to 2% in 2023, and 5% in 2025. A recently developed amendment will increase the minimum renewable fuel content to 7% in 2028 and 10% in 2030.

64 Gouvernement du Québec. (2019). Projet de règlement. Volume minimal de carburant renouvelable dans l'essence et le carburant diesel. Available from: https://cdn-contenu.quebec.ca/cdn-contenu/adm/min/energie-ressources-naturelles/publications-adm/lois-reglements/allegement/PR_Volume_minimal_carburant_renouvelable_MERN.pdf?1570737693.

65 Gouvernement du Québec. (2020). The Carbon Market, a Green Economy Growth Tool! Available from: http://www.environnement.gouv.qc.ca/changementsclimatiques/marche-carbone_en.asp.

66 Gouvernement du Québec. (2019). Discover electric vehicles. Available from: http://vehiculeselectriques.gouv.qc.ca/english/

67 Gouvernement du Québec. (2019). Québec encadre la quantité minimale de gaz naturel renouvelable et met en place un comité de suivi. Available from https://www.quebec.ca/nouvelles/actualites/details/quebec-encadre-la-quantite-minimale-de-gaz-naturel-renouvelable-et-met-en-place-un-comite-de-suivi#:~:text=Il%20pr%C3%A9cise%20%C3%A9galement%20la%20progression,5%20%25%20%C3%A0%20compter%20de%202025. & Gazette Officielle Du Québec, 22 juin 2022, 154e année, no 25. Règlement modifiant le Règlement sur le prélèvement du Comité paritaire de l'entretien d'édifices publics, région de Montréal. Available from: https://cdn-contenu.quebec.ca/cdn-contenu/environnement/territoire/Documents/AIR_PojetRG_Quantite_gaz_naturel_renouvelable_MERN.pdf?1655990587

Province	Policy	Description
Québec	Zero Emission Vehicle Standard[68]	Automakers that sell over 4,500 vehicles in the province are required to meet a zero-emission vehicle credit quota that rises over time between 2018 and 2025. The government's own impact assessment estimates that the policy will result in zero-emission vehicles accounting for 9.9% of new vehicle sales in 2025.
Saskatchewan	Boundary Dam Carbon Capture Project[69]	This project stores and captures CO2 emissions from a 115 MW coal plant.
Saskatchewan	Ethanol Fuel (General) Regulations[70]	Requires a minimum renewable fuel content of 7.5% for gasoline, by volume.
Saskatchewan	Renewable Diesel Act[71]	Specifies a minimum renewable fuel content of 2% for diesel, by volume.

6.2. Net zero policy

Under this scenario, Canada implements climate policy consistent with achieving its 2030 emissions target (a 40-45% reduction from 2005 levels) and net zero emissions by 2050. All the federal and provincial policies from the legislated policy scenario are in place and an economy-wide cap on emissions at the target levels is added. We assume that the United States also implements stringent climate policy consistent with net zero. A set amount of land-use, land-use change and forestry (LULUCF) offsets are assumed to be available Canada-wide: 30 Mt in 2030 and 50-103 Mt in 2050, based

[68] Gouvernement du Québec. (2018). The zero-emission vehicle (ZEV) standard. Available from: http://www.environnement.gouv.qc.ca/changementsclimatiques/vze/index-en.htm

[69] SaskPower. (2019). Boundary Dam Carbon Capture Project. Available from: https://www.saskpower.com/our-power-future/infrastructure-projects/carbon-capture-and-storage/boundary-dam-carbon-capture-project

[70] Government of Saskatchewan. (2020). Ethanol Fuel (General) Regulations (E-11.1 Reg 1). Available from: https://publications.saskatchewan.ca/#/products/1064.

[71] Government of Saskatchewan. (2012). Renewable Diesel Act (R-19.001). Available from: https://publications.saskatchewan.ca/#/products/64461.

on a study by Drever et al. (2021)[72]. See Section 7.2 for more detail on how this LULUCF offset assumption was varied via sensitivity analysis.

[72] Drever, R. et al. (2021). Natural climate solutions for Canada. *Science Advances, 7*(23). https://www.science.org/doi/10.1126/sciadv.abd6034

7. Treatment of uncertainty

7.1. Uncertainty in energy-economy modeling

Forecasting GHG emissions is subject to two main types of uncertainty. First, all models are, by definition, simplified representations of reality. Energy-economy models are made up of mathematical equations that model developers have designed to represent actual processes and forecast energy consumption, GHG emissions, and economic impacts. There can be uncertainty as to whether these equations accurately represent the current reality and whether they will hold into the future. For example, household and firm decisions are influenced by many factors, some of which could change over time, and even the most sophisticated model cannot capture all of these.

Second, the assumptions used to parameterize models are uncertain to varying degrees. This is especially true for assumptions about the future, including, but not limited to, oil prices, technology assumptions, and improvements in labour productivity. If any of the assumptions used in a model prove incorrect, the resulting forecast could be affected.

Despite the inherent limitations of energy-economy models, Navius has safeguards in place to reduce uncertainty in the modeling results we provide. The use of computable general equilibrium models (gTech) and linear programing models (IESD) is well founded in the academic literature. Navius undertakes significant efforts to calibrate and back-cast our models to ensure they capture key dynamics of the energy-economy system and are well parameterized. Assumptions are thoroughly researched and, in many cases, subject to external review. They are also updated based on new information, as part of a process of continued improvement. Remaining uncertainty with respect to key assumptions is addressed through sensitivity analysis, as described in the following section. A sensitivity analysis tests how varying the results of uncertain input values influences the outputs of a model.

7.2. Sensitivity analysis

Results presented in the Canada Energy Dashboard account for uncertainty surrounding technology costs, commodity prices, and offset availability, as summarized in Table 6. The sensitivity tests described in the table correspond to “levers” in the online platform.

High, reference, and low cost assumptions were tested for the cost of solar electricity generation, wind electricity generation, batteries, hydrogen production, hydrogen fuel cells, and carbon capture and storage. The costs of intermittent renewables (solar and wind) and batteries were varied together, as were the costs of hydrogen production (steam methane reformation and electrolysis) and hydrogen fuel cells. More detail about these cost assumptions can be found in Appendix D and E. The hyperlinks in Table 6 lead to the specific appendix table(s) for each type of technology.

Table 6: Uncertainties examined via sensitivity analysis

Uncertain assumption	Settings tested	Further detail
Technology cost uncertainty		
Cost of intermittent renewables (solar and wind generation) and batteries	Reference, low, high	Appendix E Table 23
Cost of hydrogen production (steam methane reformation and electrolysis) and hydrogen fuel cells	Reference, low, high	Hydrogen production: Appendix D Figure 4 Hydrogen fuel cells: Appendix D Figure 6 and Figure 7.
Cost of carbon capture and storage	Reference, low, high	Appendix D Table 12 and Table 13 Electricity generation with carbon capture: Appendix E Table 24
Commodity price uncertainty		
Global oil price forecast	Reference and low	Table 7
Offsets availability uncertainty		
Availability of LULUCF offsets in Canada (2050)	High (103 Mt) and low (50 Mt)	N/A
Availability of direct air capture	Available and unavailable	N/A

Two oil price forecasts were also tested. Table 7 provides the reference and low oil price forecasts exogenously set in gTech. The reference West Texas Intermediate (WTI) oil price forecast is calibrated to the 2021 version of Canada's Energy Future[73,74].

Table 7: WTI oil price forecast assumptions (2020 USD/bbl)

Sensitivity	2025	2030	2035	2040	2045	2050
Low	39.5	37.1	36.2	35.9	35.6	35.1
Reference	68.9	67.8	66.2	65.7	65.1	64.1

Finally, the availability of emissions offsets from direct air capture (DAC) and LULUCF were varied. DAC either becomes commercially available in 2035 or does not become commercially available prior to 2050. The availability of LULUCF offsets in Canada in 2050 was also varied. In all net zero scenarios, 30 Mt of LULUCF offsets are available in 2030 based on Environment and Climate Change Canada estimates in the Emissions Reduction Plan.[75] In the low scenario, this increases to 50 Mt of LULUCF offsets available in 2050, and in the high scenario this increases to 103 Mt available in 2050 based on based on a study by Drever et al. (2021)[76].

We conducted a modeling run for every combination of the sensitivity test settings, under both the legislated policy and the net zero policy scenario, as applicable. This led to a total of 324 modeling scenarios which are presented on the Canada Energy Dashboard.

[73] Canada Energy Regulator. (2021). *Canada's Energy Future 2021.* Available from: https://www.cer-rec.gc.ca/en/data-analysis/canada-energy-future/2021/index.html

[74] To come up with a low oil price forecast, we use the last year the CER released a low oil price forecast (2018) and scale it based on the most recent CER (2021) reference price forecast.

[75] https://publications.gc.ca/collections/collection_2022/eccc/En4-460-2022-eng.pdf

[76] Drever, R. et al. (2021). Natural climate solutions for Canada. *Science Advances, 7*(23). https://www.science.org/doi/10.1126/sciadv.abd6034

Appendix A: Model calibration

To characterize Canada's energy-economy and that of the United States, gTech and IESD are calibrated to a variety of historical data sources. Key calibration data sources for Canada include:

- Environment and Climate Change Canada's National Inventory Report[77]
- Statistics Canada's Supply-Use Tables[78]
- Natural Resources Canada's Comprehensive Energy Use Database[79]
- Statistics Canada's Annual Industrial Consumption of Energy Survey[80]
- Statistics Canada's Report on Energy Supply and Demand[81]
- Navius' technology database
- Canada's Energy Future 2021[82]
- Statistics Canada datasets on the electricity sector[83]

Each data source is generated using different methods; therefore, the sources are not necessarily consistent with one another. For example, expenditures on gasoline by

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[77] Environment and Climate Change Canada. National Inventory Report. Available from: www.canada.ca/en/environment-climate-change/services/climate-change/greenhouse-gas-emissions/inventory.html

[78] Statistics Canada. Supply and Use Tables. Available from: www150.statcan.gc.ca/n1/en/catalogue/15-602-X

[79] Natural Resources Canada. Comprehensive Energy Use Database. Available from: http://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/menus/trends/comprehensive_tables/list.cfm

[80] Statistics Canada. Annual Industrial Consumption of Energy Survey. Available from: www.statcan.gc.ca

[81] Statistics Canada. Report on Energy Supply and Demand in Canada. Available from: https://www150.statcan.gc.ca/n1/en/catalogue/57-003-X

[82] Canada Energy Regulator. (2021). *Canada's Energy Future 2021.* Available from: www.cer-rec.gc.ca/en/data-analysis/canada-energy-future/index.html

[83] Statistics Canada. (n.d.). *Data.* Available from: https://www150.statcan.gc.ca/n1/en/type/data?subject_levels=25%2C2504

households in Statistics Canada's Supply-Use tables may not be consistent with fuel consumption reported by Natural Resources Canada's Comprehensive Energy Use Database. Further, energy expenditures are a function of consumption and prices, so if prices vary over the course of the year, it is difficult to perfectly align consumption and expenditures.

gTech's calibration routine places greater emphasis on some data sources relative to others. This approach means that gTech achieves near perfect alignment with data sources receiving the highest priority weight, but alignment starts to diverge from data sources that receive a lower weight.

For this project, the datasets that received the highest weight are:

- Revised Environment and Climate Change Canada's National Inventory Report
- Natural Resources Canada's Comprehensive Energy Use Database
- Navius' technology database
- Canada's Energy Future 2021

A trade-off exists between: (1) simulating competitiveness dynamics and (2) achieving alignment with external data sources. gTech's calibration routine places a priority on being able to simulate competitiveness dynamics, which may at times sacrifice alignment with external data sources.

Appendix B: Covered sectors, fuels, and end-uses in gTech

Table 8: Covered sectors

Sector name	NAICS code
Soybean farming	11111
Oilseed (except soybean) farming	11112
Wheat farming	11114
Corn farming	11115
Other farming	Rest of 1111
Animal production and aquaculture	112
Forestry and logging	113
Fishing, hunting and trapping	114
Agriculture services	115
Natural gas extraction (conventional)	211113
Natural gas extraction (tight)	
Natural gas extraction (shale)	
Light oil extraction	
Heavy oil extraction	
Oil sands in-situ	211114
Oil sands mining	
Bitumen upgrading (integrated)	
Bitumen upgrading (merchant)	
Coal mining	2121
Metal mining	2122
Non-metallic mineral mining and quarrying	2123
Oil and gas services	213111 to 213118
Mining services	213119
Fossil-fuel electric power generation	221111
Hydro-electric and other renewable electric power generation	221112 and 221119
Nuclear electric power generation	221113
Electric power transmission, control and distribution	22112
Natural gas distribution	222

Sector name	NAICS code
Construction	23
Food manufacturing	311
Beverage and tobacco manufacturing	312
Textile and product mills, clothing manufacturing and leather and allied product manufacturing	313-316
Wood product manufacturing	321
Paper manufacturing	322
Petroleum refining	32411
Coal products manufacturing	Rest of 324
Petrochemical manufacturing	32511
Industrial gas manufacturing	32512
Other basic inorganic chemicals manufacturing	32518
Other basic organic chemicals manufacturing	32519
Biodiesel production from oilseed feedstock	
Ethanol production from grain feedstock	
HDRD (or HRD) production from canola seed feedstock	
Renewable gasoline and diesel production	
Cellulosic ethanol production	
Resin and synthetic rubber manufacturing	3252
Fertilizer manufacturing	32531
Other chemicals manufacturing	Rest of 325
Plastics manufacturing	326
Cement manufacturing	32731
Lime and gypsum manufacturing	3274
Other non-metallic mineral products	Rest of 327
Iron and steel mills and ferro-alloy manufacturing	3311
Electric-arc steel manufacturing	
Steel product manufacturing from purchased steel	3312
Alumina and aluminum production and processing	3313
Other primary metals manufacturing	3314
Foundries	3315
Fabricated metal product manufacturing	332
Machinery manufacturing	333
Computer, electronic product and equipment, appliance and component manufacturing	334 and 335
Transportation equipment manufacturing	336
Other manufacturing	Rest of 31-33

Sector name	NAICS code
Wholesale and retail trade	41-45
Air transportation	481
Rail transportation	482
Water transportation	483
Truck transportation	484
Transit and ground passenger transportation	485
Pipeline transportation of crude oil	4861 and 4869
Pipeline transportation of natural gas	4862
Other transportation, excluding warehousing and storage	4867-492
Landfills	Part of 562
Services	Rest of 51-91
Hydrogen production from methane	n/a
Hydrogen production via electrolysis	n/a
Hydrogen pipeline transportation	n/a
Direct air capture of carbon dioxide	n/a
Carbon dioxide pipeline transportation	n/a
Carbon dioxide storage	n/a
Enhanced oil recovery with carbon dioxide	n/a
Direct reduction steel manufacturing	n/a
Recovery of logging residue	n/a
Recovery of agricultural residue	n/a

Table 9: Covered fuels

Fuel
Fossil fuels
Coal
Coke oven gas
Coke
Natural gas
Natural gas liquids
Gasoline and diesel
Heavy fuel oil
Still gas
Electricity
Electricity
Hydrogen
Steam methane reformation
Steam methane reformation with carbon capture
Electricity
Renewable fuels (non-transportation)
Spent pulping liquor
Wood
Wood waste (in industry)
Renewable natural gas
Renewable fuels (transportation)
Ethanol produced from grains
Cellulosic ethanol
Biodiesel produced from oilseeds
Hydrogenated renewable diesel (HDRD)
Renewable gasoline and diesel from pyrolysis of biomass
Renewable natural gas

Table 10: Covered end-uses

End-use
Stationary industrial energy/emissions sources
Fossil-fuel electricity generation
Process heat for industry
Process heat for cement and lime manufacturing
Heat (in remote areas without access to natural gas)
Cogeneration
Compression for natural gas production and pipelines
Large compression for LNG production
Electric motors (in industry)
Other electricity consumption
Solvent-based extraction
Transportation
Air travel
Buses
Rail transport
Light rail for personal transport
Marine transport
Light-duty vehicles
Trucking freight
Off-road vehicles
Diesel services (for simulating biodiesel and other renewable diesel options)
Gasoline services (for simulating ethanol options)
Oil and gas fugitives
Formation CO2 removal from natural gas processing
Flaring in areas close to natural gas pipelines
Flaring in areas far from natural gas pipelines
Venting of methane (oil and gas sector)
Leaks of methane (oil and gas sector)
Surface casing vent flows
Industrial process
Mineral product GHG emissions
Aluminum electrolysis
Metallurgical coke consumption in steel production
Hydrogen production for petroleum refining and chemicals manufacturing
Hydrogen production for transportation
Hydrogen production for heating

End-use
Non-fuel consumption of energy in chemicals manufacturing
Nitric acid production
Integrated steel production
Agriculture
Process CH4 for which no know abatement option is available (enteric fermentation)
Manure management
Agricultural soils
Waste
Landfill gas management
Residential buildings
Single family detached shells
Single family attached shells
Apartment shells
Heat load
Furnaces
Air conditioning
Lighting
Dishwashers
Clothes washers
Clothes dryers
Ranges
Faucet use of hot water
Refrigerators
Freezers
Hot water
Other appliances
Commercial buildings
Food retail shells
Office building shells
Non-food retail shells
Educational shells
Warehouses (shells)
Other commercial shells
Commercial heat load
Commercial hot water
Commercial lighting

End-use
Commercial air conditioning
Auxiliary equipment
Auxiliary motors (in commercial buildings)
Other
Direct air capture

Appendix C: Defining the low-carbon economy

To categorize the low-carbon economy in gTech, we assign economic activity into one of three categories:

- **Low-carbon energy** (i.e., as defined below).
- **Rest of energy** (i.e., most activities related to fossil energy supply and use, other than those considered low carbon such as emissions control efforts).
- **Non-energy** (e.g., insurance services, education).

This report builds on previous work by Navius that defines the clean energy economy as:

> *"The technologies, services and resources that increase renewable energy supply, enhance energy productivity, improve the infrastructure and systems that transmit, store and use energy while reducing carbon pollution."*

Naturally, this definition could be applied in different ways. For example, what is the baseline level of carbon intensity that distinguishes clean from not clean? This study generally applied definitions with reference to net zero; in other words, is a technology or fuel likely to be consistent with net zero in Canada?

Table 11 lists the specific low-carbon energy sectors that are considered under this definition for the purposes of this project. Each sector includes jobs spread out across multiple activities related to the low-carbon technologies or fuel in questions. Jobs are attributed to one of three categories:

- **Direct.** This category includes employment of (1) sectors producing low-carbon energy services (e.g., renewable electricity) and (2) value-added associated with the use of low-carbon technologies in other sectors (e.g., a plug-in electric vehicle may be used to provide transport services).
- **Indirect.** This category includes indirect jobs related to the low-carbon technology or fuel, such as construction (e.g., building an automotive manufacturing plant),

manufacturing (e.g., assembling an electric vehicle) and services (e.g., selling an electric vehicle).

gTech is well suited to the task of forecasting the development of (most) low-carbon energy sectors because it combines the following features:

- A realistic representation of how households and firms select technologies and processes that affect their energy consumption and greenhouse gas emissions.
- An exhaustive accounting of the economy and jobs, including how provinces interact with each other and the rest of the world.
- A detailed representation of liquid fuel (crude oil and biofuel) and gaseous fuel (natural gas and renewable natural gas) supply chains.
- Incorporation of the most substantive energy and climate mitigation policies in Canada.
- Representation of how mitigation policies can change labour and capital markets, household income and household consumption of goods and services.

Table 11: Low-carbon energy taxonomy

Sector category	Low-carbon energy sector
Energy supply	
Low-carbon energy	Renewable electricity
	Conventional nuclear
	Small modular reactors
	Bioenergy
	Waste to energy
	Hydrogen
	Carbon capture
	Emission detection and control
Supply infrastructure	Electricity transmission & distribution
	Hydrogen pipelines & storage
Energy demand	
Buildings	Efficient building envelopes
	Efficient HVAC and building controls systems
	Efficient appliances & lighting
Transport	Plug-in electric vehicles
	Hydrogen fuel cell electric vehicles
	Low-carbon transit
Industry	Low-carbon machinery
	Low-carbon steel
	Emission detection and control
	Carbon capture and storage
	Hydrogen consumption
	Direct air capture

Appendix D: gTech technology assumptions

Carbon capture and storage

Carbon capture and storage (CCS) technologies are parameterized in gTech based on studies from the Global CCS Institute[84] and the International Energy Agency[85]. Table 12 below presents current costs of CCS (first of a kind), and Table 13 presents future minimum costs (nth of a kind). All costs are presented as levelized incremental costs for carbon capture for each technology using a 15% discount rate, 30-year life, electricity price of $27.13/GJ, coal price of $2.20/GJ, and natural gas price of $2.64/GJ. Additionally, we assume emissions of 0.05 tCO_2e/GJ of natural gas combusted and 0.09 tCO_2e/GJ of coal combusted for the purpose of the tables below. Costs are presented per tCO_2 captured for three different sensitivities. Energy prices are determined by the model and will change depending on the scenario.

Table 12: Current (first of a kind) levelized cost of CCS (2020 CAD/tCO_2 captured)

CCS application	Reference cost	Low cost	High cost
Cement heat (coal with CCS)	151.1	103.2	172.4
Cement heat (natural gas with CCS)	221.3	128.1	262.6
Industrial heat (coal with CCS)	141.5	96.6	161.4
Industrial heat (natural gas with CCS)	221.3	128.2	262.6
Low-temperature industrial heat (coal with CCS)	141.5	96.2	161.4
Low-temperature industrial heat (natural gas with CCS)	221.3	128.1	262.6
SMR hydrogen production (with CCS)	100.5	65.6	135.5
Formation CO_2 (with CCS)	48.9	36.4	61.3

84 Global CCS Institute. (2021). *Technology Readiness and Costs of CCS.* Available from: https://www.globalccsinstitute.com/wp-content/uploads/2022/03/CCE-CCS-Technology-Readiness-and-Costs-22-1.pdf

85 International Energy Agency. (2021). *Is carbon capture too expensive?* Available from: https://www.iea.org/commentaries/is-carbon-capture-too-expensive

Table 13: Future minimum (n^{th} of a kind) levelized cost of CCS (2020 CAD/tCO_2 captured)

CCS application	Reference cost	Low cost	High cost
Cement heat (coal with CCS)	87.4	59.6	99.6
Cement heat (natural gas with CCS)	107.2	62.1	127.2
Industrial heat (coal with CCS)	75.3	51.4	85.9
Industrial heat (natural gas with CCS)	126.8	73.4	150.5
Low-temperature industrial heat (coal with CCS)	75.3	51.4	85.9
Low-temperature industrial heat (natural gas with CCS)	126.8	73.4	150.5
SMR hydrogen production (with CCS)	96.5	63.0	130.0
Formation CO_2 (with CCS)	27.1	20.2	34.1

Direct air capture

Figure 3 below provides the levelized cost of direct air capture (DAC). DAC techno-economic parameters are based on Fasihi (2019)[86], Larsen et al. (2019)[87] and Keith et al. (2018)[88]. The reference case sensitivity is based on an average of the literature reviewed. Costs were harmonized using a 15% discount rate, 30-year life, $27.13/GJ electricity price, and $2.64/GJ natural gas price[89]. Energy prices are determined by the model and will change depending on the scenario.

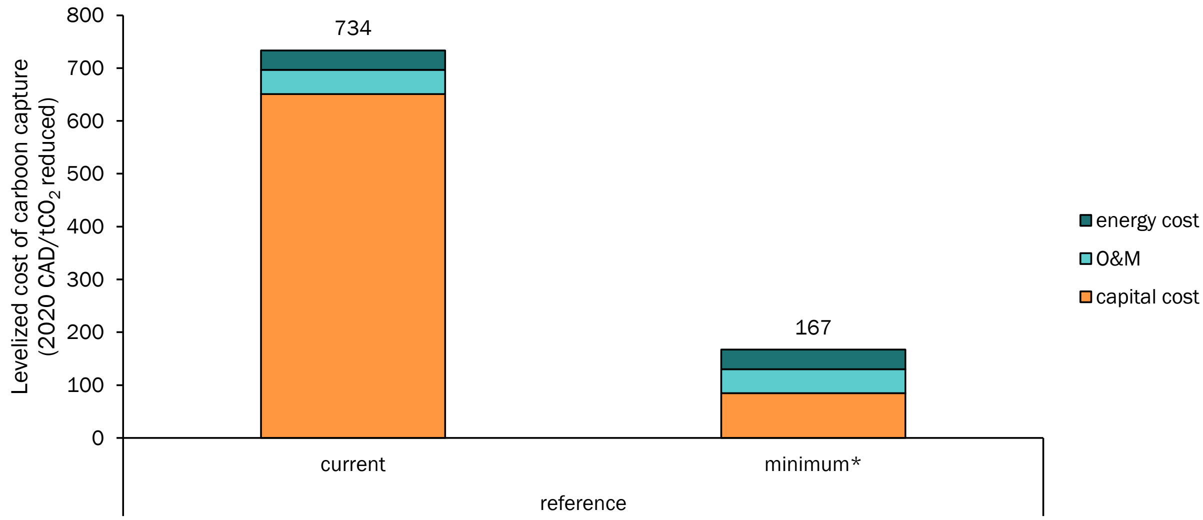
[86] Fasihi et al. (2019). Techno-economic assessment of CO2 direct air capture plants. Journal of Cleaner Production, 224, 957-980.

[87] Larsen et al. (2019). Capturing Leadership, Policies for the US to Advance Direct Air Capture Technology. Rhodium Group.

[88] Keith et al. (2018). A process for Capturing CO2 from the Atmosphere. Joule, 2, 1-22.

[89] 2020 CAD.

Figure 3: Current and future minimum levelized cost of carbon capture from DAC



*Future minimum costs are based on 1557 Mt CO_2 of capture.

Hydrogen production

Two production technologies are available for low-carbon hydrogen - electrolysis and steam methane reforming with carbon capture and storage (SMR with CCS). The electrolysis technology parameters are based on IEA's "The Future of Hydrogen" report[90] and NREL's H2A Hydrogen Analysis Production Models[91]. The SMR with CCS technology parameters are based on IEA's "The Future of Hydrogen" report, NREL's H2A Hydrogen Analysis Production Models, and the GCCSI "Global Costs of Carbon Capture and Storage: 2017 Update" report[92].

Figure 4 below provides the levelized cost of electrolysis hydrogen production in gTech under reference, low, and high-cost assumptions. Hydrogen can also be produced using natural gas via steam methane reformation in gTech. The cost assumptions are coming!

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90 IEA. (2019). *The Future of Hydrogen*. Available from: https://www.iea.org/reports/the-future-of-hydrogen

91 NREL. (2019). *H2A: Hydrogen Analysis Production Models*

92 GCCSI. (2017). *Global Costs of Carbon Capture and Storage: 2017 Update.*

Figure 4: Levelized cost of electrolysis hydrogen production

Technology	Current capital cost	Future minimum capital cost		
		Reference	Low cost	High cost
Power costs for charging seasonal hydrogen storage (2015 CAD/kW)	1,969	573	515	630
Fixed operating cost (2015 CAD/kW)	16.5	Same as current		
Variable operating cost (2015 CAD/MWh)	0.3	Same as current		
Fuel (GJ of electricity per GJ of H2 production)	1.45			

Figure 5: Levelized cost of steam-methane reformation hydrogen production

Bioenergy

We estimate anaerobic digestion plant costs using information from Hallbar (2017)[93] and IEA ETSAP (2013)[94]. The Hallbar (2017) cost estimates are used for the total cost of the plant, while the IEA ETSAP (2013) medium-sized plant is used to obtain the breakdown of capital, operating and electricity costs. This ratio is applied to the Hallbar (2017) cost estimate to identify the cost breakdown. We use a discount rate of 10% and a technology life span of 20 years to provide levelized costs in Table 14.

Landfill gas derived RNG is estimated based on the EPA Landfill Methane Outreach Program in the EIA LFGcostWeb tool (v3.4).[95] The tool provides a breakdown of capital, operating and energy costs. We calculate the cost using the weighted average of landfills smaller than 1,149 ft^3/min as Canadian landfills are significantly smaller than

93 Hallbar RNG Cost Curve Estimates (Final).xlsx, supporting data for Hallbar Consulting. (2017). Resource Supply Potential for Renewable Natural Gas in B.C., provided to us by the Government of British Columbia in April 2018.

94 IEA ETSAP. (2013). Biogas and Bio-syngas Production. Available from: https://iea-etsap.org/E-TechDS/PDF/P11_BiogasProd_ML_Dec2013_GSOK.pdf

95 EPA. (n.d.). Landfill Methane Outreach Program. Available from: https://www.epa.gov/lmop/download-lfgcost-web

U.S. landfills. We use a discount rate of 10% and a technology life span of 20 years to provide levelized costs in Table 14.

Table 14: Levelized costs of first generation RNG ($2020/GJ)

Parameter	Anaerobic digestion derived RNG	Landfill gas derived RNG
Capital cost	12.1	10.0
Operation and management	6.0	2.6
Electricity cost	1.2	1.6
Total	19.3	14.2

We assume that 328 PJ/year of agricltural ligno-cellulosic residue (18.2 million ODt/year) and 238 PJ/year of forest harvest residue (15.7 million ODt/year) are available in 2015 [96,97,98,99]. The model estimates the available ligno-cellulosic feedstock in future years as a function of agricultural and forestry activity.

The cost of these feedstocks is a function of the capital, labour, and other inputs (e.g., fuel, fertilizer for nutrient replacement) required to produce them (Table 15). The costs are given as the baseline inputs per "oven dry tonne" (Odt) but these costs can increase if the cost of the inputs increases. Furthermore, the price of the feedstocks may be well above the cost if demand is larger than the available supply.

[96] Agriculture and Agri-Food Canada. (2017*). Biomass Agriculture Inventory Median Values*. Available from: www.open.canada.ca

[97] Statistics Canada, CANSIM 001-0017

[98] Yemshanov et al. (2014). Cost estimates of post harvest forest biomass supply for Canada*, Biomass and Bioenergy, 69, 80-94*

[99] Government of Canada, National Forestry Database, accessed May 28, 2018

Table 15: Baseline biomass feedstock costs, 2020 CAD/ODt

Parameter	Agricultural Residue	Forest Harvest Residue
Capital cost	15.2	15.2
Labour cost	15.7	35.1
Other input cost	30.5	36.6
Total	61.4	86.8

The levelized cost of second generation RNG from wood/crop residue in the model is consistent with values found in the literature when holding constant factors such as feedstock and energy prices.[100,101,102,103] While we account for the difference in cost of agricultural and forestry residue feedstock, we do not capture the difference in cost of processing the two. Because of this limitation, we use a production cost that is at the high end of literature values. For the levelized cost, we use a capital discount rate of 10% and a life span of 30 years to provide levelized costs in Table 16.

Table 16: Levelized cost of second-generation RNG ($2020/GJ)

Parameter	Ligno-cellulose derived RNG
Capital cost	19.5

[100] Hallbar Consulting (2017). Resource Supply Potential for Renewable Natural Gas in B.C.

[101] Carbo, M., Smit, R., Drift, B.v.d, Jansen, D. (2011) Bio Energy with CCS (BECCS): Large potential for BioSNG at low CO2 avoidance cost. Energy Procedia, 4, 2011, pp 2950-2954.

[102] Müller-Langer, F. (2011) Analyse und Bewertung ausgewählter zukünftiger Biokraftstoffoptionen auf der Basis fester Biomasse. Thesis, 2011, Technische Universität Hamburg-Harburg, Hamburg.

[103] The Energy Research Centre of the Netherlands (ECN) (2014). The Economy of Large-Scale Biomass to Substitute Natural Gas (bioSNG) plants.

Operation and management	1.3
Electricity cost	0.3[104]
Feedstock cost	5.1
Total	26.2

Second generation biofuels can also be used to produce renewable gasoline and diesel. The cost of renewable gasoline and diesel production is presented in Table 17.[105,106,107,108]

Table 17: Levelized cost of renewable gasoline and diesel from biomass ($2020/L)

Parameter	Renewable gasoline and diesel
Capital cost	1.29
Operation and management	0.26
Natural gas cost	0.04
Electricity cost	0.08

104 Based on an illustrative electricity price of $23/GJ

105 Jones S. et al. (2013). Process Design and Economics for the Conversion of Lignocellulosic Biomass to Hydrocarbon Fuels

106 Dutta A. et al. (2015). Process Design and Economics for the Conversion of Lignocellulosic Biomass to Hydrocarbon Fue

107 Tan E. et al. (2018). High-Octane Gasoline from Lignocellulosic Biomass via Syngas and Methanol/Dimethyl Ether Intermediates: 2018 State of Technology and Future Research; Analysis Production Case Studies

108 Swanson R. et al. (2010). Techno-Economic Analysis of Biofuels Production Based on Gasification

Feedstock cost	0.21
Total	1.89

Zero emission vehicles

Figure 6 below shows the current and assumed future minimum cost of battery electric vehicles. Cost is a function of electrification market share, with lower costs corresponding to greater infrastructure deployment and sharing. Figure 7 shows the current and assumed future minimum cost of fuel cell electric vehicles. All electric vehicles have intangible costs to represent market barriers in addition to financial costs. Intangible costs and capital cost decline as a function of adoption of the technology across Canada and the U.S.

Figure 6: Current and future cost of light-duty vehicles

Archetype	1st of a kind capital cost (2015 CAD per vehicle)	Nth of a kind capital cost (2015 CAD per vehicle)			Fixed operating cost (2015 CAD per vehicle)	Output (vehicle km per year)	Fuel (GJ per vkt)
		Low	Reference	High			
gasoline	21,302				860	14,614	2.40
gasoline efficient	22,540				860	14,614	1.77
hybrid	25,765	23,212	22,873	24,058	656	14,614	1.31
plug-in hybrid	40,040	27,252	26,545	28,925	656	14,614	0.90
battery electric	57,429	23,746	22,335	26,969	452	14,614	0.62
fuel cell	85,544	33,330	26,869	51,010	542	14,614	1.41

Figure 7: Current and future cost of heavy-duty vehicles

Archetype	1st of a kind capital cost (2015 CAD per vehicle)	Nth of a kind capital cost (2015 CAD per vehicle)			Fixed operating cost (2015 CAD per vehicle)	Output (vehicle km per year)	Fuel (GJ per vkt)
		Low	Reference	High			
diesel new	164,242				12,307	597,420	1.48
diesel efficient	168,461				13,538	597,420	1.38
lng	220,164	249,131	236,233	277,721	15,568	597,420	1.48
battery electric	777,368	187,931	169,881	235,987	6,153	597,420	0.56
fuel cell	332,072	249,131	236,233	277,721	13,538	597,420	1.04

Sources for ZEV parameterization:

- Bloomberg. (2020). Electric Vehicle Outlook.
- NREL. (2019). Market segmentation analysis of medium and heavy-duty trucks with a fuel cell emphasis.
- ICCT. (2017). Transitioning to zero-emission heavy-duty freight vehicles.
- ATRI. (2018). An analysis of operational costs of trucking: 2018 Update
- Earl et al. (2018). Analysis of long-haul battery electric trucks in EU.
- ICCT. (2019). Estimating the infrastructure needs and costs for the launch of zero-emission trucks.
- Fries et al. (2017). An Overview of Costs for Vehicle Components, Fuels, Greenhouse Gas Emissions and Total Cost of Ownership Update 2017.
- SA Consultants. (2017). Mass Production Cost Estimation of Direct H2 PEM Fuel Cell Systems for Transportation Applications: 2016 Update.
- Fueleconomy.gov. (2019). Compare Fuel Cell Vehicles.

- SA Consultants. (2019). 2019 DOE Hydrogen and Fuel Cells Program Review Presentation.

Heat pumps

Table 18 and Table 19 present capital costs and energy efficiencies for heat pumps used for space heating in the residential sector. Costs are based on a 2016 report from the EIA[109] and were updated based on feedback from NRCan. Costs include equipment and labour, and average equipment life is assumed to be between 20 and 25 years.

The costs shown in Table 18 apply to building retrofits (i.e., replacing heating equipment in an existing building) and include costs such as those associated with electric panel upgrades ($3,000). Costs in Table 19 apply to heating equipment choices in new builds.

Table 18: Heat pump archetypes for the residential sector (retrofit cost)

Archetype	Capital cost (2020 CAD)	Energy Efficiency (GJ_{out}/GJ_{in})	Cost difference to standard gas furnace
Ground source heat pump	31,500	320%	26,500
Cold climate air-source heat pump	14,500	230%	9,500

Table 19: Heat pump archetypes for the residential sector (new construction cost)

Archetype	Capital cost (2020 CAD)	Energy Efficiency (GJ_{out}/GJ_{in})	Cost difference to standard gas furnace
Ground source heat pump	28,500	320%	23,500
Cold climate air-source heat pump	11,500	230%	6,500

[109] EIA (U.S. Energy Information Administration). (2016). Updated Buildings Sector Appliance and Equipment Costs and Efficiencies. Available from: https://www.eia.gov/analysis/studies/buildings/equipcosts/archive/2016/pdf/full.pdf

Appendix E: IESD technology assumptions

Electricity generation technologies

Table 20: Utility generation cost and efficiency assumptions

Technology	Capital cost	Fixed operating cost	Variable operating cost	Heat rate
	2015 CAD/ kW	2015 CAD/ kW	2015 CAD/ MWh	GJ/ MWh
Existing coal	200	87	9.4	see notes
New coal	3,621	87	9.4	8.9
Existing nuclear	2,000	172	3.3	11.0
New nuclear	8,762	172	3.3	11.0
Existing natural gas	200	87	9.4	see notes
Combined cycle gas turbine	1,223	33	2.4	7.7
Single cycle gas turbine	1,086	25	5.9	10.3
Existing diesel	200	25	5.9	see notes
New diesel	940	25	5.9	11.4
Existing fuel oil	200	87	9.4	see notes
Coal with 90% capture	6,525	147	17.7	11.4
Combined cycle gas turbine with 90% capture	3,097	79	7.1	8.7
Solar PV	1,570	27	0.0	
Onshore wind	1,721	51	0.0	
Offshore wind	4,060	126	0.0	
Existing run-of-river hydro	500	15	0.0	
New run-of-river hydro	5,091	89	0.0	

Table 21: Renewable generation capacity factors[110]

Province	Solar PV	Onshore wind	Run-of-river hydro
British Columbia	15%	20% - 44%	34%
Alberta	16%	32% - 39%	19%
Saskatchewan	15%	35% - 39%	52%
Manitoba	15%	36% - 40%	75%
Ontario	15%	29% - 41%	44%
Quebec	14%	23% - 47%	53%
New Brunswick	14%	31% - 45%	40%
Prince Edward Island	14%	34% - 42%	40%
Nova Scotia	14%	17% - 45%	30%
Newfoundland Labrador	14%	36% - 50%	68%

Batteries and seasonal storage

Table 22: Electricity storage cost assumptions

Type of cost	Lithium ion (1-hour battery)	Seasonal hydrogen storage
Power costs for charging		
Capital cost (2015 CAD/kW)	294	1,969
Fixed operating cost (2015 CAD/kW)	4.5	16.5
Variable operating cost (2015 CAD/MWh)	0.3	0.3
Power costs for discharging		
Capital cost (2015 CAD/kW)		1,658
Fixed operating cost (2015 CAD/kW)		17.0
Variable operating cost (2015 CAD/MWh)	0.3	0.3
Storage cost		

[110] The improvement in capacity factors over time are shown below.

Capital cost (2015 CAD/kWh)	435	4
Roundtrip efficiency (%)	85%	35%

Technology learning

Table 23: Future minimum capital cost: Solar, wind, and storage

Technology	Current capital cost	Future minimum capital cost		
		Reference	Low cost	High cost
Generation costs (2015 CAD/kW)				
Solar PV	1,570	730	550	888
Onshore wind	1,721	900	622	1,066
Offshore wind	4,060	2,124	1,467	2,515
Storage costs				
Power costs for lithium ion (2015 CAD/kW)	294	181	162	228
Storage costs for lithium ion (2015 CAD/kWh)	435	138	114	190
Power costs for charging seasonal hydrogen storage (2015 CAD/kW)	1,969	573	515	630
Power costs for discharging seasonal hydrogen storage (2015 CAD/kW)	1,658	501	286	856

Table 24: Future minimum capital cost: Electricity generation with carbon capture (2015 CAD/kW)

Technology	Current capital cost	Future minimum capital cost		
		Reference	Low cost	High cost
Coal with 90% capture	6,525	5,462	4,422	5,923
Combined cycle gas turbine with 90% capture	3,097	2,411	1,740	2,709

Table 25: Maximum capacity factor adjustment (2020 = 1)

Technology	Reference	Low	High
Solar PV	1.29	1.13	1.46
Onshore wind	1	1	1
Offshore wind	1	1	1
Coal with 90% capture	1	1	1
Combined cycle gas turbine with 90% capture	1	1	1

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