# The Future of Building Heat and the Natural Gas Network in a Net Zero Canada

## Technical Report – NATEM

**For Canadian Climate Institute, Canada**

ESMIA
Energy Super Modelers
and International Analysts

# About ESMIA

ESMIA offers a solid expertise in 3E (energy-economy-environment) integrated system modelling for strategic decision making at city, regional, national and global scales. We specialize in economy-wide energy system optimization models. We have participated in the development of turnkey large-scale energy system models using a large variety of platforms. Many high-profile public and private organizations worldwide have called upon our expertise, in both developed and developing countries. Additionally, we offer advisory services using our proprietary models that focus on analyzing complex and long-term problems such as energy security, electrification, energy transitions, and climate change mitigation.

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SECTION 1

# 1. Introduction & objective

## 1.1. Introduction

The Canadian Climate Institute ("the Institute") retained ESMIA Consultants ("ESMIA") to assess pathways for future building heat in Canada that are consistent with an economy-wide net zero GHG (greenhouse gas) emissions by 2050. ESMIA's analysis covered different roles for heating and cooling technologies, fuel and energy types, energy efficiency and deep retrofit measures. This technical report documents the analytical approach and assumptions for the analysis. Results of the analysis are provided in *Heat Exchange: How today's policies will drive or delay Canada's transition to clean, reliable heat for buildings*.

ESMIA uses an economy-wide optimization energy system model (NATEM—North American TIMES Energy Model), to derive minimum cost solutions for meeting designated GHG reduction targets. NATEM includes a highly detailed database of technologies that represent options for investments by businesses and homes over the next three decades. NATEM is the main engine for developing the technology pathways that:

- meet the net-zero emissions goals of Canada,
- represent regional differences in energy systems and economies,
- use realistic and detailed assumptions of current and future technologies,
- follow an energy systems logic for matching energy demand and supply, and
- are the least cost over the entire economy and timeframe.

This report describes the pathways (Section 1) and key modelling assumptions (Section 2) employed in this analysis.

## 1.2. Main scenario

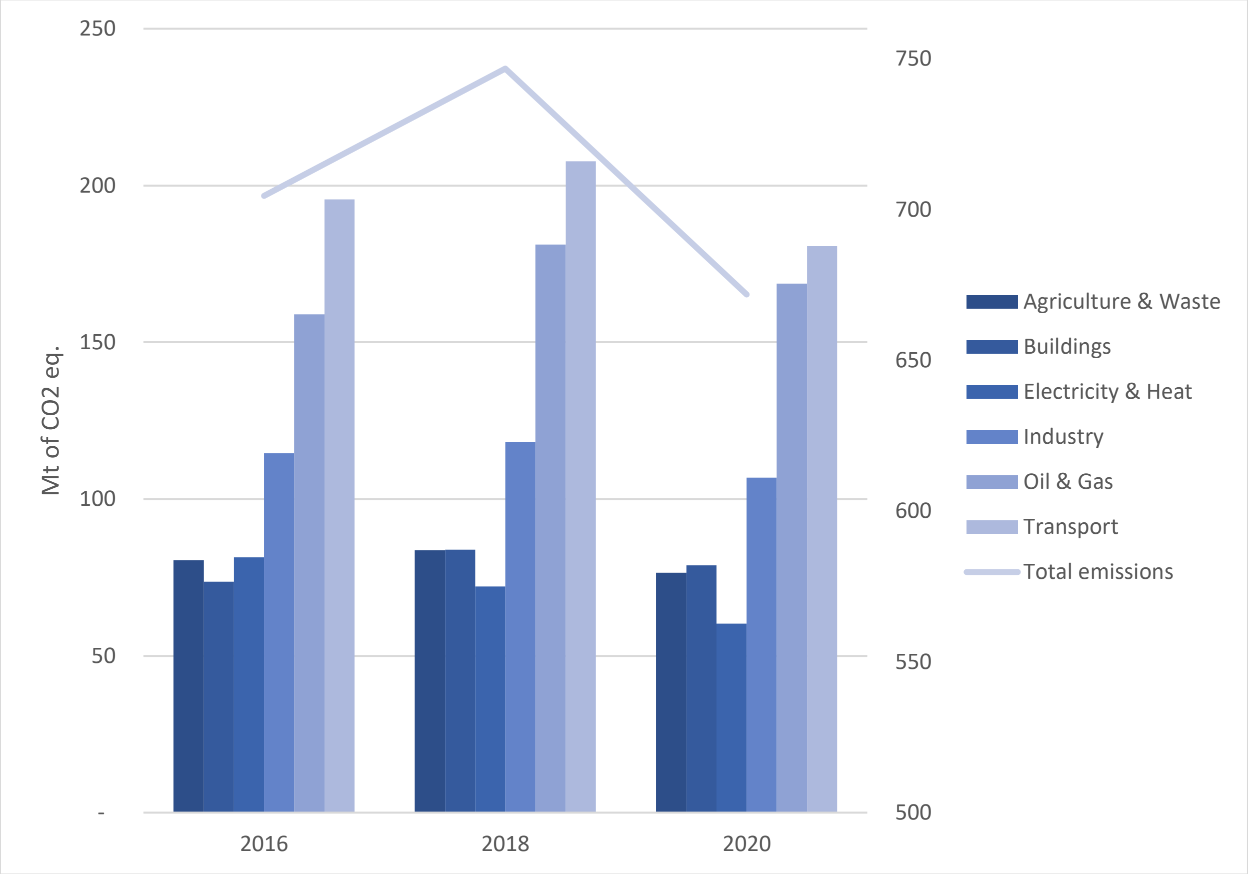
### 1.2.1. High-level overview of NATEM

NATEM provides optimal solutions by identifying the set of technology options that meet energy service demands in all sectors at the least system cost, under a given set of techno-economic assumptions as well as resource and policy constraints. The energy system covers all steps to produce, generate, and transport energy commodities, whether imported or produced in Canada. The set of assumptions and constraints is referred to as a *scenario*.

NATEM optimization is driven by end-use demands. The end-use sectors are agriculture, buildings, industry, and transport. A comprehensive figure including the disaggregated demands for each sector is shown in section 2.1.1 (see Figure 4 for further details). Each of these end-use demands requires energy services. For instance, in the residential buildings, these energy services are space heating, space cooling, water heating, lighting, clothes drying, and so on. An extensive list of technologies is described in NATEM, and the technology mix is optimized based on technology costs, energy costs, policies, and other binding constraints.

Emissions related to each fuel and sector are calibrated with historical ECCC's National Inventory Report (ECCC, 2023) and are used for policy modelling. Figure 1 shows NATEM's calibrated historical emissions by sector for 2016, 2018 and 2020.

Figure 1: Canada's total GHG emissions by sector



### 1.2.2. Scenario design

In this study, the analysis is structured around one core scenario: reaching net-zero emissions in 2050 at the optimal least cost.

The "Optimal NZ50" scenario aligns with Canada's ambitious emissions targets. Here, the model is directed towards achieving specific emissions levels—440 Mt in 2030 and a remaining 10 Mt in 2050. The GHG trajectory is shown in Figure 2. The optimization process seeks the most cost-effective combination of mitigation technologies within each sector to achieve and sustain the net-zero trajectory. The economy-wide nature of the constraint ensures that no single sector or province is compelled to reach net-zero in isolation. Instead, the optimization process considers the collective effort required across sectors and provinces, fostering a holistic approach to emission reduction. By probing the least-cost pathways and optimal combinations of technologies, the study aims to unravel the dynamic interplay between technological advancements, economic viability, and regional considerations in achieving a net-zero future for Canada.

Figure 2: GHG trajectory for NZ50 scenario

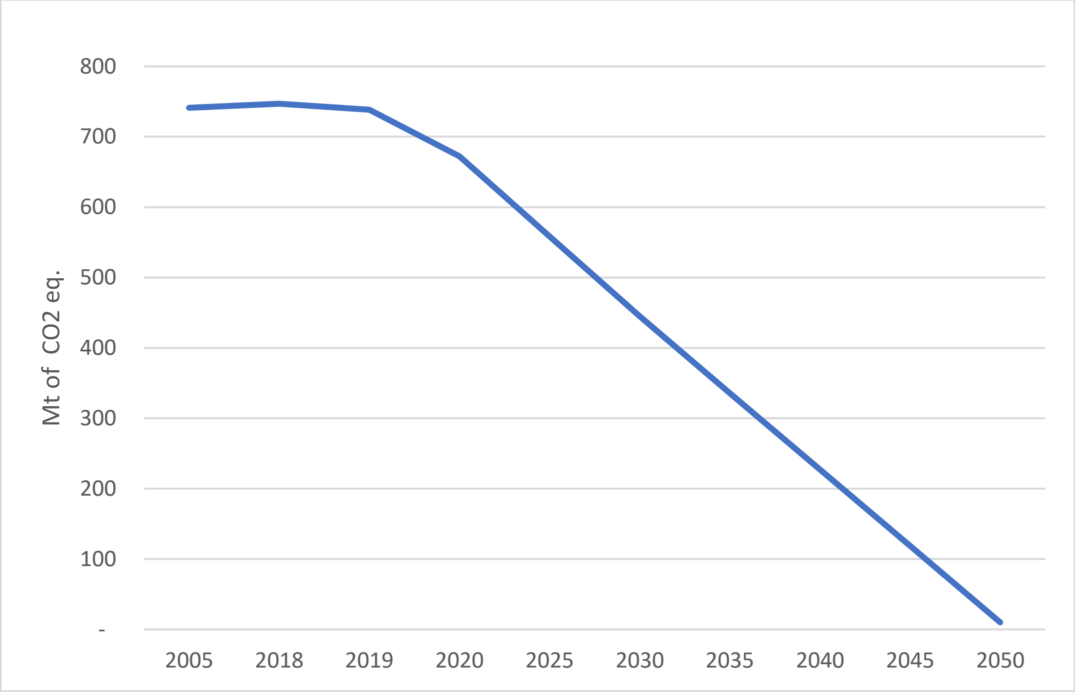


Table 1 summarizes the main scenarios.

## 1.3. Sensitivities

Beyond the exploration of the "Optimal NZ50" scenario, the study incorporates a comprehensive suite of sensitivity analyses. These analyses involve the systematic alteration of specific parameters to gauge their impact on the overall solution, providing nuanced insights into the robustness the optimal solution. Given the nature of the optimization, which is centred on lowest cost, the sensitivities place particular emphasis on variations of long-term evolution of costs. This approach recognizes the critical role of cost dynamics as a key parameter influencing the feasibility and effectiveness of decarbonization strategies within the buildings sector.

The following parameters were selected for the sensitivity analysis:

- Costs and efficiencies of heat pumps
- Retrofit levels and peak shaving measures
- Costs of clean technologies for electricity generation
- Costs of supply hydrogen technologies
- Costs of end-use hydrogen technologies
- Quantity of biomass available and costs of RNG (renewable natural gas) production technologies
- Hydrogen blend ratio in natural gas

Table 1 shows an overview of the parameters that were changed in the sensitivity analyses.

## Table 1 Sensitivity analyses description

| # | Description | Parameters | Numerical inputs |
|---|---|---|---|
| 1 | Heat pumps evolution from now until 2050 | Heat pump investment cost evolution<br>Heat pump efficiency evolution | **Heat Pump Costs**: Decrease to 85% of 2020 costs in 2030 then to 65% in 2050.<br>**Heat Pump Efficiency**: Gradual *increase* of current efficiency to reach a maximum of 130% by 2050. |
| 2 | Lower peak from the buildings sector | Deep retrofit penetration<br>Geothermal heat pump market share | **Deep retrofits**: All modelled retrofits measures are maximized to their full potential by 2050. |
| 3 | Higher peak from the buildings sector | Heat pump efficiency conservative assumptions<br>Limited retrofit penetration | **Heat pump efficiency**: *Decrease* in current modelled efficiency by 30%, no improvements over time.<br>**Retrofit**: Only allow 20% of the maximum potential for retrofit. |
| 4a | Lower clean electricity technology costs | Clean electricity technology investment costs | **Costs**: All costs for renewables and natural gas with CCS are aligned with NREL ATB 2022 (National Renewable Energy Laboratory, 2022) **optimistic** scenario. SMR costs are aligned with CER 2023 net-zero analysis (CER, 2023). |
| 4b | High clean electricity technology costs | Clean electricity technology investment costs | **Costs**: All costs for renewables and natural gas with CCS are aligned with NREL ATB 2022 (National Renewable Energy Laboratory, 2022) **conservative** scenario. SMR costs are kept constant, modelling no decrease of investment over time. |
| 5a | Lower cost of H2 supply and transmission | Hydrogen supply and transmission investments costs | **Costs**: 30% cost reduction for green hydrogen technologies (biomass and electricity), 8% for Autothermal reforming with CCS and 6% for other technologies. |
| 5b | Lower cost of H2 end-use technologies | Hydrogen appliances investments costs | **Costs**: 10% decrease in 2022 going to 50% decrease in 2050 for space heating, water heating and cooking appliances. |
| 6 | Biomass availability & RNG production costs | Maximum biomass feedstock quantities<br>RNG production technologies investment costs | **All biomass feedstocks**: 200% increase of each type of biomass feedstocks.<br>**Costs**: 30% reduced costs for RNG production technologies by 2050. |
| 7 | Increase of hydrogen blending in natural gas | Energy ratio of hydrogen blend in natural gas | **Hydrogen ratio**: Increase hydrogen blending rate with natural gas from 5% of energy content to 20% of energy content. Emissions are recalculated accordingly. |

SECTION 2

# 2. The North American TIMES Energy Model (NATEM)

This project uses the Canadian module of the North American TIMES Energy Model (NATEM). NATEM-Canada describes the entire integrated energy system, as well as non-energy emitting sectors of the 13 Canadian jurisdictions, and provides a rigorous analytical basis for identifying least-cost solutions to achieve energy and climate objectives. More information on NATEM is provided in Annex A.1.

NATEM's core strengths are its:

1. rigorous representation of the entire integrated energy system,
2. detailed database of technologies (including existing and emerging technologies that are important for meeting net-zero emissions), and
3. robust identification of lowest-cost solutions over multiple regions and years.

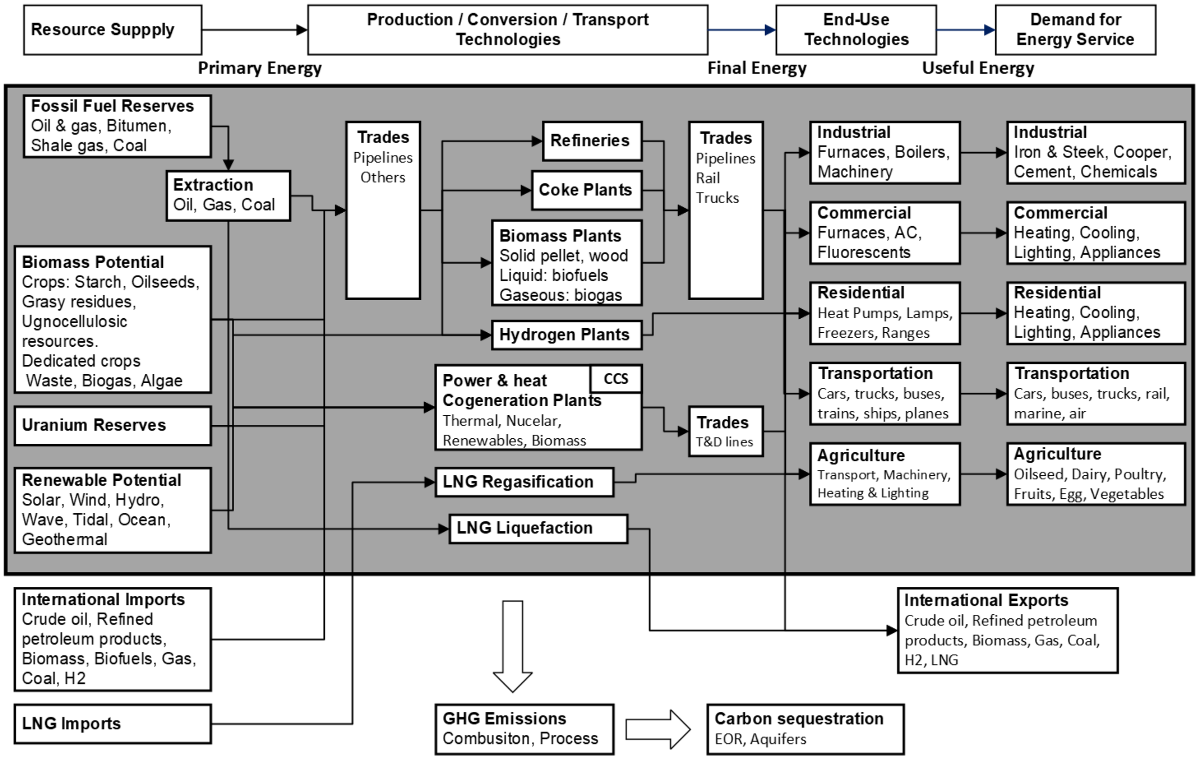
NATEM follows a techno-economic modelling approach of defining all the goods and services required by an economy and the choices for producing these goods and services. The basic unit of production is a technology that consumes energy and produces an intermediate or final end-use. A final good or service generally requires the combination of end-uses, provided by technologies. The energy system describes all the connections between resources, technologies, and end-uses to final goods and services.

The main result of a NATEM run is the quantity by type of technologies that were used to provide the final goods and services. Each technology is defined by its costs, energy consumption, and GHG emissions. Knowing the type, quantity, and operation of technologies allows NATEM to then calculate the total costs, energy u,se and GHG emissions.

## 2.1. Rigorous representation of the entire integrated energy system

NATEM represents the energy system from resource supply (extraction or imports) through conversion and production to final goods and services for domestic use and exports, including the transportation needed at any step. Figure 3 is a simplified representation of NATEM. The optimization is driven by end-use demands. Energy production will be optimized as a function of these demands, with constraints on resources available and a set of policies.

**Figure 3: Simplified illustration of the energy systems modelled in NATEM**



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### 2.1.1. Energy value chain

**Primary energy resources** are reflected from the best available Canadian data, including conventional and unconventional fossil fuels reserves (oil, gas, and coal), renewable potential (hydro, geothermal, wind, solar, tidal, and wave), uranium reserves and biomass (various solid, liquid, and gaseous sources).

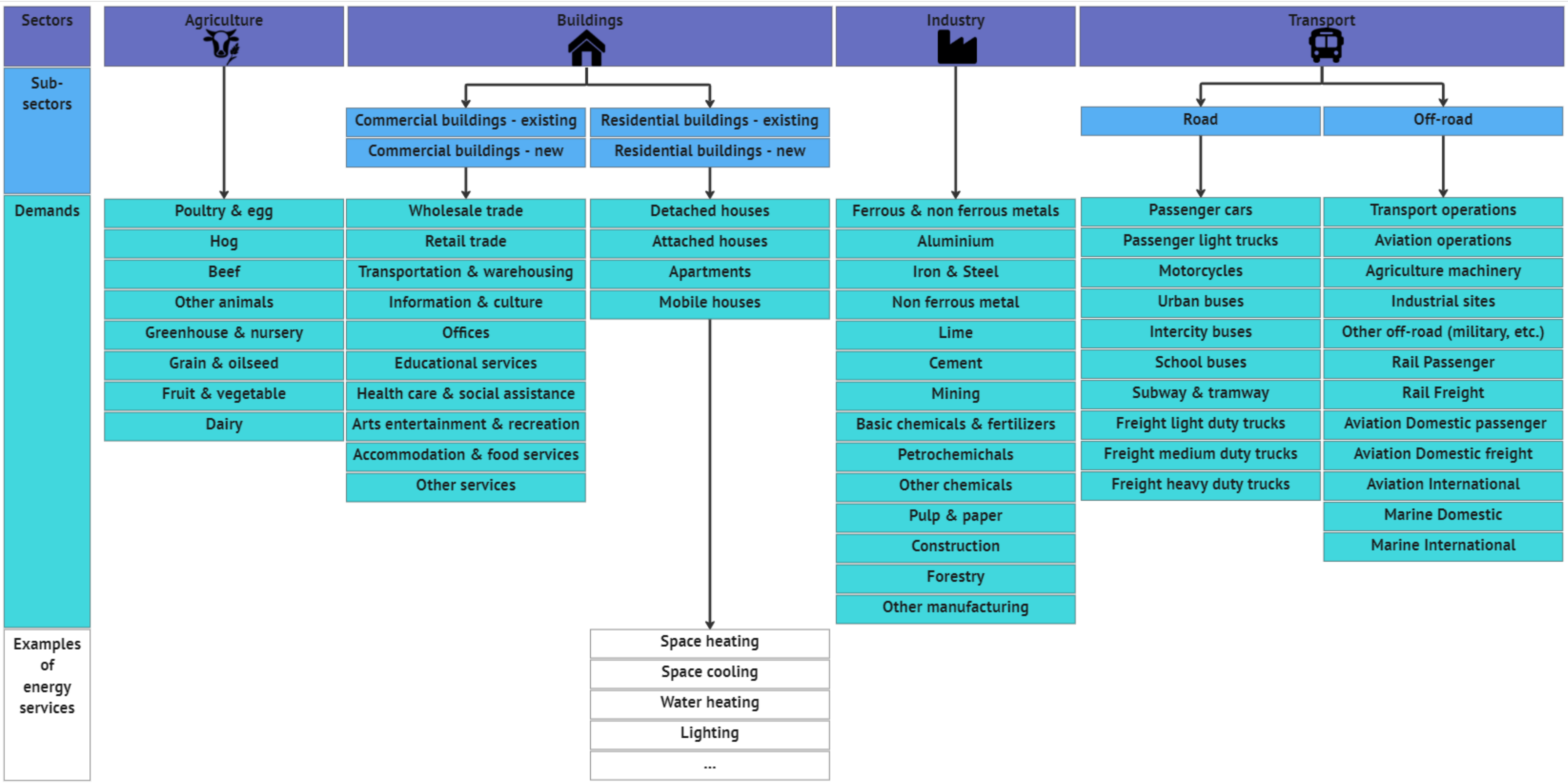
For **energy supply**, NATEM captures extensive details for all sectors, including electricity and heat generation, fossil fuel extraction, upgrading and transport, uranium extraction and transport, petroleum refining, bioenergy production, natural gas liquefaction and exports, hydrogen, and renewable natural gas production, as well as capturing new energy products and processes through on-going model development.

The **energy system** in NATEM has been carefully developed, based on engineering studies, to represent each step required for production of goods and supply of services. Steps requiring input from other parts of the energy system are explicit in the model design, which solves to find the least cost across all the interconnected steps. For example, using a heat pump with a back-up gas furnace for heating and cooling in a commercial building requires natural gas extraction and processing, electricity generation, and distribution of gas and electricity to the building. The energy or materials that flow from one part of the energy system to another are referred to as commodities. Representing the complete energy system ensures that NATEM solutions are rational, comprehensive, and readily capture unexpected impacts.

As a model, NATEM must apply some **simplifications**. It represents the steps that are common over the majority of production facilities, buildings, or transportation options with a focus on the steps that consume the most energy. Even with this simplification, NATEM's energy system retains extensive detail with each jurisdiction's representation including over 65 final end-uses, 475 commodities, and 7,000 explicit technologies.

**End-use demands,** shown in Figure 4, are the drivers of the energy system evolution in NATEM. These are an exogenous input to the model, projected through 2050 in physical units (e.g., passengers- and tons-kilometres for transport segments) using a coherent set of socio-economic projections (GDP, population, etc.) from the Canadian Energy Regulator and other factors such as future announced projects. Section 2.4.3 describes the main information sources for end-use demand.

Figure 4: Simplified illustration of the end-use demands modelled in NATEM



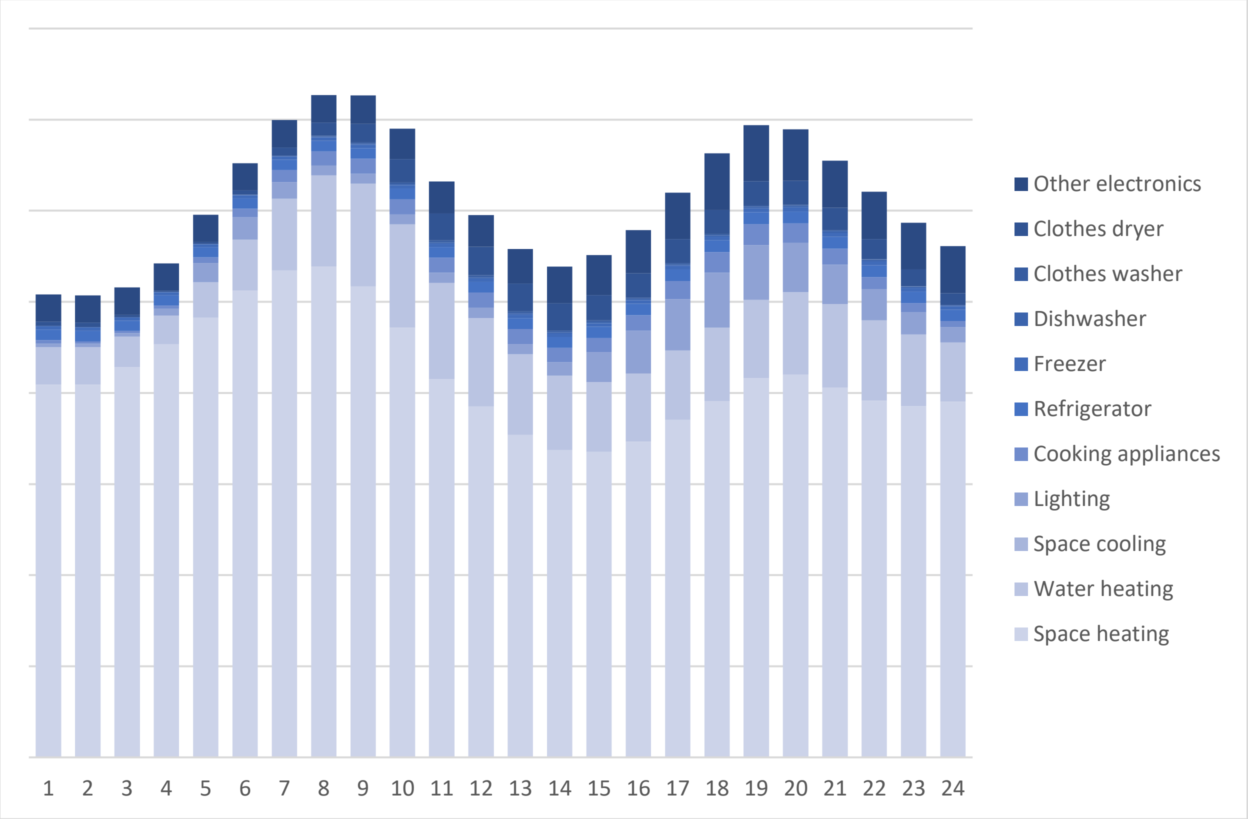
### 2.1.2.NATEM temporal framework

The temporal scope of NATEM spans the years 2016 to 2050, with fixed historical years calibrated using various sources (refer to section 2.4.1 for details). Investment decisions within the model are made over defined *time periods,* each characterized by a five-year increment. Within these periods, further time divisions called *time slices* capture seasonal variations and intra-day fluctuations during a year.

The model typically uses 16 time slices: four seasons with four intra-day segments in combination to represent the **average** winter, spring, summer, and fall days. Load curves, which detail the energy demand over the course of those average days, can be assigned to end-use demands.

In the buildings sector, load curves are meticulously calibrated using an internal model. This calibration draws primarily on annual hourly public data from electricity utilities in regions where the information is available, such as British Columbia, Alberta, Ontario, Quebec, and New Brunswick. Each energy service in the residential and commercial buildings is modelled with typical load curves. A graph of an hourly residential load curve for an average winter day is represented in Figure 5. Peak shavings measures and load shifting are modelled and will be discussed in the next section on electricity generation (section 2.1.3).

Figure 5: Example of hourly residential load curves for an average winter day



The model assumes a flat load profile for the agriculture and industry sectors. For the transport sector, diverse load profiles are incorporated to model varying charging habits, considering factors such as home charging during nighttime or workplace charging during the day. It's important to note that load curves specifically apply to end-use demands. The energy consumption within the energy production sector or processes like Direct Air Capture (DAC) is optimized separately by the model, ensuring a comprehensive and detailed approach to temporal and sector-specific dynamics.

In the context of this project and with the aim of comprehensively assessing the implications of electrifying the buildings sector, two novel "seasons" have been introduced to specifically account for three-day cold snaps and three-day heat waves. These additional seasons effectively capture the extremes of peak winter and summer days, providing a more nuanced understanding of the impact on the electricity system.

To extrapolate the effects of cold days on electricity systems, ESMIA’s internal model and historical data from Hydro-Quebec were employed, since Quebec has the highest concentration of electric space heating in Canada. Conversely, IESO data was utilized to extrapolate the impact of hot days on electricity systems, because Ontario experience more frequent heat waves. Projected temperatures for each province, accounting for the effects of climate change, were then used to extend the assessment of cold and hot days to other provinces. Additionally, the parameters for heat pumps are adjusted to account for the influence of the coldest days, offering a more accurate representation of their performance under extreme conditions.

This approach, with six “seasons” and four intra-days segments is a balance of capturing the electricity system requirements for meeting peak demand without the excessive computation time required for simulating all 8760 hours of a year. A representation of NATEM’s temporal framework is displayed in Figure 6.

## Figure 6: NATEM temporal framework

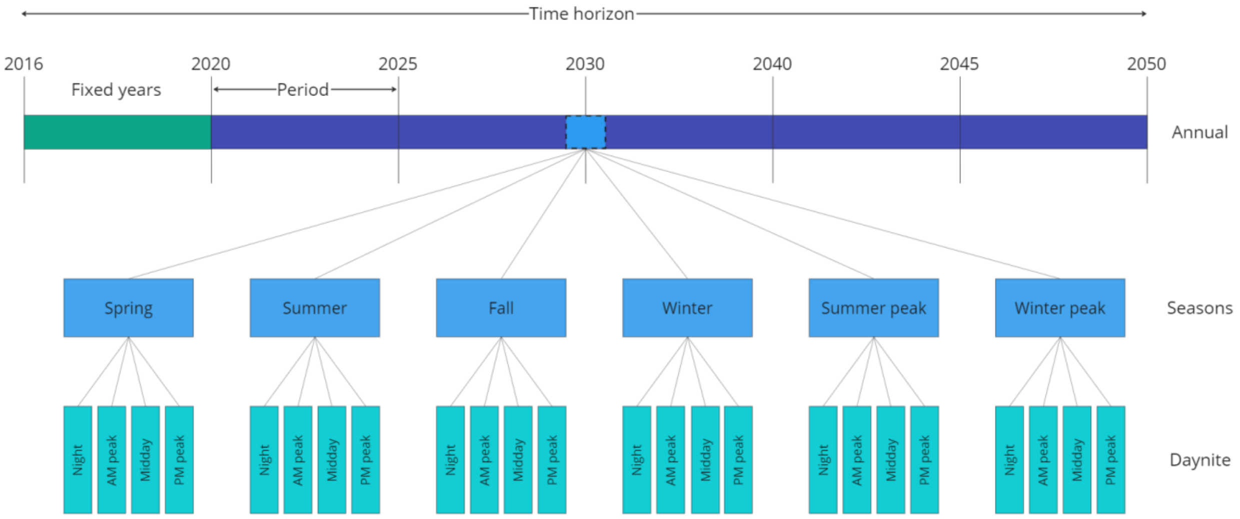


Table 2 gives a summary of the estimated peak demand in the buildings sector for each province in Canada for 2020 and 2050. Note that this is a calculation of the total peak energy demand, regardless of the fuel used and efficiency, for each province including all energy services. It represents the peak "time slice" for the peak day modelled in NATEM. Peak demand is consistently in the winter season in all Canadian provinces, even accounting for the future rise in temperature due to climate change. For each province, the evolution of the peak in 2050 is impacted by climate change forecasted temperatures and the projections of floorspace by housing and building types (see section 2.4.3 for further details).

## Table 2: Buildings sector peak demand (all fuels combined) by province

| **Province** | **Total peak demand (all fuels) for the buildings sector (MW)** | |
|---|---|---|
| | ***2020*** | ***2050*** |
| Alberta | 34,491 | 35,556 |
| British Columbia | 18,727 | 21,974 |
| Manitoba | 9,035 | 8,929 |
| New Brunswick | 3,341 | 3,503 |
| Newfoundland | 2,353 | 2,615 |
| Nova Scotia | 4,634 | 4,881 |
| Northwest Territories | 204 | 224 |
| Nunavut | 38 | 27 |
| Ontario | 79,839 | 80,763 |
| Prince Edward Island | 626 | 728 |
| Quebec | 45,847 | 48,482 |
| Saskatchewan | 8,789 | 8,498 |
| Yukon | 108 | 130 |

### 2.1.3. Electricity modelling in NATEM

#### Electricity generation

NATEM optimizes **electricity generation** to meet the demands of end-use technologies consuming electricity, taking into account the load curves discussed earlier. The existing generators in each province are thoroughly researched to model their capacities and expected lifetimes.

When it comes to renewable energy sources, the modelling approach differentiates between constant-input technologies like natural gas, coal, or biomass-fueled generators, and those dependent on seasonal or intra-day variations, such as hydro, wind, and solar. For hydro, the availability is described seasonally, while wind and solar exhibit variations within intra-day periods. To encapsulate the regional availability of renewable energy, an internal database has been established, incorporating data from medium to large wind and solar farms across Canada. Leveraging tools like the Renewable Ninja simulation and an internal analysis, the availability of different sites by province is computed, enabling the modelling of supply curves that distinguish between optimal and less favourable locations. Collaborative efforts with utilities, private entities, and government stakeholders over the years have further enriched NATEM's database to more accurately represent the potential of renewable resources in each province over the course of the modelling horizon. The model has the option to mitigate the variability of renewables by employing storage solutions, such as batteries or pumped hydro.

#### Peak constraint

NATEM solves by ensuring reliable capacity is available for intra-day periods of the representative days, plus a reserve margin of about 10%-20%, depending on province/territory. For peak calculation, the model introduces a parameter known as the "guaranteed contribution to peak" for various types of generators, determined by their availability and responsiveness to changes in demand. This parameter is near 100% for thermal-based generators and diminishes significantly for variable renewables like wind and solar. Additionally, for wind and solar, a supply curve has been developed to decrease the contribution to peak factor as the share of renewable capacity in the energy mix increases. Table 3 provides details on the average assumed contribution to the peak factor for wind and solar.

Table 3: Modelled guaranteed contribution to peak average by season for wind and solar

| Season | Wind | Solar |
|---|---:|---:|
| Spring | 9% | 13% |
| Summer | 5% | 26% |
| Fall | 9% | 13% |
| Winter | 13% | 10% |

Certain technologies within the model also contribute to peak shaving or load shifting. In the case of electric vehicles, for instance, the model optimizes a set of load curves detailing when vehicles are recharged, allowing a portion of the recharge to be shifted from one intra-day period to another. This optimization of load curves minimizes the impact on peak electricity demand. In the case of buildings, thermal storage serves as a tool for charging during one period and discharging during another. Additionally, programmable thermostats are integrated into control measures to mitigate the impact on peak demand. The model incorporates various strategies and options, including batteries, geothermal heat pumps, dual fuel systems, and more. Furthermore, the model accounts for energy efficiency measures, such as building retrofits, to ensure reduced energy consumption during peak periods. This comprehensive approach addresses a spectrum of technologies and strategies aimed at optimizing energy use and minimizing peak demand.

#### Trade

It should be noted that in Canada, each of the 13 jurisdictions is currently largely responsible for electricity self-sufficiency. This includes both guaranteed electrical energy and dependable generating capacity for meeting energy demand at all times, especially during peak periods. There are three exceptions, resulting in reliance on neighbouring jurisdictions: the Churchill Falls interconnection with Newfoundland and Labrador supplying Quebec through a contract to 2041; a contract between Newfoundland and Labrador and Nova Scotia for 20% of Muskrat Falls production for 35 years; and a contract between New Brunswick and Prince Edward Island for transfer of 5% of the nuclear energy generated at Point Lepreau. Other interconnections exist, but electricity imports cannot be used to account for dependable capacity. These constraints are captured in NATEM.

### 2.1.4. Oil, natural gas, and hydrogen

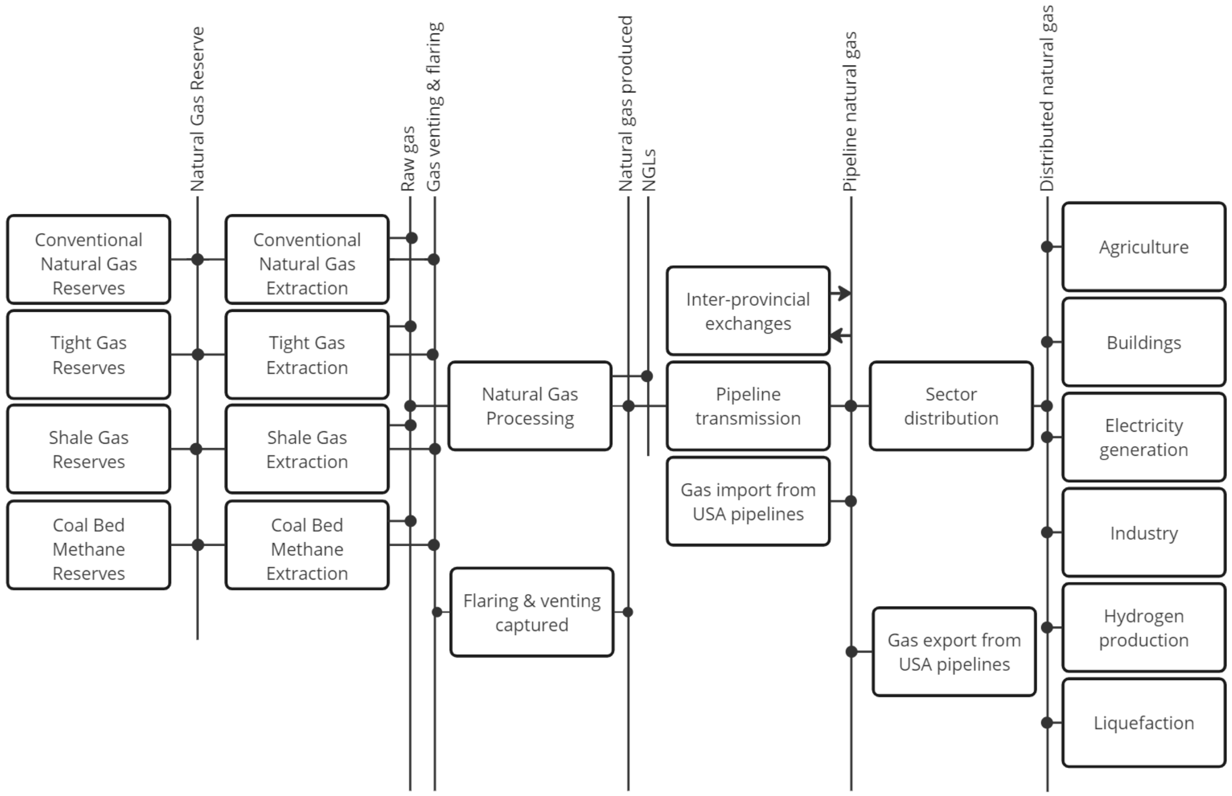
NATEM uses the following approach for projecting Canada’s **oil and gas production**:

1. Oil, gas, and coal production profiles in the Reference case of Canada’s Energy Future 2021 (Canadian Energy Regulator, CER) are used to derive upper bounds on oil, gas, and coal production for all scenarios.
2. The production is optimized based on domestic and international demand.
    - Export demand is represented by the international prices for commodities. See Section 2.4.5 for assumed international prices.
    - Domestic demand depends on technology choices and is dynamic based on energy production costs and competing technologies, with total oil, gas and coal production constrained by the upper bounds noted above.

NATEM represents the **gas network** including extraction, processing, production, transport, and delivery for the 13 provinces and territories. This network will evolve over time in the different modelling cases based on the amount and location of natural gas demand. As an additional example of energy system representation in NATEM, Figure 7 shows the reference energy system diagram for the steps from extraction to pipeline transportation.

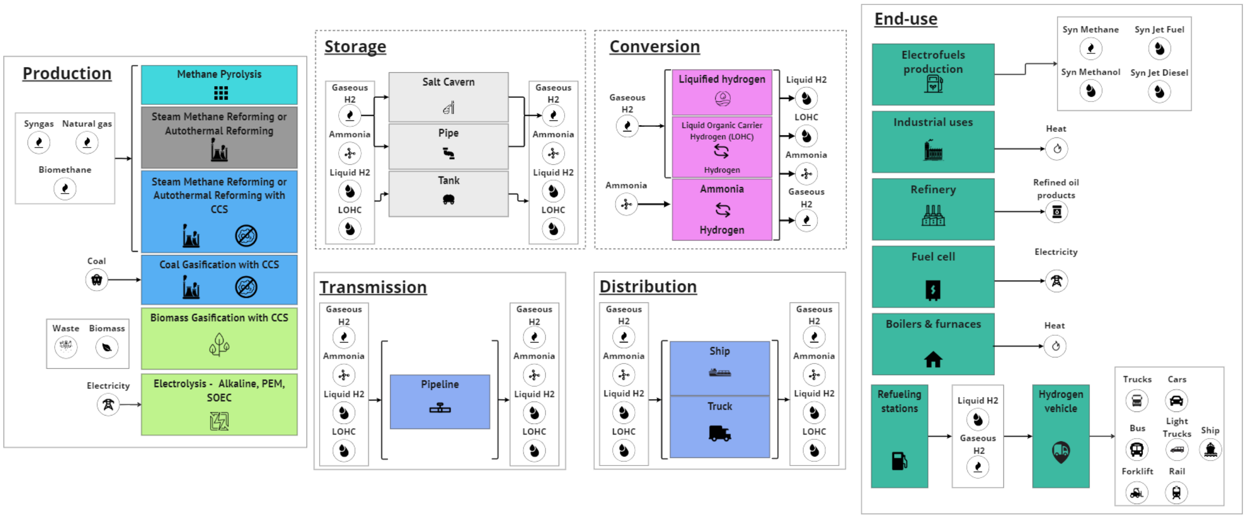
Existing pipelines for gas transport are modelled with existing capacity values and capacity factors. The model allows gas flow in existing pipelines up to their maximum theoretical capacity and invests in additional transport capacity as needed to meet demand. Note however that existing infrastructure investment costs are not accounted for in NATEM.

**Figure 7: Simplified illustration of the natural gas supply chain modelled in NATEM**



**Hydrogen** is being considered as a prospective alternative to natural gas. In recent years, ESMIA has extensively researched hydrogen, engaging in consultations with governments, private sector entities, and utilities to refine the modelling of this particular energy source. Figure 8 provides an overview of all the stages encompassed in NATEM, including supply, conversion, storage, transmission, and more. Through these consultations, the team determined that significant investments should be made in new transmission pipelines to facilitate the large-scale transport of hydrogen. This decision stemmed from ongoing evaluations regarding the refurbishment of existing natural gas transmission systems, with mitigated reports regarding their potential. However, discussions with gas utilities led to the presumption that the distribution network would not necessitate substantial investments. Consequently, the assumption that hydrogen can leverage the existing gas distribution system for its distribution needs in the building and industrial sectors was made.

Figure 8: Simplified illustration of the hydrogen value chain modelled in NATEM



## 2.2. NATEM techno-economic database

The NATEM techno-economic database has extensive detail for over 7,000 technologies. Each technology is characterized by its technical and economic attributes as well as its pollutant coefficients. Table 4 shows the type of information used for describing technology options. For proprietary reasons, this level of detail is not shared for technologies in this study.

Table 4: Technology characteristics input to NATEM

| Attribute | Description |
|---|---|
| Investment cost | Capital/purchase cost of a technology |
| Fixed operation cost | Fixed operation cost |
| Variable operation costs | Variable operation cost, excluding energy cost |
| Taxes or tax credits | Relevant taxes or tax credits to include on technologies and/or fuels |
| Subsidies | Relevant subsidies for technologies and/or fuels |
| Efficiency | Output/input – can be defined by time slices (for heat pumps) |
| Transmission and distribution losses | Energy lost during electricity transport |

| Attribute | Description |
|---|---|
| Construction time | Time needed for physical construction (excludes permitting and delays that could be shortened by policy) |
| Technical life | Expected technical life of the technology |
| Economic life | Economic life used for interest accounting |
| First year of availability | Expected year of commercial availability for emerging technologies |
| Annual capacity factor | Maximum availability for production (account for shutdowns or resource intermittency) |
| Seasonal and daily capacity factor | Maximum availability for production |
| Guaranteed contribution to peak by class of generation plants | For long-term electricity planning in capacity expansion |
| Average contribution to winter and summer peak | For each hour peak in summer and winter |
| Achievable supply | Any constraints that may limit the availability of the technology / fuel (if quantitative information is available) |

NATEM includes technologies for all end-uses in the energy system from generation technologies that convert primary energy into secondary energy (e.g., refineries, power plants, etc.) to end-use devices that transform final energy into energy services (e.g., cars that serve a demand for mobility, light bulbs that serve a demand for lighting). Existing technologies, improved versions of the same technologies, and emerging technologies are included, each characterized by technical and economic attributes.

Explicitly tracking technology stock turnover is an additional advantage of NATEM. The database includes estimated quantities for existing stock and the remaining lifespan plus all new stock is tracked with the year of installation and typical lifetime. Technologies can be retired early, if required for the optimal solution, which accounts for decommissioning costs, and the information on forced retirement allows analysis of future stranded assets.

The model tracks all GHGs, including carbon dioxide ($CO_2$), methane ($CH_4$), nitrous oxide ($N_2O$), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulphur hexafluoride ($SF_6$), and nitrogen trifluoride ($NF_3$) from all sectors of the national inventories. NATEM excludes changes in emissions from land use, land-use change and forestry (LULUCF), except for biochar technology.

Energy costs (part of variable operation costs) are endogenous to NATEM based on the technology and process choices for production and provided as output for each run.

## 2.3. Identifying optimal solutions

NATEM provides optimal (least-cost) solutions in terms of technology mix in all supply and demand sectors of the economy to meet energy service demands over the entire time-horizon.

NATEM's optimal solution must meet user-defined specifications. The robust solution space in the model allows for a wide range of such specifications. It can be used to derive minimum cost solutions for meeting prescribed GHG reduction targets in selected jurisdictions or for several and/or all jurisdictions. Alternatively, it can be used to derive projected GHG reductions in response to defined policies. Policies include GHG prices (carbon tax), subsidies, taxes on specific technologies, renewable portfolio standards, minimum renewable content in conventional fuels, phase out programs and moratoria on energy types (e.g., nuclear or coal), investment growth rate projections, etc.

NATEM's basic specification comprises three components:

- The first component (objective and exogenous service demand) corresponds to the overall goal. By default, NATEM's objective is to provide the exogenous service demand for the energy system, at the minimum net total discounted cost, over the entire time period and all jurisdictions.
- The second component (endogenous decision variables) corresponds to determining the future technology mix, which includes decisions on investments, retirements, and operations of technologies at each time period. The amount of energy produced or consumed by technologies, energy trade, and emissions are determined by the technology mix and operations.
- The third component (constraints) corresponds to various limits and obligations to be respected. Some constraints are policy-based (such as GHG emission caps), others are due to physical resource availability (e.g., biomass) or technology specifications (e.g., hydrogen blend allowed in pipelines or technologies). Many constraints are a function of the energy system connections where one part of the system will demand production from a different part (e.g. energy balances throughout the system, useful energy demand satisfaction). NATEM can also use constraints to represent supply chain or investment growth limitations.

**In summary:** NATEM solves by mathematically determining (decision variables) the mix of technologies (from the techno-economic database) that meet the energy service demands (inputs), subject to constraints such as government policies and resource availability, *at the least cost* over the full planning horizon.

## 2.4. Key assumptions

### 2.4.1. Historical calibration

Historic information in NATEM includes energy consumption and production and GHG emissions by fuel and economic sector for the 13 provinces and territories.

Examples of the sources for this information include but are not limited to:

- Environment and Climate Change Canada. 2023. *National Inventory Report*. (ECCC, 2023)
- Natural Resources Canada. n.d. *Comprehensive Energy Use Database*. (NRCan, n.d.)
- Statistics Canada. *Annual Industrial Consumption of Energy Survey, 2022*. (Statistics Canada, 2022)
- Statistics Canada (2023). *Energy Supply and Demand in Canada – Interactive database.* (Statistics Canada, 2023)

### 2.4.2. Discount rate

For this project, ESMIA used a global discount rate of 3%. This choice follows the direction from *Canada's Cost-Benefit Analysis Guide for Regulatory Proposals* (Treasury Board of Canada Secretariat, 2022), which notes that projects considering environmental goods and services can use the social discount rate of 3%. The 2020 regulatory impact assessment statement of the *Clean Fuel Regulation* used the same approach of 3% for the main analysis (Government of Canada, 2020).

Note that the global discount rate is used for setting the objective function where total cost is minimized. Decisions for individual technologies use technology-based discount rates that account for elements such as limits to capital, short-term decision by types of consumers (for example, higher hurdle rates for residential purchases of equipment with low capital costs and relatively lower hurdle rates for industrial customers for larger purchases using credit but still high enough to cover a return on investment).

### 2.4.3. Projections for population, economic growth, and climate change impacts

NATEM requires **exogenous projections** for end-use demand, the units of goods and services that a model solution must meet. These inputs are derived from official sources to describe a set of coherent future conditions. The sources of the future conditions are shown in Table 5. The model also uses price elasticities for endogenous demand reductions under GHG mitigation scenarios, such as lower demand for floorspace (smaller homes and buildings) when energy costs increase.

**Table 5: Select sources of forecasts used to derive final end-use projections.**

| Variable | Purpose | Source |
|---|---|---|
| **Population** | To project future demand for residential housing, personal transportation, and services | *Population Projections for Canada (2021 to 2068), Provinces and Territories (2021 to 2043)*. (Statistics Canada, 2022) |
| **Gross domestic product** | To project future demand for goods and services | (CER, 2023) *Canada's Energy Future 2023: Energy Supply and Demand Projections to 2050*. Reference scenario<br>(Canadian Climate Institute, 2022). *Damage Control: Reducing the costs of climate impacts in Canada* |
| **Oil and gas export prices** | To develop costs for consumption and demand for exports. | (International Energy Agency, 2022)). *World Energy Outlook.* Announced Pledges Scenario.<br>(IEA, 2021). Net Zero by 2050 A Roadmap for the Global Energy Sector p 51 |

**Impacts of climate change** are expected to change some end-use demands (for example, increasing cooling demand) and areas for economic growth. Such changes are applied exogenously to NATEM. For heating and cooling demand changes, ESMIA adjusted the energy intensity of service demands by building types (e.g., TJ/m2 of useful energy for space cooling in detached houses) using information for one major city in each province and territory, derived from Pacific Climate Impacts Consortium (n.d.) based on the moderate-case scenario (RCP4.5; see ANNEX B for further details). For changes to economic structure from climate impacts, the agriculture and industrial output were adjusted based on information from Canadian Climate Institute (2022).

### 2.4.4. Climate mitigation environment

The net-zero pathway uses the GHG emissions trajectory shown earlier in Figure 2. It is based on:

- Historic to 2021 – Model calibration to ECCC's National Inventory Report (ECCC, 2023)
- 2022 to 2030 - The GHG constraint decreases linearly from 2020 to 2030
    - 2030 GHG emissions are 440 Mt, which represents a 40% reduction of Canada's 2005 emissions level.
- 2031 to 2049 – The GHG constraint decreases linearly from 2030 to 2050
    - 2050 GHG emissions are 10 Mt $CO_2e$. This constraint is above zero to represent the estimated contribution of carbon removed by LULUCF, nature-based climate solutions,

and agriculture (removal) based on assumptions in *Canada's Energy Future 2023* (CER, 2023). However, since biochar technology is modelled and it is part of soil carbon management, a lower potential for LULUCF was assumed.

Note that the model assumes there are no contributions from international emissions offsets (such as Article 6 of the Paris Agreement or from the Quebec and California cap-and-trade).

### 2.4.5. Prices for fossil energy imports and exports

In NATEM, most energy prices are endogenous to the model; only prices of energy commodities imported/exported from/to outside Canada are exogenous inputs.

The following assumptions reflect the international context for this modelling. The energy prices reflect IEA's Net Zero report (IEA, 2021). This source was used rather than the most recent Energy Futures report from the Canadian Energy Regulator, because the majority of the modelling was completed before the release of the 2023 version (CER, 2023).

**Table 6: Prices for fossil energy imports and exports for net-zero scenario**

| **Net-zero scenario - Import** | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Type** | **Price (2021$/GJ)** | | | | | | |
| | **2020** | **2025** | **2030** | **2035** | **2040** | **2045** | **2050** |
| Crude oil | 7.44 | 7.24 | 7.04 | 6.34 | 5.63 | 5.23 | 4.83 |
| Natural gas | 2.48 | 2.36 | 2.24 | 2.30 | 2.36 | 2.36 | 2.36 |
| Liquified natural gas | 6.08 | 5.96 | 5.84 | 5.90 | 5.96 | 5.96 | 5.96 |

Source: (IEA, 2021)

| **Net-zero scenario - Export** | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Type** | **Price (2021$/GJ)** | | | | | | |
| | **2020** | **2025** | **2030** | **2035** | **2040** | **2045** | **2050** |
| Crude oil | 7.04 | 6.84 | 6.64 | 5.94 | 5.23 | 4.83 | 4.43 |
| Natural gas | 2.08 | 1.96 | 1.84 | 1.9 | 1.96 | 1.96 | 1.96 |
| Liquified natural gas | 5.68 | 5.56 | 5.44 | 5.5 | 5.56 | 5.56 | 5.56 |

Source: (IEA, 2021)

### 2.4.6. Policies

The following are policies simulated, based on policy designs as of January 2023:

- Clean Fuel Regulation (SOR/2022-140);
- Zero-emissions vehicle sales mandate (Quebec and BC);
- Incentives for Medium- and Heavy-Duty Zero-Emission Vehicles (iMHZEV);
- Clean Technology Investment Tax Credit;
- Investment Tax Credit for Carbon Capture, Utilization and Storage;
- Clean Technology Tax Incentives – Air-Source Heat Pumps;
- Oil to Heat Pump Affordability (OHPA) Grant;
- Net Zero Accelerator/Strategic Innovation Fund;
- Canada Greener Homes Grant;
- Greener Homes Loan Program.

It can be noted that the federal fuel charge, performance standards, Quebec cap and trade, and provincial carbon pricing are not included in the optimization. This is because the emissions limit discussed in Section 2.4.4 is applied. NATEM solves most effectively when only one economy-wide price-based policy is applied per model run. Using a GHG target and a carbon tax would be redundant.

### 2.4.7. Technologies sources

As noted above, NATEM includes detailed technology characteristics for over 5,000 technologies; sharing this proprietary database is out of scope for this report. Table 7 provides a list of key sources for technology types of high relevance to this study.

**Table 7: Key sources for technology characteristics, not comprehensive**

| Technology Type / Sensitivity | Main reference |
|---|---|
| **Heat pumps and other heating equipment for buildings** | (US Energy Information Association, 2023) *Updated Buildings Sector Appliance and Equipment Costs and Efficiencies* |
| **Electricity generation – wind and solar** | (National Renewable Energy Labratory, 2022) Annual Technology Baseline, Moderate case |
| **Hydrogen production** | (Ahluwalia, 2019), (Element Energy Ltd, 2018), (IEA, 2019a), (IEA, 2019b), (TEQ, 2020) |

### 2.4.8. Buildings' space heating technologies & retrofit potential

The NATEM database incorporates various space heating systems, each meticulously modelled to capture their nuanced characteristics:

- Biomass
- Standard electricity
- Natural gas
- Propane
- Oil
- Electric heat pumps with electric back-up
- Electric heat pumps with gas back-up
- Natural gas heat pumps
- Hydrogen

For each of these systems, the model has a range of technologies available with varying levels of efficiency. Costs are derived from an extensive literature review and are contingent on housing archetypes and the specific type of system (furnaces, rooftop units, boilers, etc.).

The assessment of current costs for heat pumps is anchored in the Canadian Climate Institute report *Heat Pumps Pay Off: Unlocking Lower-Cost Heating and Cooling in Canada*. The NATEM model incorporates supply curves for heat pump costs, factoring in major, moderate, and minor changes needed for their installation, such as adapting electric systems. These supply curves align with the historical stock of space heating in each province, reflecting regional variations.

In terms of retrofit, collaborative efforts with Dunsky have evaluated the high-level potential for each province, housing type, and vintage. A literature review has categorized various energy efficiency measures, including envelope measures (insulation and air sealing) and control measures (programmable thermostats, heat recovery). Each measure is divided into different levels and come with a retrofit degree and associated cost. Each level of a measure is assigned a maximum capacity by housing and building type, representing a realistic level of penetration for the energy efficiency or retrofit measure in buildings. The model then selects the cost-optimal level of retrofit for buildings, ensuring a realistic representation of the potential for each measure.

# ANNEX A: Models description

## A.1. The North American TIMES Energy Model (NATEM)

For this project, we used the Canadian module of the North American TIMES Energy Model (NATEM). NATEM-Canada describes the entire integrated energy system, as well as non-energy emitting sectors of the 13 Canadian jurisdictions, and provide a rigorous analytical basis for identifying least-cost solutions to achieve energy and climate objectives without compromising economic growth. NATEM-Canada is part of a larger framework covering the whole North American continent. It includes a large number of technologies allowing jurisdictions to reach deep decarbonization levels (including net-zero targets by 2050).

### An economy-wide and dynamic optimization approach

Optimization models of energy-economy-environmental (E3) systems such as NATEM provide a rigorous analytical basis for studying the transition toward a clean energy future in a detailed multi-regional, multi-sector and multi-fuel framework.

- Optimization models provide a very detailed representation of the technological changes required in the long term, as well as their costs, to meet growing demands and/or to reach specific goals.
- In addition, they provide important additional features compared with other types of energy system models, such as simulation models. They endogenously provide an optimal configuration of the energy sector which makes it possible to satisfy the total demand for energy services at lower cost, while respecting system constraints (resource limitations, renewable targets, GHG taxes or mitigation targets, energy policies, etc.). These models are typically projected to very long-term horizon, which makes it possible to study the structural changes within the energy sector. In addition, the linear programming approach quickly solves very complex problems.
- The TIMES optimization model generator in particular is the most advanced and widespread; it is used by numerous teams in 70 countries. It is a rigorous methodology, well documented[1] and which is constantly improved through an international collaboration network (ETSAP-International Energy Agency).
- NATEM is an application of the TIMES model generator for North America and represents the only optimization model covering the Canadian energy systems in many details.

NATEM is a dynamic least-cost optimization model based on the linear programming approach, and as such contains three components.

- The first component (objective) corresponds to minimizing the net total discounted cost (e.g. 3-5% is typically used in deep decarbonisation studies) of the entire energy system. A single optimization, which searches for the maximal net total surplus, simulates market equilibrium for each commodity (energy, material, demand). Maximizing the net total surplus (i.e. the sum of producers' and consumers' surpluses) is operationally done by minimizing the net total cost of the energy system.

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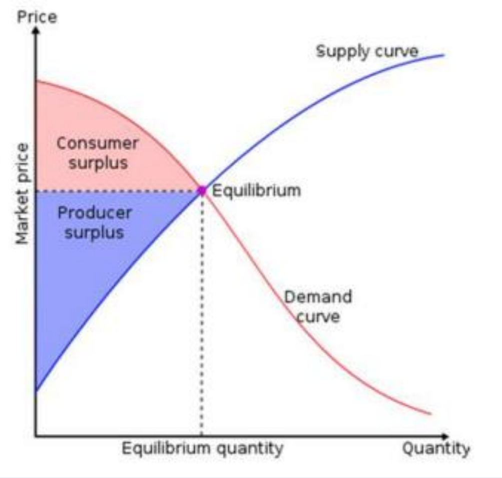
[1] Loulou R, Goldstein G, Kanudia A, Lehtila A, Remme U. (2016). Documentation for the TIMES Model. Energy Technology Systems Analysis Program (ETSAP) of the International Energy Agency (IEA). Retrieved from http://iea-etsap.org/index.php/documentation.

- The second component (variables) corresponds mainly to future investments and activities of technologies at each time period, amount of energy produced or consumed by technologies, as well as energy imports and exports. An additional output of the model is the implicit price (shadow price) of each energy form, material, and emission, as well as the reduced cost of each technology (reduction required to make a technology competitive).
- The third component (constraints) corresponds to various limits (e.g. amount of energy resources available) and obligations (e.g. energy balances throughout the system, useful energy demand satisfaction) to be respected.

**Computing partial equilibrium on energy markets with elastic demands to capture feedback from the economy to the energy system**

By default, TIMES assumes competitive markets for all commodities, unless specified differently by the modeller, with perfect foresight. The model computes both the flows of energy (materials and pollutants) and their prices, in such a way that the suppliers of energy produce exactly the amounts that the consumers are willing to buy. The total economic surplus is maximized when all markets are in equilibrium (or total system cost is minimized). Energy services are elastic to their own prices, capturing the main feedback from the economy to the energy system.

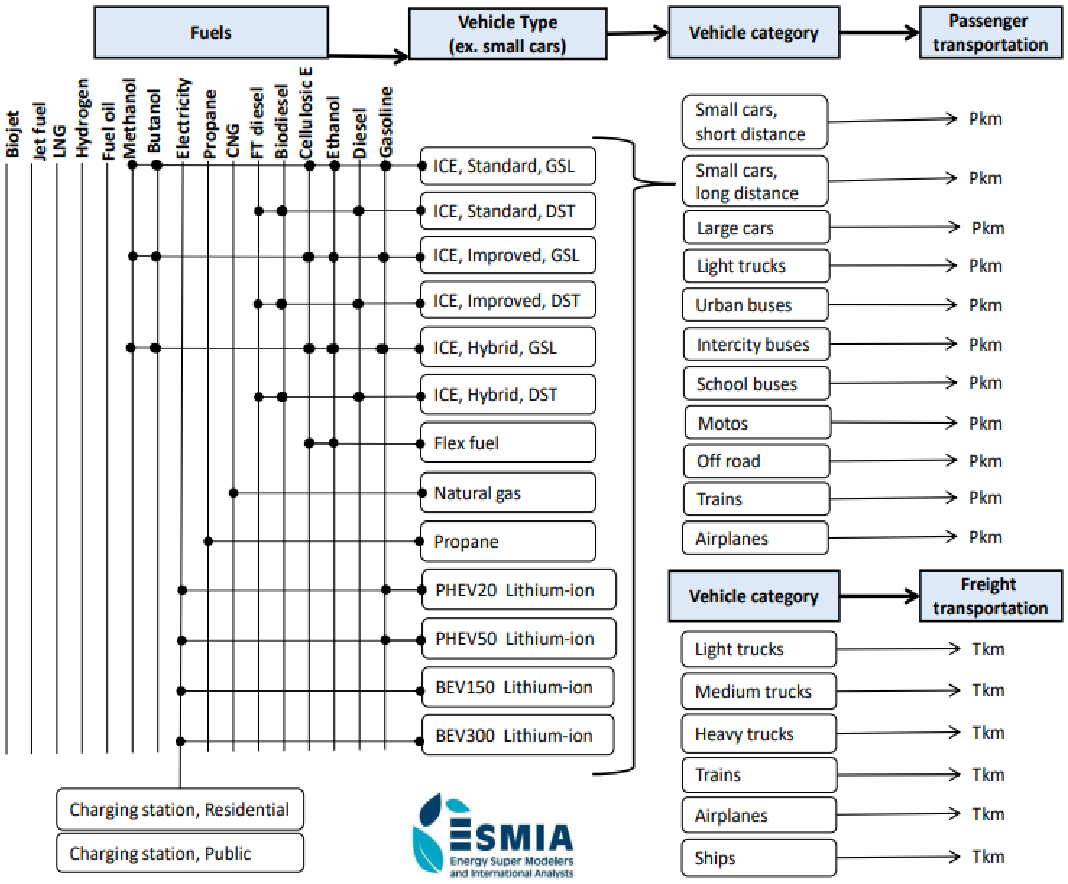


## A detailed representation of North American energy systems

NATEM follows a techno-economic modelling approach to describe the energy systems of North American jurisdictions through a large variety of specific energy technologies characterized with their technical and economic attributes as well as pollutant coefficients. It thus offers a detailed representation of an energy sector, which includes extraction, transformation, distribution, end uses, and trade of various energy forms and materials.

NATEM distinguishes between generation technologies that convert primary energy into secondary energy (e.g., refineries, power plants, etc.) and end-use devices that transform final energy into energy services (e.g., cars that serve a demand for mobility, light bulbs that serve a demand for lighting). In particular, they include existing technologies, improved versions of the same technologies and emerging technologies, all characterized by their technical and economic attributes. Consequently, it allows for detailed accounting of all energy flows within the energy sector from primary energy extraction to final energy consumption.

**Example from the road passenger transport by small cars travelling long distance (not exhaustif)**



## An extremely rich technology database for all 13 Canadian jurisdictions

NATEM describes the entire integrated energy system of the 13 Canadian jurisdictions, including inter-jurisdictional flows of energy commodities and transportation infrastructure, as well as non-energy emitting sectors such as industrial processes, agriculture, and waste.

- The model database describes 475 such commodities in each jurisdiction, as well as more than 5,000 explicit technologies.
- NATEM is driven by 65 end-use demands for energy services, projected to the 2060 horizon in physical units (e.g., passengers- and tons- kilometres for transport segments).
- Demands for energy services are currently projected through 2060 using a coherent set of socio-economic projections (GDP, population, industrial gross outputs, etc.) from national and provincial sources. Other factors are considered for adjustments such as future announced projects.
- For the energy supply side, NATEM captures all sectors, including electricity and heat generation, in many details. Other supply sectors include fossil fuel extraction, upgrading and transport, uranium

extraction and transport, petroleum refining, bioenergy production, natural gas liquefaction and exports, hydrogen supply chain, renewable natural gas production and upgrading, etc.

- Primary energy resources include conventional and unconventional fossil fuels reserves (oil, gas, and coal), renewable potential (hydro, geothermal, wind, solar, tidal, and wave), uranium reserves and biomass (various solid, liquid, and gaseous sources).
- Carbon capture options are available in the electricity, hydrogen, oil upgrading, and industrial sectors. Sequestration potential exists for enhanced oil recovery, in oil and gas fields (onshore and offshore), and in deep saline aquifers. Direct air capture is also covered.
- The model is currently solved for the 2016-2060 timeframe. These projections rely on time periods of variable and flexible length, shorter at the beginning (1 to 2 years) and longer (5 years) at the end of the horizon. Besides, each time period is divided into flexible and hierarchical annual time slices. There are currently sixteen time slices representing four seasons a year (spring, summer, fall and winter) and four intraday periods (day, night, morning peak, evening peak).
- The model tracks all GHGs, including carbon dioxide (CO2), methane (CH4), nitrous oxide (N20), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulphur hexafluoride (SF6), and nitrogen trifluoride (NF3) from all sectors of the national inventories, except land use, land-use change and forestry (LULUCF).

NATEM is currently used in several research and consulting projects in Canada.

### A powerful decision-making tool that is regularly used to inform climate action in North America

NATEM represents most major low-carbon technologies that are envisaged being available for at least the first half of the 21st century. By capturing the substitution of low-carbon for high-carbon technologies in response to their relative costs, as well as emissions constraints and/or carbon prices, the NATEM model simulates mitigation. It enables capturing in particular substitutions of energy forms (e.g., switching to low-carbon fuels) and energy technologies (e.g., use of battery-electric vehicles instead of vehicles equipped with an internal combustion engine running on conventional fuels) to comply with renewable electricity or climate policy targets. NATEM also has the capability of estimating the price-based response of these energy service demands to the changing conditions of scenarios in which mitigation occurs via a set of demand price elasticities.

NATEM predominantly works by specifying either a GHG price (e.g., a carbon tax) or a GHG limit (e.g., a carbon cap, target, constraint) in one or several regions, or alternatively for all regions simultaneously. Additionally, the following further policies and measures can be implemented: subsidies or taxes on specific technologies, renewable portfolio standards, minimum renewable content in conventional fuels, phase out programs and moratoria on some energy type (e.g., nuclear or coal), investment growth rate projections, etc.

This allows NATEM to perform a number of energy and climate policy-relevant investigations. Indeed, NATEM has been used to assess the implications of meeting ambitious GHG mitigation goals on the energy system configuration and cost, under many different economic and technical assumptions. NATEM model's results have been used by decision makers from public and private organizations to : i) draft climate action plans, with optimal sequences for the introduction of mitigation measures, ii) identify strategic research priorities to reduce mitigation costs, while contributing to economic development, iii) prepare Canadian energy outlooks including net-zero scenarios, iv) prepare technological roadmaps, v) evaluate the economic and environmental impacts of energy projects, and vi) analyze energy security issues. Results on different topics were also validated in numerous peer-reviewed journals.

# ANNEX B: Temperature forecast

The temperature forecast between 2020 and 2060 is generated using a morphing methodology. This methodology combines the observed weather data with results from climate models. It allows to represent future weather conditions depending on selected climate scenario while preserving realistic weather sequences and climate patterns.

For this analysis, the temperature projections were done for the 20 most populated cities in different Canadian regions and territories. For each city, the minimum and maximum daily temperature data for the RCP 2.6, 4.5, and 8.5 scenarios for the years 1970-2060 (daily actual and forecast) were extracted from the CANESM2 database (Pacific Climate Impacts Consortium, n.d.). Hourly measured air temperature data for the same cities for the years 2000-2020 were obtained from (Renewables, 2023).

The average of 1980-2009 was chosen to sample historical data, 2020-2039 to sample the 2030s and 2040-2059 to sample the 2050s. In order to project future temperatures depending on climate scenarios, the following factors are used (Ek M., 2018):

- Shift factor, representing the absolute change between the future and present-day baseline;
- Stretch factor, representing predicted fractional change in daily value.

These factors were calculated for each sample and then applied to the hourly data provided between 2000-2020. Hourly temperature forecasts for 2020-2059 were then made. These calculations were repeated for the RCP 2.6, 4.5, and 8.5 scenarios and for all selected cities.

According to the results, the average temperatures increase between 1.1-celsius degrees in the RCP 2.6 scenario and 2.2-celsius degrees in the RCP 8.5 scenario.

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