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Is there a future for new hydrocarbon projects in a decarbonizing energy system? A case study for Quebec (Canada)

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Abstract: Signatories of the Paris Agreement under the United Nations Framework Convention on Climate Change (UNFCCC) are exploring avenues to drastically abate their greenhouse gases (GHG) emissions. This demands a rapid transition to low-carbon energy systems. However, some regions may be tempted to exploit new hydrocarbon deposits due to energy security concerns or because of oil companies seeking additional profits. This paper proposes prospective energy scenarios for the Province of Quebec up to 2050 under GHG emission reduction constraints with and without new hydrocarbon exploitation. The main objective is to measure impacts of developing new hydrocarbon projects on achieving stringent GHG reduction objectives (up to -80%). Our analysis relies on the North American TIMES Energy Model (NATEM) that belongs to the MARKAL/TIMES family of models supported by the International Energy Agency. In terms of hydrocarbon exploitation, a recent project proposed by the oil industry for exploiting deposits in the Anticosti Island. In our GHG abatement scenarios, results indicate that the hydrocarbons of Anticosti Island would be exported and have virtually no effect on the energy consumption mix in Quebec. However, 2050 GHG emission levels would increase by nearly 7% in the reference case (baseline). Greater total GHG reductions would thus be required from the baseline at a significantly higher marginal abatement cost.

Keywords: GHG emission targets, decarbonization scenarios, optimization, TIMES model, fossil fuel impacts, mitigation costs

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1 Introduction

The effects of global warming have been a growing concern internationally for the last few decades. These concerns culminated in 2015 at the 21^{st} Conference of the Parties of the UNFCCC (COP21) in Paris, where more than 174 countries and the European Union acknowledged the need to significantly reduce their GHG emissions [1]. For example, Canada aimed at a 30 % reduction below 2005 levels by 2030, China pledged to peak its emissions by 2030 at the latest and to lower its carbon intensity of GDP by 60%-65% below 2005 levels, and the European union pledged to decrease its emissions by 40% by 2030 and by 80-95% by 2050 from 1990 levels [2]. While exact strategies to meet these targets have not been extensively laid out, it is generally agreed that countries will need to expand the use of renewable energy, develop more efficient technologies, and limit emissions by implementing new regulations and/or economic mechanisms such as carbon taxes or carbon trading [3].

In some countries, switching energy production capacities from coal to natural gas, for example, could be enough to meet their reduction objectives. For others, the challenge is more complex. One such regions is the Quebec province in Canada, which has set more ambitious GHG reduction targets than Canada, namely: 20%, 37.5% and 80-95% (from 1990 levels) by 2020, 2030, and 2050, respectively [4]. However, the province already relies on an electricity mix that is one of the least carbon intensive in the world; composed of nearly 99% renewable energy, 95% of which is hydroelectricity. It also implemented a cap and trade program in 2013, which expanded in 2014 with the addition of California, to be joined in 2018 by Ontario (another Canadian province). Even with all these efforts, Quebec is presently emitting around 81 Mt CO_2-eq per year, a decrease of only 8.6% relative to 1990 levels [5], with 43% of the emissions stemming from the transport sector, 30.8% from the industrial sector, 9.5% from the residential and commercial sectors, 9.2% from the agricultural sector, 7.2 % from waste management and 0.3 % from the electricity production sector. Without solutions that can be easily imported, an in-depth analysis for Quebec needs to be conducted to determine *what is the most cost-efficient option(s) to meet the given ambitious targets.*

In parallel, the province has been looking into hydrocarbon extraction in the last few years. As in several other jurisdictions on the continent (e.g., the Bakken Basin in North Dakota), exploration and exploitation of new hydrocarbon deposits is attractive for energy security issues and additional profit opportunities. However, hydrocarbons in the province are mostly shale gas and shale oil. Only hydraulic fracturing has proved effective until now - a method which requires considerable installations and poses risks to the environment. However, an extraction project on Anticosti Island, located at the outlet of the Saint Lawrence River into the Gulf of Saint Lawrence, has recently been considered before being finally abandoned by the Quebec government. This stand has been criticized by the main opposition party in Quebec and the political decision not to exploit Anticosti Island could be reversed in the future. In that case, *would it still be possible to meet ambitious reduction targets? And at what additional costs?*

This paper proposes prospective scenarios of energy consumption and production for the Province of Quebec up to 2050 under GHG emission constraints and possible new hydrocarbon extraction. The main objective is to measure impacts of developing new hydrocarbon projects on achieving stringent GHG emission reduction targets. The analysis is based on the North American TIMES Energy Model (NATEM), which is a highly detailed multi-regional optimization model for Canada [6,7]. NATEM belongs to the MARKAL/TIMES family of models supported by the Energy Technology Systems Analysis Program (ETSAP) of the International Energy Agency [8]. The analyses of six scenarios allow to simultaneously assess the impact of meeting the provincial GHG reduction targets for the energy system, with and without hydrocarbon development on Anticosti Island. Moreover, a sensitivity analysis is carried out to further explore the role of behavior changes in the context of climate change mitigation policies. While the Province of Quebec has set ambitious GHG reduction targets, no specific action plan supported by rigorous analyzes has yet been proposed to achieve these goals. This paper thus brings new and relevant information about the sectors to be targeted and the priority actions to be implemented for achieving the targets with or without hydrocarbon exploitation.

The paper is organized as follows. Section 2 briefly introduces the NATEM model. Section 3 presents the different scenarios and their underlying assumptions. Section 4 gives an overview of the main results in terms of GHG emissions, energy profiles and mitigation costs. Section 5 briefly discusses these results. Section 6 concludes with a summary of key points and limitations of the study.

2 Methodology

2.1 The TIMES energy model generator

NATEM was developed based on the TIMES optimization model generator [8]. A TIMES model describes the entire integrated energy system of a region through specific technologies with their techno-economic attributes and emission coefficients. The model is demand-driven: end use demands for energy services are specified exogenously over a specific time horizon.

TIMES is a dynamic linear programming model which maximizes net total surplus (the sum of consumer and producer surpluses), which is operationally achieved by minimizing the net total discounted cost of the whole energy system. The model is based on the assumption that energy markets are under perfect competition. The main model outputs are technology specific investment and activity levels for each specified time period, the shadow price of each energy, material and emission commodity, and the reduced cost of each technology. Finally, TIMES models include own-price elasticity of demand allowing for behavioral changes and their impacts on the energy system to be captured through endogenous changes in demand in constrained scenarios (i.e., GHG reduction scenarios) compared to the baseline.

TIMES models are currently used in nearly 70 countries for climate policy analysis. Important insights can be gained from the use of optimization models, namely the ranking of the technology options that are most likely to play a significant role in the future energy system of a given region as well as the marginal costs of energy commodities and GHG reductions. The role of optimization models for exploring clean energy transition pathways has been effectively demonstrated in specific regions through a large variety of scenario definitions. For instance, a scenario where GHG emissions are limited to 2.5% above 1990 levels in 2030 was examined for Macedonia [9]. For Austria [10], transformation scenarios with GHG reduction to 20% of the Kyoto baseline were explored, and for Taiwan, a study [11] reports on low-carbon development scenarios reducing CO_2 emissions by up to 79% compared with a business-as-usual scenario by 2050. Some studies focus a similar target such as pathways reducing GHG emissions by 80% by 2050 and show in which sectors composing the energy system of a region are the priority actions: California [12], Ireland [13] and the United Kingdom [14]. Similarly, at the global level, scenarios compatible with meeting the 2^{o}C target were commonly studied for identifying long term mitigation options, for China [15] and India [15,16], for example. Others propose decarbonization pathways through renewable penetration targets for the power sectors such as in France [17] and Greece [18].

Similarly, optimization models are powerful decision support tools for addressing energy policies or project developments that can potentially maintain or improve energy security in a given region. In the United States for instance, the energy security and climate change issues associated with the boom of the shale gas industry have been studied using a MARKAL model [19]. The complex trade-offs between climate change and energy security policies have also been analyzed for the European Union using a TIMES model [20]. Other studies look at the impacts of reducing fuel imports on the diversification of supply, costs and GHG emissions such as in Pakistan [21] and Ireland [22]. However, the conclusions of these studies are hardly duplicable between regions as energy security is affected differently depending on the location and composition of the energy system. This is particularly true for the Province of Quebec with a unique energy system characterized by an almost carbon-free electricity sector.

2.2 The NATEM model

NATEM offers a comprehensive representation of the energy system of each of the 13 Canadian provincial and territorial jurisdictions (Figure 1). It also models inter-jurisdictional and international flows of energy and material commodities. The model is calibrated to a 2011 base year [23,24,25] and covers 40 years up to 2050 through nine time periods and 16 annual time slices. The database (described in [7]) includes more than 4,500 specific technologies and 475 commodities in each province and territory. All costs are in 2011 Canadian dollars ($) and the global annual discount rate has been set to 5%.

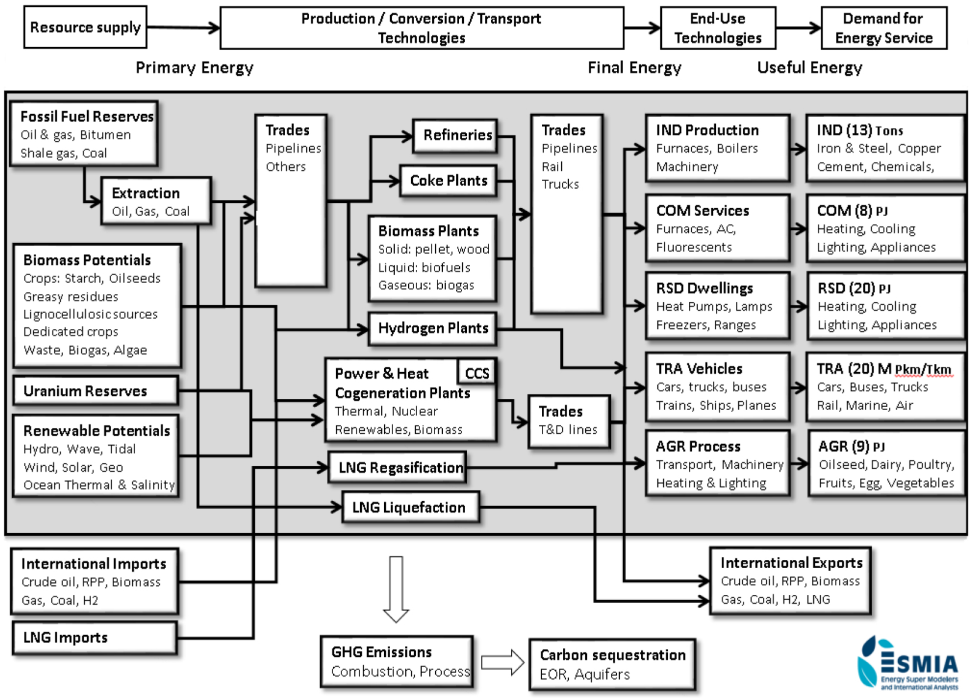

Figure 1: Simplified representation of the reference energy system

3 Scenarios and assumptions

The scenario definition allows assessing the techno-economic impact of meeting (or not) the GHG reduction targets depending on the possibility of buying emission credits on a North American carbon market and the development of hydrocarbons on Anticosti Island. The six scenarios are as follows:

- REF NH: The main reference scenario (REF), representing a business as usual scenario, without GHG targets and without the exploitation of hydrocarbons on Anticosti Island (NH stands for No Hydrocarbon).
- REF WH: An alternative reference scenario (REF), without GHG targets, but with the exploitation of hydrocarbons on Anticosti Island (WH stands for With Hydrocarbons).
- GHG NH R1: A GHG reduction scenario, without the exploitation of hydrocarbons on Anticosti Island (NH) and without access to the North American carbon market (R1).
- GHG NH R2: A GHG reduction scenario, without the exploitation of hydrocarbons on Anticosti Island (NH) and with access to the North American carbon market (R2); a fraction of the reduction is done outside Quebec through carbon credit purchase.
- GHG WH R1: A GHG reduction scenario, with the exploitation of hydrocarbons on Anticosti Island (WH) and without access to the North American carbon market (R1).
- GHG WH R2: A GHG reduction scenario, with the exploitation of hydrocarbons on Anticosti Island (WH) and with access to the North American carbon market (R2); a fraction of the reduction is done outside Quebec through carbon credit purchase.

In addition, we carried out sensitivity analysis to explore behavioral changes within society, i.e. beyond what the current version of the model can handle endogenously. Three additional variants are explored for the hydrocarbon scenarios with a significant reduction to energy service demands in specific sectors. These new scenarios are labeled: REF WH*, GHG WH R1*, and GHG WH R2*.

3.1 Reference scenarios

In reference scenarios, demands for energy services are projected from the 2011 base year through 2050 using a coherent set of socio-economic and sector-specific drivers provided by the Canadian Energy System Simulator (CanESS) model [7,26]. The CanESS model is calibrated with historical data from the Canadian Socio-Economic Information System (CANSIM) for the period 1978 to 2010, as well as projections of the National Energy Board [27]. The main background assumptions are: i) a GDP that is expected to more than double between 2010 and 2050, from 1,461 to 3,080 Billion Canadian dollars; ii) an average population growth rate of 0.98% for the 2010-2035 period and 0.63% beyond 2035; and iii) an average GDP per capita growth rate of 1.86% (2010-2035) and 1.31% beyond 2035. Moreover, reference scenarios include existing policies such as: the 2013-2020 Action Plan on Climate Change [28], the Transport Electrification Action Plan [29] aiming to decrease 66 million liters of consumed fuel in Quebec, and the existing domestic carbon market whose floor price is set to increase by 5% per year (from $9.9 per tonne in 2012 to $66.0 per tonne in 2050). The other reference scenario (REF WH) is based on the same assumptions, but includes the exploitation to its full potential of hydrocarbons on Anticosti Island (see section 3.3 for more details).

3.2 Scenarios with GHG reduction targets

The NATEM-Canada model covers GHG emissions from fuel combustion and fugitive sources in the energy sector, accounting for 66% of all GHG emissions in Canada in 1990 (58.6 Mt CO_2-eq) and 69% in 2013 (56.3 Mt CO_2-eq) [30]. The current version of the model excludes emissions from industrial processes, agriculture (other than from combustion of energy) and waste. Reduction targets are applied to the GHG emissions from the energy sector and we assume that non-energy sectors could achieve the same reduction rate, which is uncertain. The analysis is carried out for two sets of GHG targets, without (R1) and with (R2) access to the North American carbon market (Table 1); the amount of emission rights purchased outside Quebec is set exogenously following assumptions developed by the Quebec Ministry of Environment (MDDELCC) [4].

Table 1: GHG emission reduction targets for the energy sector

Scenario	R1 – Without access to the North American carbon market		R2 – With access to the North American carbon market	
Target	**Reduction under 1990 levels**	**Target in Mt**	**Reduction under 1990 levels**	**Target in Mt**
2020	20.0%	46.8	14.8%	49.9
2030	37.5%	36.6	25.9%	43.4
2050	80.0%	11.7	68.4%	18.5

3.3 Scenarios with exploitation of hydrocarbons

These scenarios assume that the Government of Quebec will let the oil industry exploit hydrocarbons on Anticosti Island to their full potential (as given in Figure 2), no matter GHG emission reduction targets it may want to reach. Oil and natural gas production profiles follow assumptions from the Quebec Ministry of Finance [31]. The production on Anticosti Island would begin in 2020 to reach its maximum level between 2049 and 2069, and declines rapidly thereafter. The hydrocarbons are composed of oil at 22.5% and gas at 77.5%. Regarding natural gas transport to final markets, two options are considered in NATEM [31,32,33]: i) the use of a gas pipeline connected to the continental grid with processing facilities on Anticosti for domestic consumption or exports, and ii) the use of a factory ship with liquefaction facilities for international exports of liquefied natural gas. The model will select the optimal transport option based on costs, energy uses and GHG emissions.

Further details are provided in Appendix A.

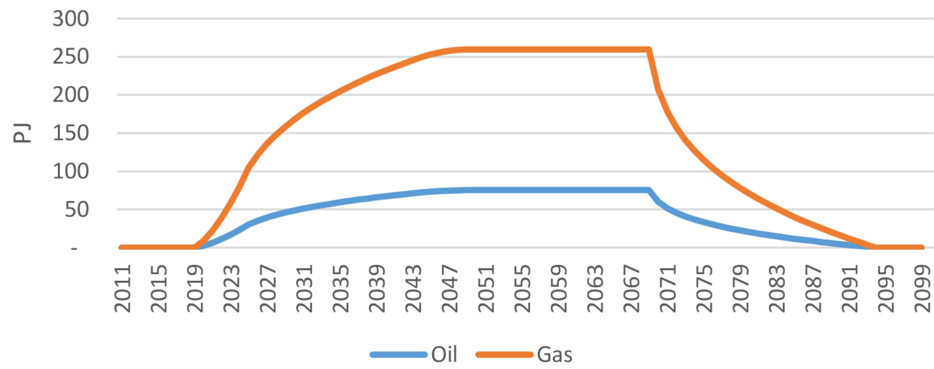

Figure 2: Production profile of hydrocarbons on Anticosti Island

3.4 Scenarios with reduced energy service demands

While the model provides an endogenous response of energy service demands to price signals in policy scenarios, it does not optimize fundamental changes in the structure of these demands such as a major transition from individual vehicles to public transit. The role of reduced demands in the context of ambitious GHG reduction is however important. As a sensitivity analysis, the hydrocarbon scenarios are modeled with a different set of exogenous demands for transport, residential and commercial sectors by 2050, to reflect a sober energy future. The following highlights these changes:

- Freight transportation: A 50% decrease for heavy trucks with a partial transfer to smaller trucks (that can be electrified) and a global 25% decrease in the trucking industry overall.
- Passenger transportation: A decrease for personal vehicles traveling on short distance (44%) and on long distance (35%), as well as for light trucks (22%), that is compensated by a 2.5-time increase in the demand for urban buses and subways, a 2-time increase for school buses and a 1.5-time increase for trains.
- Commercial sector: A 29% decrease for all energy service demands, except for public lighting (20%).
- Residential sector: A decrease varying between 30% and 47% for air cooling depending on the building type, between 11% and 28% for water heating and between 1% and 17% for space heating. For appliances, the demand is reduced by 8% to 32%

More details are provided in Appendix B.

4 Results

In this section, we present the optimal solutions computed by the NATEM model for Quebec.

4.1 Effects of GHG reduction targets

In a first step, we present consequences of introducing limits on GHG emissions in a context without hydrocarbon extraction in Anticosti.

4.1.1 GHG emissions

In the REF NH scenario, GHG emissions increase by 22% between 2015 and 2050. Achieving GHG targets without the North American carbon market implies emission reductions of 26%, 43%, and 84% in 2020, 2030, and 2050, respectively (GHG NH R1). With access to the carbon market (GHG NH R2), these reductions are 21%, 32% and 74% in 2020, 2030, and 2050, respectively. The breakdown of emissions by sector (Figure 3) shows that the transportation sector is the largest contributor with more than half of the total GHG emissions over the horizon, while industrial emissions account for another 30%. The former is responsible for 22% of the increase in emissions between 2015 and 2050. Reductions then mostly stem from the transport sector where GHG emissions decrease from 36.4 Mt CO_2-eq to 2.0 Mt CO_2-eq and to 7.4 Mt CO_2-eq in 2050 for GHG NH R1 and GHG NH R2, respectively (Figure 3 and Figure 4). Given the limited availability of reduction options in the industrial sector, industrial GHG emissions account for the majority of emissions by 2050, with 70% and 46% of the total, respectively.

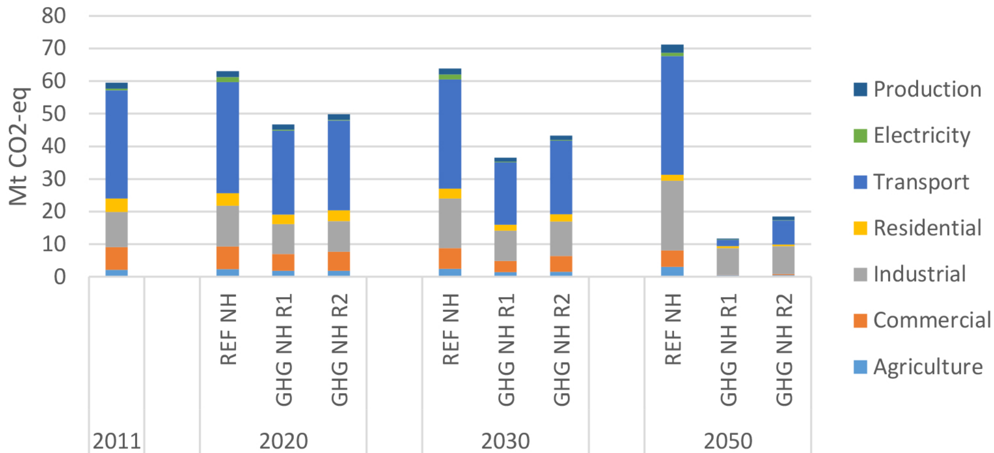

Figure 3: Breakdown of GHG emissions by sector

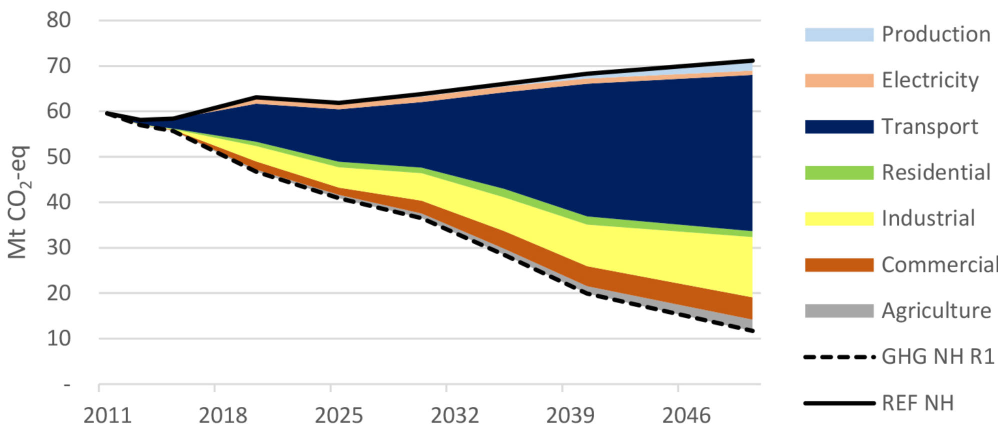

Figure 4: Breakdown of emission reductions by sector in the GHG NH R1 scenario

4.1.2 Final energy consumption

Figure 5 illustrates the final energy consumption by type. In the REF NH scenario, final energy demand is expected to increase by 20% by 2050 (compared to 2015). Society continues to consume petroleum products and electricity, accounting for 39% and 45% of the total consumption by 2050, respectively. Electricity growth accounts for three quarters of the additional demand between 2015 and 2050. GHG emission reduction scenarios limit final energy consumption; it should not rise by more than 8% (GHG NH R1) to 12% (GHG NH R2) between 2015 and 2050. Significant transitions in the energy system are then observed, such as: i) an endogenous reduction in energy service demands under the effects of price elasticity, in particular for air, marine and heavy freight transport (up to 18% without access to the North American carbon market and 10% with access); ii) energy efficiency improvements in all sectors by replacing existing technologies with improved versions or newer technologies; iii) high electricity penetration in all sectors (67% and 63% respectively of the total consumption in 2050 for scenarios R1 and R2) to the detriment of oil (4% and 8% respectively); and iv) a larger share of biomass in 2050, reaching 23%-24% comparatively to 5% in the reference scenario.

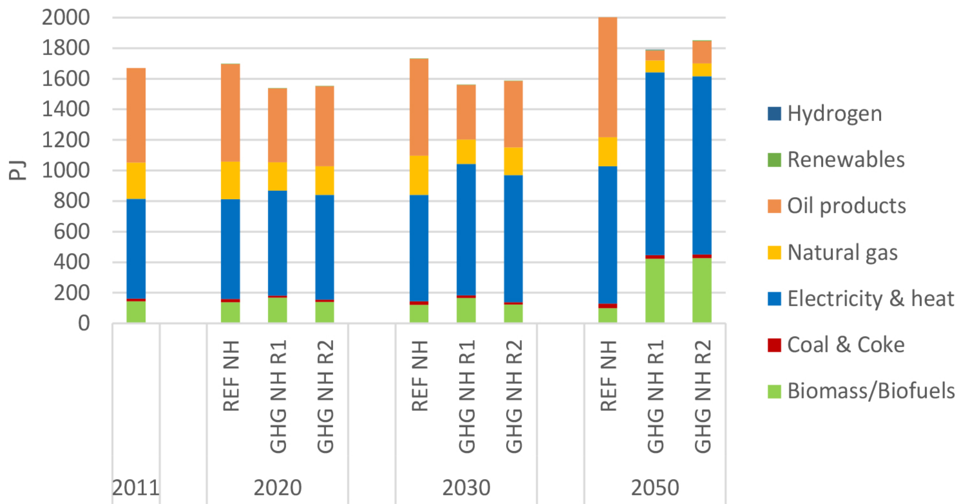

Figure 5: Final energy consumption by type

Important changes occur in the transport sector (Figure 6). In the REF NH scenario, the sector remains dependent on gasoline and diesel: 42% and 44% respectively of total consumption by 2050. The mild increase in energy demand before 2030 is due to the effects of existing transportation policies (CAFE standards, electrification). Electricity consumption represents less than 1% of the total over the entire horizon. However, this consumption reaches 3 PJ by 2020, which represents approximately 80 million liters of avoided gasoline and 20% more than the objective of the *Transport Electrification Action Plan* [29]. In GHG reduction scenarios, we observe a substantial decrease in the total amount of energy consumed in 2050 (32% for the GHG NH R1 scenario and 22% for the GHG NH R2 scenario) due to the replacement of internal combustion engines by electric motors for passenger transportation which are at least three times more efficient. As for freight transportation, heavy freight especially, diesel is predominantly replaced with biofuels of first and second generations (third generation biofuels are not included in the model due to lack of reliable data). Hydrogen is not part of the optimal energy mix given its high cost – particularly in the development of its supply chain.

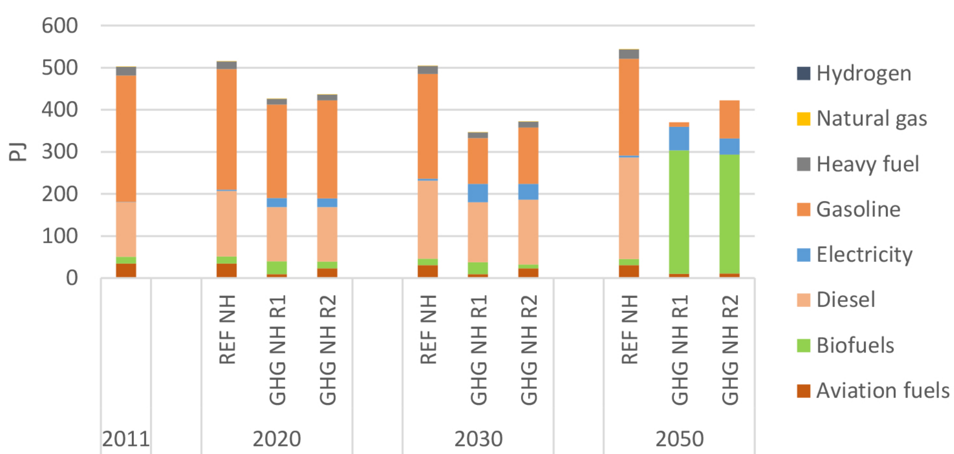

Figure 6: Final energy consumption by type in the transport sector

Figure 7 shows the evolution of energy consumption by type in the residential, commercial and agricultural sectors. While electricity already accounts for a large proportion of the mix in the REF NH scenario with a share increasing to 72% of total consumption in 2050, this proportion reaches 86%–87% in GHG reduction scenarios. Solid biomass and liquid biofuels also meet a fraction of the space heating requirements and commercial vehicle fleets (transport activities in the service sector).

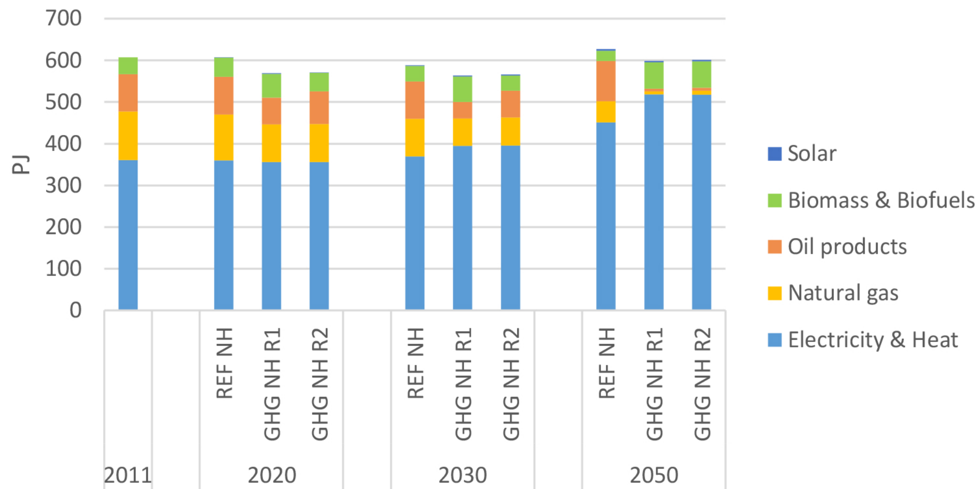

Figure 7: Final energy consumption by type in the residential, commercial and agriculture sectors

Figure 8 shows the evolution of energy consumption by type in the industrial sector. Again, electrification represents the main change. While electricity fills 53% of the industrial needs in the REF NH scenario on average, this proportion reaches 74% and 73% in 2050 under GHG reduction scenarios to the detriment of natural gas and petroleum products. Other reduction options are: the projected demand decline in the pulp and paper industry, energy efficiency gains in energy-intensive industries (aluminum production, chemicals, iron and steel), endogenous demand reductions in other sectors (other manufacturing, other mining and other industries). Energy efficiency gains are related both to the replacement of existing technologies with more efficient versions and to the increase in metal recycling, which requires less energy. Gains can reach 1.3% per year on average over the 2011–2050 period for aluminum production and up to 1.4% per year on average for iron and steel production. The use of biomass as an alternative to coal in the cement and copper industries is limited due to the competition for other uses such as the massive production of second-generation biofuels. However, with the recent Canadian regulation on coal-related emissions, coal should either be replaced by a less polluting source or combined with a CCS option (not available for the industrial sector in the current version of NATEM).

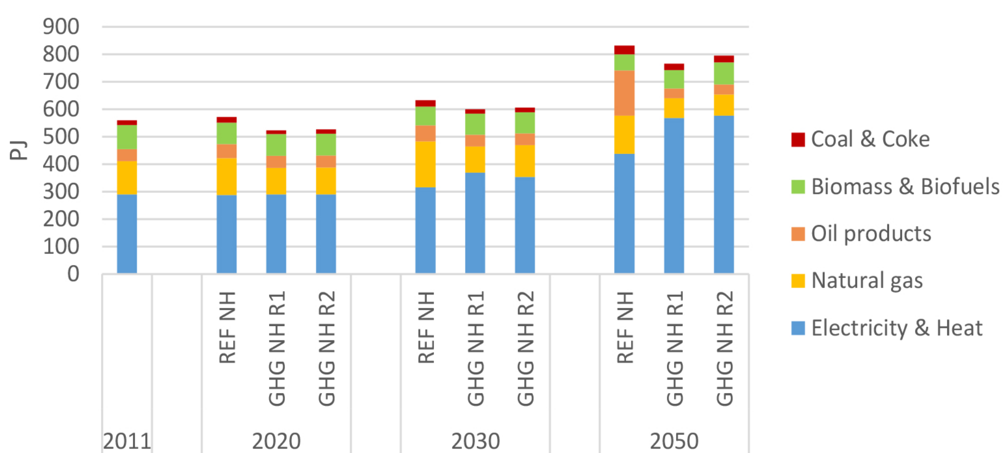

Figure 8: Final energy consumption by type in the industrial sector

4.1.3 Primary energy production

To meet this energy demand, primary energy production in Quebec is strongly dominated by the development of hydroelectricity and by using a large amount of the biomass feedstock (Figure 9). Results show the positive consequences in developing its own clean energy sources and reducing its imports of GHG intensive fuel. The development of intermittent renewable energies, such as wind and solar, remains marginal.

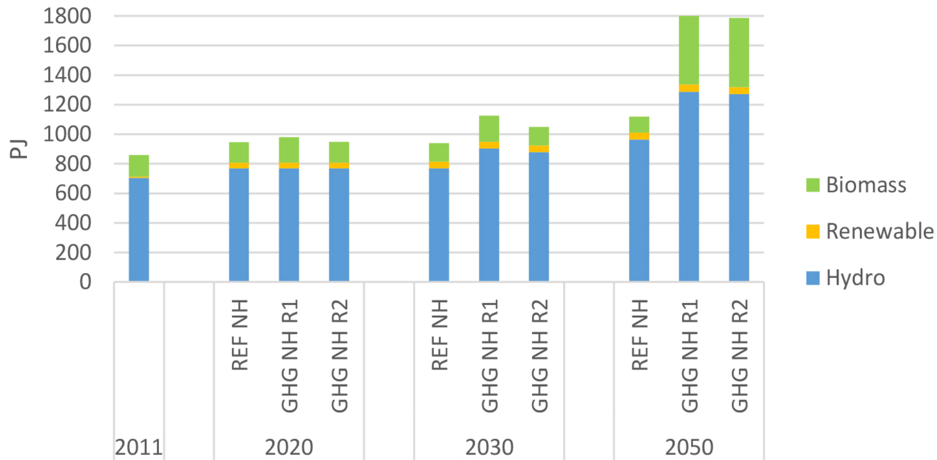

Figure 9: Primary energy production by type

The technical potential for hydroelectric generation capacity is estimated at 81.6 GW in Quebec [34], i.e. almost the double of the current installed capacity (approximately 39 GW). The hydraulic resource represents a major asset in meeting the growing demand for electricity, with 52 GW of installed capacity in 2050 in the REF NH scenario. Additional investments are therefore required for 3.1 GW of additional capacity in 2040 and another 6.7 GW in 2050. In GHG reduction scenarios, 27.7 GW and 26.5 GW of additional capacity would be required in 2050 to meet the demands and GHG reduction targets for a total of 70 GW and 69 GW, respectively; see Figure 10. In addition to projects under construction or approved already included in all scenarios, the model is free to invest in new hydroelectric capacities at an average capital cost of \$ 5,486/kW. Investment costs are \$ 2.762/kW for wind energy and \$ 4.472/kW (in 2012) to \$ 1.290/kW (in 2050) for solar energy. However, the development of intermittent renewables is limited by their low capacity factors (about 36% for wind and 13% for solar) and peak contributions (5%) as well as the need for corresponding investments in dependable capacity [7].

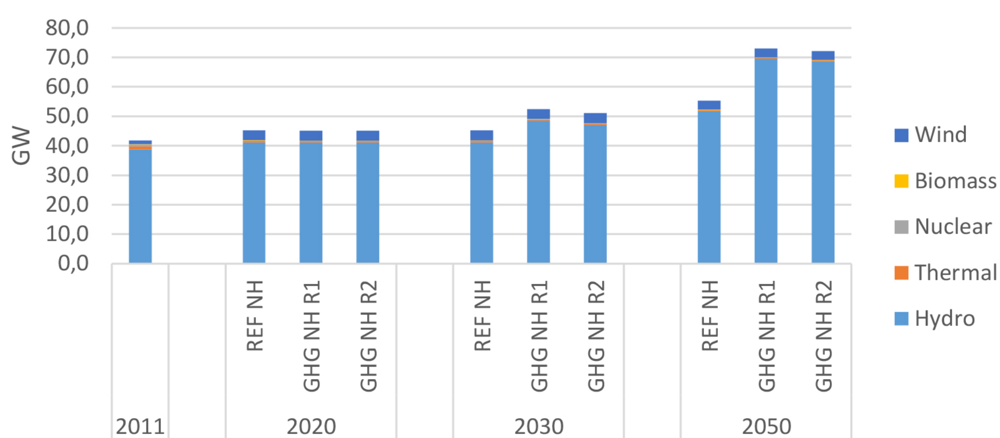

Figure 10: Installed capacity for electricity generation

Total electricity generation increases from 196 TWh in 2011 to 269 TWh in 2050 in the REF NH scenario and to 354 TWh and 349 TWh respectively in the GHG reduction scenarios. While thermal power plays a marginal role in the REF NH scenario, it almost completely phased out in the reduction scenarios. Indeed, electricity consumption ranges from 194 TWh in 2011 to 260 TWh in 2050 in the REF NH scenario, and to 340 TWh and 344 TWh respectively in the reduction scenarios (Figure 11). Additional electricity needs come from all end-use sectors, and from the energy production and transformation sectors (biofuels, hydrogen, petroleum refining. . .).

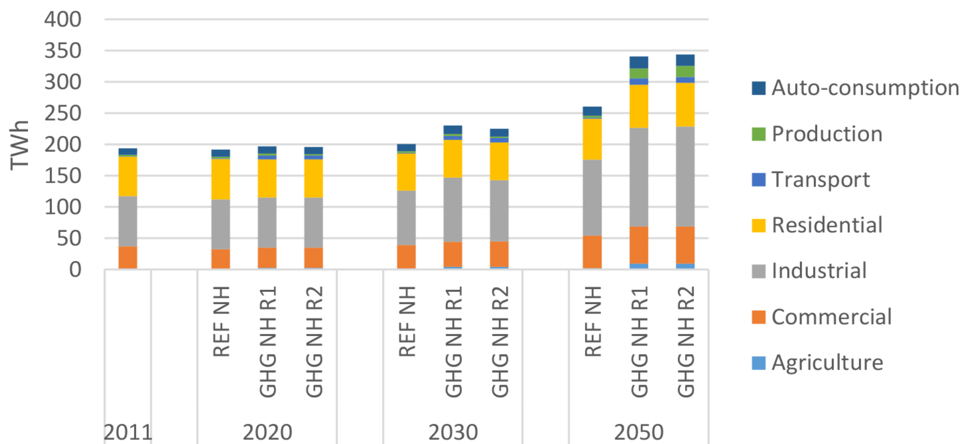

Figure 11: Electricity use by sector

Biomass also plays a major role for second-generation biofuel production in reduction scenarios, mainly after 2030, where biofuels account for 63% and 61% of the total bioenergy in 2050 (Figure 12). These biofuels include cellulosic ethanol, biojet, and especially synthetic diesel from the Fischer-Tropsch process. The different types of bioenergy also play an important role in achieving the targets in all sectors, but especially for freight transportation.

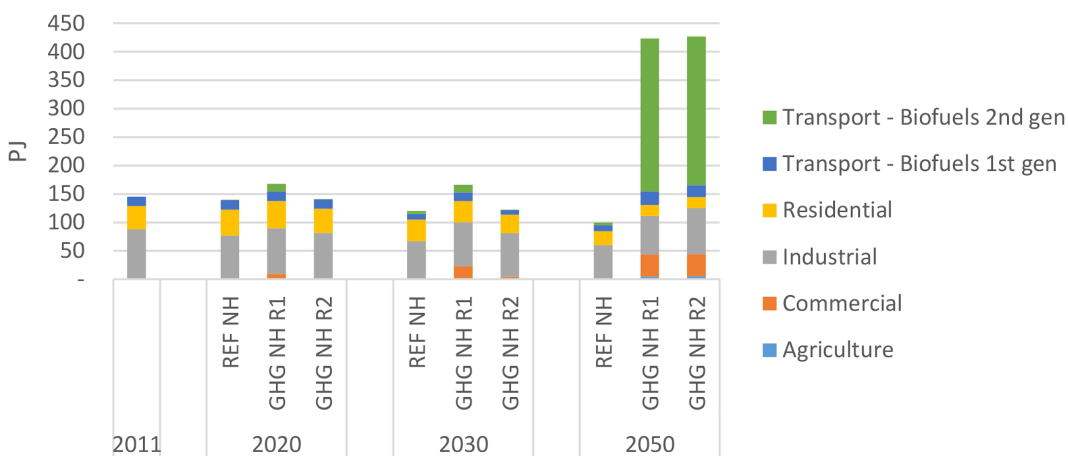

Figure 12: Bioenergy use by sector

The amount of feedstocks coming from agricultural crops for first-generation biofuel production remains limited by the availability of agricultural land and the need for food and feed. These feedstocks allow producing up to 20.0 PJ of biodiesel and 11.2 PJ of ethanol, a maximum achieved in 2050 under the two GHG reduction scenarios. However, a more appreciable amount of forest biomass is available for second-generation biofuel production, space heating, and electricity generation [35] with 174 PJ coming from harvesting activities and 416 PJ from unharvested quantities.

4.1.4 Energy trade

Quebec imports all the crude oil for its two refineries (Figure 13). While most of the imports came from international markets in 2015, they are gradually being replaced with synthetic oil from Alberta (Canada) given the lower price for oil sands. An important fraction of Canadian oil is redirected to New Brunswick where the largest Canadian refinery is located (Figure 14). However, the activity of both Quebec refineries is decreasing to achieve the reduction targets, especially when there is no access to the North American carbon market. Slightly more petroleum products are imported as this is generally less expensive than to pay for the reduction or compensation of emissions from refining activities. Natural gas comes from Alberta (Canada) through existing pipelines; volumes remain stable over time and across scenarios. A greater amount of natural gas, however, could come from the United States with the development of shale gas in North Dakota.

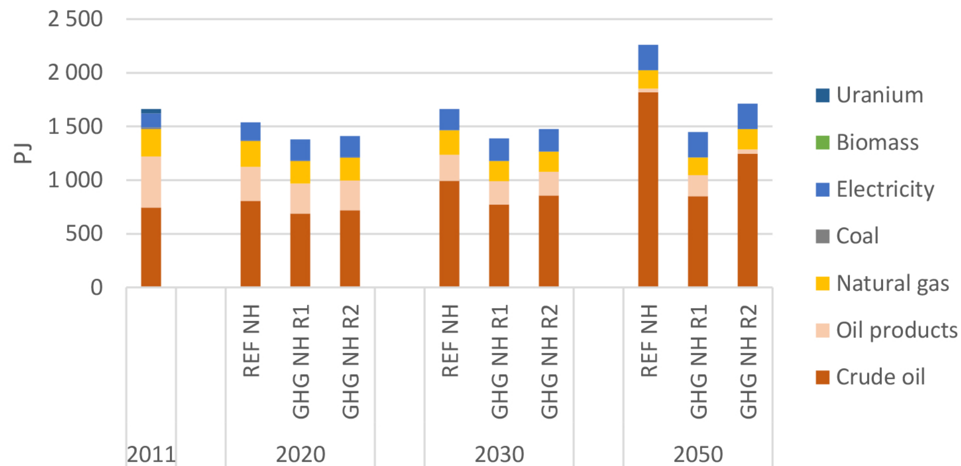

Figure 13: Imports to Canadian and international markets

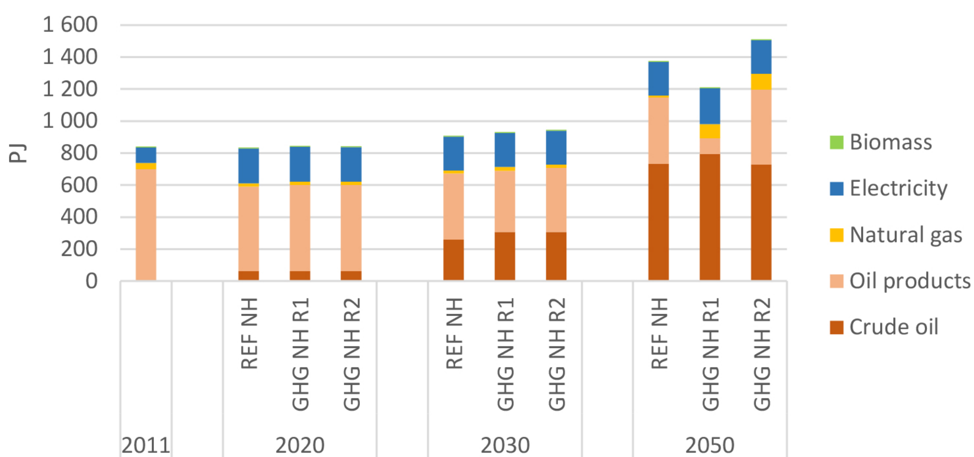

Figure 14: Exports to Canadian and international markets

Exports are predominantly composed of the Albertan crude oil to New Brunswick (Figure 14). These exports increase over time as oil prices rise in international markets. In a GHG reduction context, more natural gas is sent to the United States as domestic needs are decreasing. In the reduction scenario without access to the North American carbon market (GHG NH R1), the decline in petroleum product exports reflects the additional efforts required by the refining sector to achieve more stringent targets.

Table 2: Breakdown of GHG emissions by sector in 2050 with and without hydrocarbon exploitation

Mt CO_2-eq	REF NH	REF WH	GHG NH R1	GHG WH R1	GHG NH R2	GHG WH R2
Agriculture	3.00	3.00	0.49	0.49	0.50	0.49
Commercial	5.09	5.11	0.16	0.16	0.29	0.19
Industrial	21.39	21.38	8.16	8.01	8.59	8.42
Residential	1.83	2.04	0.54	0.53	0.57	0.54
Transport	36.38	36.41	1.97	1.49	7.38	6.28
Electricity	1.04	2.30	0.09	0.09	0.09	0.09
Production	2.45	4.60	0.26	0.41	1.07	1.91
Fugitive sources	-	0.68	-	0.49	-	0.54
Total	71.18	75.50	11.68	11.68	18.47	18.47

4.2 Effects of hydrocarbon exploitation

In a second step, we assess the impacts of hydrocarbon exploitation on GHG emissions and the energy system in both reference and reduction scenarios.

With hydrocarbon development, GHG emissions in the new reference scenario (REF WH) is slightly higher (by 0.5 Mt in 2020 and 4.3 Mt in 2050) than in the original reference scenario (REF NH): emission grows (from 2015 levels) by 9% in 2025 and 29% in 2050 (Figure 15). Achieving the same targets implies thus a slightly greater reduction in GHG emissions when considering the new reference trajectory; recalling that we assume the Government of Quebec let the oil industry exploit hydrocarbons to their full potential, despite its climate policy.

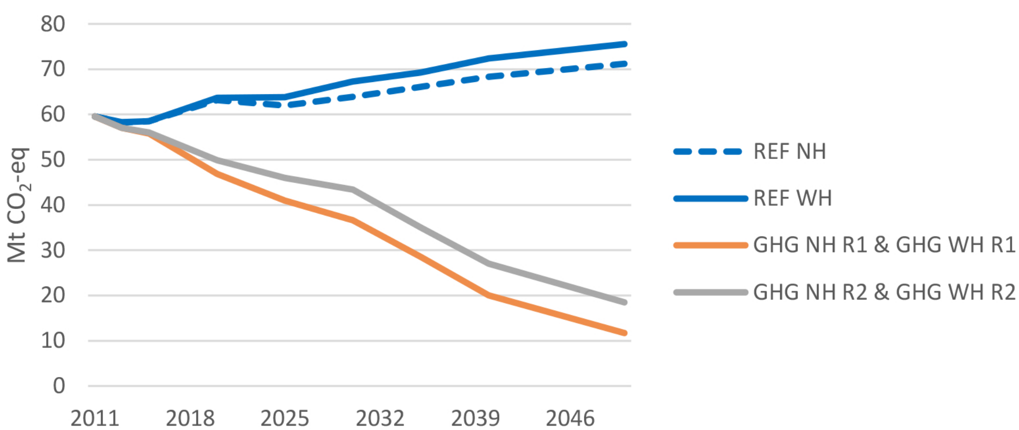

Figure 15: Total GHG emissions with and without hydrocarbon exploitation

The main difference regarding the breakdown of emissions by sector in both reference scenarios in 2050 (Table 2) relates to the additional emissions associated with the development of hydrocarbons on Anticosti Island (REF WH compared with REF NH), namely combustion and fugitive emissions from the energy production sector. A greater consumption of natural gas for electricity generation and residential heating is also worth mentioning; the development of hydrocarbons decreases natural gas prices resulting in a higher demand. However, additional reductions must be made in other sectors to achieve the same GHG targets in the reduction scenarios.

The development of hydrocarbons on Anticosti Island has very little impact on the energy mix and similar transitions to meet the GHG reduction targets are observed. Given the greater pressure placed on the energy system in this context, however, an additional endogenous 2% reduction of energy service demands is observed for air and marine transport. Oil and natural gas are entirely exported to international markets (Figure 16). Oil is not refined in Quebec as the price of unconventional oil is lower. For natural gas, demand is relatively low with ambitious GHG reduction targets. Exportation of liquefied natural gas to international markets with a factory ship is selected as the optimal solution in the REF WH scenario. However, this option is replaced with the export of natural gas by pipeline in the reduction scenarios, despite its higher costs (GHG WH R1 and GHG WH R2). Natural gas liquefaction and transport by ship involve a greater fossil fuel consumption than the gas pipeline option leading to more GHG emissions.

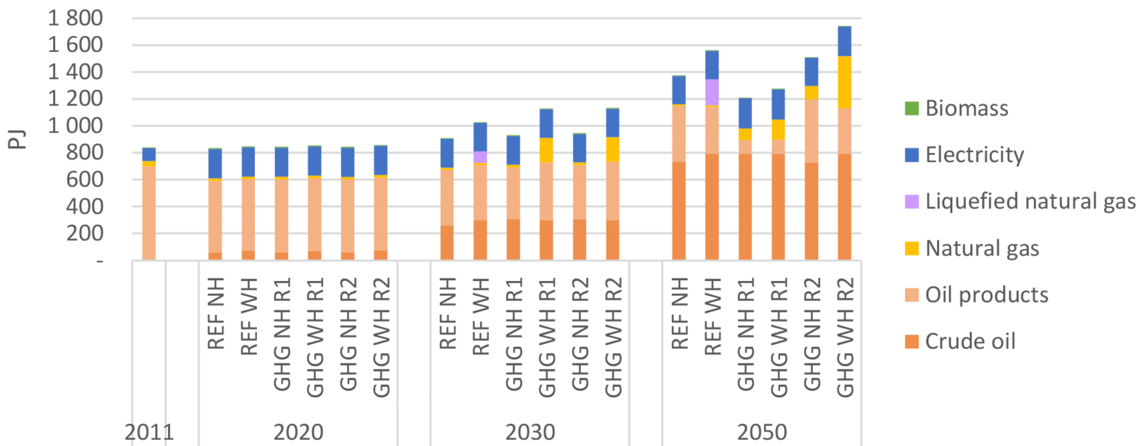

Figure 16: Energy exports with and without hydrocarbon exploitation

4.3 Effects of reduced energy service demands

In a third step, we analyze the effects of reducing energy service demands on the evolution of the energy system when the exploitation of hydrocarbons is allowed. A significant reduction in GHG emissions takes place in the new reference scenario with reduced service demands (REF WH*); see Figure 17. Achieving the same reduction targets implies thus smaller emission reductions when considering the new reference trajectory: 24%, 42%, and 83% in 2020, 2030, and 2050 without access to the North American carbon market (GHG WH R1*) compared to 26%, 46%, and 84% in 2020, 2030, and 2050 originally (GHG WH R1). In the transport sector, the gap is particularly significant as emissions reach 31.8 Mt CO_2-eq in 2050 rather than 36.4 Mt CO_2-eq originally (Table 3).

The main difference with the original scenarios is the decrease of additional electricity requirements to substitute for fossil fuels toward 2050 (Figure 18). Consequently, there is a decrease of 7.7 GW and 7.9 GW in electricity generation capacity for scenarios GHG WH R1* and GHG WH R2*, respectively, compared to the original scenarios. In addition, the amount of biomass is reduced by 5% due to the decrease in heavy freight transportation. A lower demand for petroleum products also results in a decrease in oil imports from Western Canada and in refining operations. Finally, the endogenous reduction of energy service demands under the effects of price elasticity is slightly less important for reaching the same GHG targets.

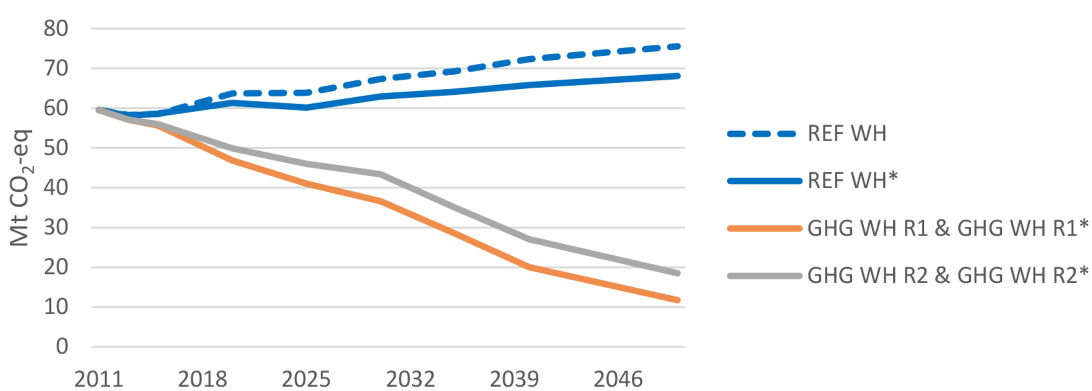

Figure 17: Total GHG emissions with and without reduced energy service demands

Table 3: Breakdown of GHG emissions by sector in 2050 with and without reduced energy service demands

Mt CO_2-eq	REF WH	REF WH*	GHG WH R1	GHG WH R1*	GHG WH R2	GHG WH R2*
Agriculture	3.00	2.96	0.49	0.50	0.49	0.50
Commercial	5.11	3.61	0.16	0.12	0.19	0.14
Industrial	21.38	21.09	8.01	8.08	8.42	8.41
Residential	2.04	1.28	0.53	0.48	0.54	0.48
Transport	36.41	31.80	1.49	1.51	6.28	6.57
Electricity	2.30	2.01	0.09	0.09	0.09	0.09
Production	4.60	4.59	0.41	0.41	1.91	1.74
Fugitive sources	0.68	0.68	0.49	0.49	0.54	0.54
Total	75.50	68.02	11.68	11.68	18.47	18.47

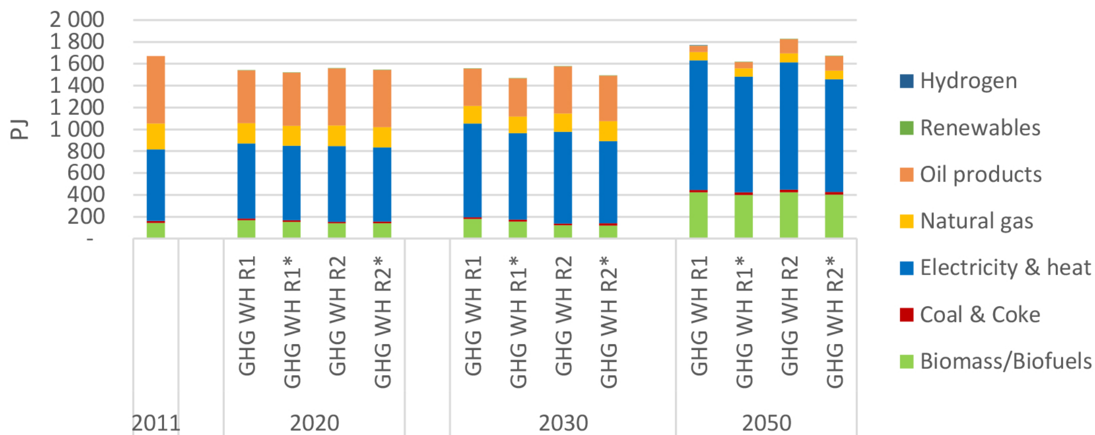

Figure 18: Final energy consumption by type with and without reduced energy service demands

4.4 Mitigation costs

Achieving the 2020 GHG reduction target involves high marginal abatement costs, varying between \$ 464 and \$ 467/tCO_2-eq without access to the North American carbon market (GHG NH R1 and GHG WH R1), and between \$ 333 and \$ 338/tCO_2-eq with access (GHG NH R2 and GHG WH R2). These represent the costs of reducing the last tonne of CO_2-eq to reach the target and exclude the purchasing cost of emission rights. These high costs are due to the large reduction to be achieved in a short period of time, the rapid replacement of technologies that have not yet reached the end of their useful life, and the fact that some reduction options are not yet available (Figure 19).

Marginal abatement costs to meet the 2030 target are lower (\$ 400-428/tCO_2-eq and \$ 279-284/tCO_2-eq, respectively), given the availability of additional reduction options after 2020 (second-generation biofuels, more efficient technologies, etc.). Maintaining hydrocarbon production under the reduction scenarios (GHG WH R1 and GHG WH R2) increases marginal abatement costs, mainly after 2035.

Achieving the 2050 target already involves very high marginal costs without hydrocarbon exploitation (\$ 2,532/tCO_2-eq and \$ 690/tCO_2-eq, respectively). With the exploitation of hydrocarbons, these costs increase further to \$ 3,717/tCO_2-eq and \$ 1,328/tCO_2-eq, respectively. The pressure is greater on end-use sectors, and each additional tonne is reduced at a higher marginal cost. In both cases, the transition from a 19 Mt CO_2-eq target in 2050 (GHG NH R2 and GHG WH R2) to a target of 12 Mt CO_2-eq (GHG NH R1 and GHG WH R1), when there is no access to the North American carbon market, represents a sensitive point from where abatement costs start to increase exponentially due to the lack of reduction options in the industrial sector (based on our current knowledge).

The total net discounted cost for the whole energy system over the next 35 years (2015-2050) increases by 21.3% and 14.1% respectively in the two reduction scenarios without hydrocarbons compared with the corresponding reference scenario; this increase is 22.6% and 14.4% with the hydrocarbons, respectively.

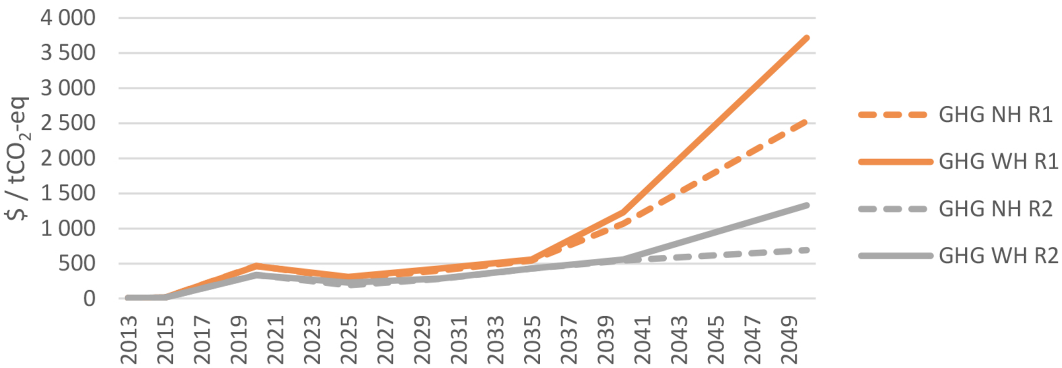

Figure 19: Marginal mitigation costs with and without hydrocarbon exploitation

With reduced energy service demands, the impact on marginal abatement costs occurs mainly in 2050 without access to the North American carbon market (GHG WH R1*), as some very costly reduction measures are avoided (Figure 20). However, high marginal costs in 2050 are rather explained by the absence of sufficient mitigation measures to achieve very low emission levels, in the industrial sector especially, than by the emission reduction efforts from the reference scenario. Indeed, the first reductions can be achieved through inexpensive fuel replacements or technological changes, while the last reductions involve more costly upheavals regardless of the reference emission starting point. Optimizing the amount of emission rights purchased on the North American carbon market simultaneously with the amount of domestic reduction options deployed could lead to different results and potentially lower reduction costs.

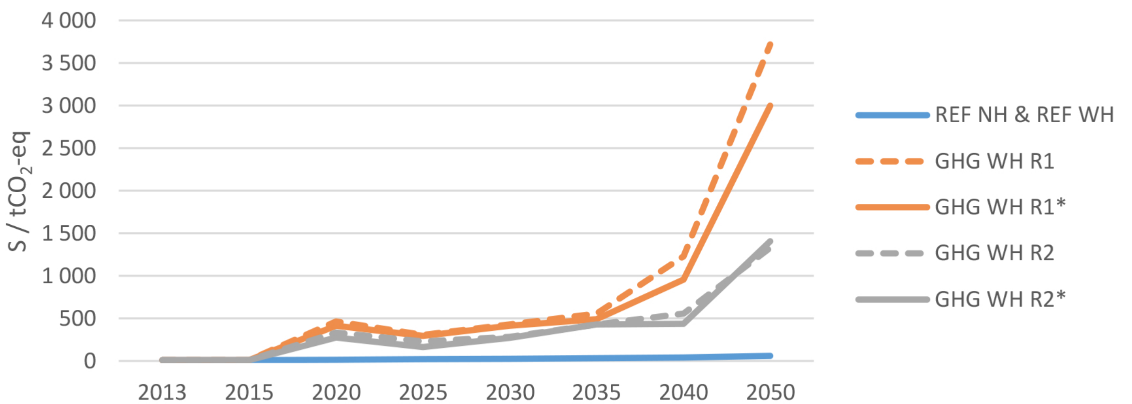

Figure 20: Marginal mitigation costs with and without reduced energy service demands

5 Discussion

5.1 Achieving GHG reductions

Achieving ambitious GHG emission reductions involves significant energy transitions. Electrification of end-uses as well as a strong demand for bioenergy in the transport sector have significant impacts on primary energy production. The production mix is strongly dominated by new hydroelectric generation and by second-generation biofuel production for heavy freight transport (the sectors with the strongest growth by 2050).

However, the hydroelectric developments is optimistic given political and social feasibility constraints and possible long delays in obtaining permits and authorizations. These new capacities add to the Churchill Falls contract renewal (representing 5.2 GW of capacity) with the Province of Newfoundland & Labrador after 2041, and a fraction of the new capacity under development at Muskrat Falls (2.2 GW). Reducing energy service demands through demand side management strategies become critical for limiting new capacity additions. Numerous other factors will influence the future composition of the electricity generation mix in an uncertain manner, such as the evolution of demands for clean electricity from neighboring jurisdictions, transportation cost of electricity from remote areas, cost and availability of small-scale storage options to support a greater penetration of intermittent renewables, etc. However, studying their impacts on the long term electricity mix is beyond the scope of this paper and require additional work in the model.

The development of the biofuel industry also faces certain issues. There are operational constraints and social issues related to a rapid development of an integrated industrial sector that would be necessary to supply, transform and distribute all this biomass for energy production after 2030. Moreover, the analysis assumes that the concept of carbon neutrality remains valid until 2050; whereas it would be more accurate to consider when the carbon debt is repaid before any GHG gains are attributed. Taking into account deeper transitions toward public transport, for example, would reduce the need for alternative fuels, technological substitutions and thereby GHG reduction costs. Our sensitivity analyzes on demand reduction for energy services provide some answers, but optimizing behavioral changes and modal shifts [as in 36] would allow a better assessment of these issues.

5.2 Exploiting new hydrocarbon projects

When exploited (to their full potential), the hydrocarbons of Anticosti Island are exported and have thus virtually no effect on the energy consumption mix in Quebec. However, GHG emissions increase by 29% between 2015 and 2050 (compared with 22% originally) in the reference case. Larger GHG reductions are thus required in the reduction scenarios and the abatement pressure on end-use sectors is stronger. Consequently, the development of hydrocarbons in the context of ambitious climate mitigation policies increases marginal abatement costs after 2030; each additional tonne is reduced at a significantly higher marginal cost.

In this context, access to the North American carbon market is critical since the lack of reduction options in the industrial sectors lead to a sharp increase in marginal abatement costs. Reduced energy service demands do help in decreasing abatement costs in 2050. However, the main cause for high abatement costs is more the absence of additional reduction options to achieve very stringent reduction targets than the reference emission trajectory. Early reductions can indeed be achieved through inexpensive fuel switching or technological changes, while the last reductions require the adoption of costly and disruptive options regardless of the starting point.

It is also important to flag that the exploitation of hydrocarbons for export to international markets will be more or less relevant depending on the willingness of other countries to move toward a green economy. The adoption of reduction targets in neighboring jurisdictions and the rest of the world was not considered in this study.

Finally, one may question the hypothesis that the Government of Quebec will let the oil industry develop new hydrocarbons projects in Quebec despite its ambitious GHG emission reduction targets. During preliminary analysis for this work, we have tested different scenarios where the NATEM model chooses optimally the level of hydrocarbon exploitation, balancing profits generated by the latter exploitation and additional GHG abatement costs. In these scenarios, the exploitation of hydrocarbons starts to decline by 2030-2035 and is abandoned by 2050. From that respect, the full exploitation of hydrocarbons under ambitious GHG reduction targets does not appear socially optimum, as measured by NATEM that maximizes net total surplus (the sum of consumer and producer surpluses).

5.3 Comparison of results

Energy models provide useful insights for the transition toward decarbonized energy systems. They help in particular identify priority actions adapted to a specific regional context. In this section, we compare the results obtained for Quebec with our NATEM model to those obtained for different world regions with energy models using a similar MARKAL/TIMES methodological framework.

While the province of Quebec already benefits from an almost carbon-free electricity sector, reducing GHG emissions from power generation become a clear priority for many regions under low-carbon scenarios. For instance, in the United Kingdom, the electricity sector needs to be decarbonised by at least 80% by 2030, using nuclear power, renewable sources and CCS to achieve cost effectively an ambitious GHG reduction target by 2050 [14]. CCS was also identified as a key option for achieving the lowest mitigation costs in California [12], as well as in China along with nuclear power [15]. For Macedonia, results show that the optimal way for achieving the reduction targets is to substitute coal-based with gas-fired generation [9]. In India, coal-based generation is replaced by a mix of nuclear, renewables, and CCS (including with biomass to get net negative emissions) [16]. The electricity sector is also the greatest contributor to carbon reduction in Taiwan [11] and in the European Union in general [20].

However, given the significant increase in electricity generation for meeting the additional demand in low-carbon scenarios, investments in the electricity sector represent the largest increase in the total system costs even in a region like Quebec: between 40% and 59% depending on the scenarios, compared with 44% for California for instance [12]. Another similar result relates to the role of bioenergy in several studies: while bioenergy appears as a crucial option for decarbonising energy systems, its share in the final mix of each sector varies largely across regions and scenarios due to uncertainties around costs, availability and competition among usages [10,14,15].

In terms of marginal abatement costs, estimations vary widely across studies based on the composition of regional energy systems, scenario definitions, and assumptions. However, most studies looking at very ambitious GHG reduction targets show high marginal abatement costs as in this study for Quebec; for instance: 2,000 US$/ton for a 72% reduction by 2050 relative to 1990 levels in California [12], 1,300 euros/ton for a 95% reduction by 2050 relative to 1990 levels for the energy sector and an overall 80% reduction in Ireland [13].

Finally, the role of hydrocarbons in a transition toward a low-carbon energy system is again dependent on each region-specific situation. In a scenario consistent with meeting a 2^{o}C target for the European Union, [20] showed that natural gas (mostly unconventional) would represent 30% of the total primary energy supply in 2050. Indeed, natural gas is the only remaining fossil fuel used for electricity generation in power plants with CCS. Similarly, the demand for natural gas increases as a result of greater mitigation in India and requires a secure access to new domestic or foreign supply sources [16]. In most regions, climate mitigation policies reduce the import dependence on fossil fuels, but this applies mainly to oil imports while natural gas imports might increase [15,16]. For energy security reasons, limitations on oil imports yield a switch toward natural gas, renewable fuels and electricity in Ireland [22], while targets to reduce energy imports (oil, oil products, coal) by up to 15% in Pakistan would rather favor a significant increase in renewables (24%) together with a decrease in natural gas (14%) [21]. Even in a transition toward a green economy, there might be a role for natural gas in some countries with fewer abatement options than the Province of Quebec.

6 Conclusion

This paper analyzes impacts of developing a new hydrocarbon project (in the Anticosti Island) on meeting ambitious GHG reduction targets (up to -80%) in the Province of Quebec (Canada). Results show that the hydrocarbons would be exported and have virtually no effect on the energy consumption mix in Quebec. However, the exploitation of hydrocarbons would result in an increase in GHG emissions of nearly 7% by 2050 in the reference case. Consequently, additional efforts (which were already significant) will have to be deployed by the other sectors to achieve the long-term GHG targets. Besides, each additional ton of GHG must be reduced at a significantly higher marginal cost.

Achieving such ambitious targets implies major transformations in the energy mix of all economic sectors in Quebec, such as: massive electrification of economic sectors (up to 67% of final energy by 2050); an increase in bioenergy (up to 24% of final energy by 2050); a reduction in final energy consumption ranging from 8% to 12% in 2050 and up to 33% in the transport sector; a reduction in energy service demands in some sectors; the penetration of numerous energy efficiency measures and technological substitutions. Emissions trading on the North American carbon market, however, reduces the pressure on the energy system by offering GHG reduction options at lower costs.

Energy security and GHG reductions are complex issues, and our analysis did not consider all the factors that could influence our results. Many factors were identified as topics for future works, such as: the endogenization of transport modal shifts, the endogenization of trade on the North American carbon market, the adoption of reduction targets in the rest of the world, the integration of more advanced reduction options not commercially available today, etc. Similarly, some limitations are inherent to the current version of the NATEM model and do not provide a full perspective on the problem such as GHGs from other sectors and non-GHG pollutants. Finally, the use of complementary tools alongside NATEM would allow evaluating other environmental impacts (for instance on human health, using e.g. a life cycle analysis), or macroeconomic impacts (for instance on gross domestic product and employment, using e.g. a general equilibrium model).

Appendices

Appendix A More information for scenarios with hydrocarbon exploitation

Energy consumption and GHG emissions. The following assumptions hold:

1. The proportion of natural gas used for natural gas liquefaction is 12%.
2. The proportion of natural gas used for ship propulsion is 1%.
3. The proportion of energy required to produce hydrocarbons is 3%, with about a quarter of diesel for drilling machinery and three quarters of natural gas for compressors. This estimation is obtained by calibration with estimated GHG emissions [32] and appears to be low in comparison with information from experts saying that up to 10% of the natural gas produced could be used for production.
4. The proportion of fuel oil used for oil transport by ship is estimated at 5%.
5. The proportion of natural gas used for gas transport by pipeline is estimated at 4.4%.

GHG emissions associated with the exploitation of hydrocarbons on Anticosti Island are computed from specific coefficients (Table 4) per well in exploration, development and production [31,32]. The number of wells comes from a scenario developed by the Quebec Ministry of Finance [31]. As for fugitive emissions, it is assumed that gas recovery facilities would be operational from the beginning of the exploitation scheduled for 2020, as per [31].

Table 4: GHG emissions coefficients for the exploitation of hydrocarbons

Well type	Well in exploration	Well in development		Well in production	
GHG type	All GHG	CH4	CO2	CH4	CO2
Unit	tCO2eq/well	tCO2eq/well	tCO2eq/well	tCO2eq/well	tCO2eq/well
Total fugitive	82	836		245	
Total flaring	976		615	1	16
Total combustion	2,701	3	856	1	43

Production and transportation costs. Costs have been adapted from [31,32,33]; they exclude energy production or purchase costs as they are computed endogenously by the model (Table 5):

1. Investment costs for production include drilling and platform costs based on the number of wells developed and operated each year. Unlike conventional oil, the extraction costs of shale oil and gas do not increase over time with resource scarcity. Each well allows access to a portion of the deposit and the decrease in production is rapid (approximately 1 year). Therefore, new drilling is done at equivalent costs to maintain production which is primarily a function of the number of wells in operation.

2. Investment costs for transportation include the collection network costs, non-energy services, hydrocarbon processing and other infrastructure. For natural gas, it also includes investment costs for the factory ship or the gas pipeline.
3. Fixed operating costs are the expenditures for operating and restoring the wells and the field.
4. Variable operating costs are the expenditures for production, liquefaction and transportation of hydrocarbons. Production costs include the purchase of non-energy products for processing hydrocarbons.
5. Taxes, permits and royalties are not included to avoid double counting as they are recovered by other system agents. The model accounts for the full costs of the energy system without distinction of various economic agents (government, industry, citizens, etc.).

Table 5: Costs associated with the development of hydrocarbons

Hydrocarbon	**Oil**	**Gas**	
Transportation option		**Factory ship**	**Pipeline**
Unit	**$/GJ/an**	**$/GJ/an**	**$/GJ/an**
Exploration		0.000005	
Investment for production (exc. energy infrastructure costs)		1.435	
Fixed operating costs for production (exc. energy costs)		0.322	
Variable operating costs for production (exc. energy costs)		0.290	
Investment for transport (exc. energy costs)	0.038	0.525	0.711
Variable operating costs for liquefaction (exc. energy costs)		1.270	
Variable operating costs for transport (exc. energy costs)	0.253	1.289	0.387
Total	2.338	5.131	3.145

Commodity prices on international markets. While the price of energy commodities produced and traded within Canadian borders is determined endogenously by the model (at the marginal cost of production), the price of energy commodities imported and exported from/to international markets must be specified exogenously (Table 6).

Table 6: Prices of hydrocarbons exported to international markets

$ CND 2011	**Unit**	**2020**	**2025**	**2030**	**2035**	**2040**	**2050**
Liquefied natural gas	$/mcf	7.49	7.93	9.00	9.09	9.46	10.20
Natural gas	$/mcf	4.41	4.67	5.29	5.35	5.56	6.00
Crude oil	$/bbl	94.79	102.11	119.65	122.68	126.47	128.27

More information can be found in [37,38] about the modeling of the hydrocarbon production sector in Canada.

Appendix B More information for scenarios with reduced energy service demands

Scenarios with reduced energy service demands were developed based on a literature review and discussions with experts. While the model already captures efficiency improvements for meeting a demand using less energy, these scenarios aim to address energy sobriety, by accounting for behavioral changes and reducing energy service demands directly. The main assumptions are:

Freight transport. The 'Physical Internet' concept has led to the development of these scenarios. Starting from the principle that "*the way in which physical objects are supplied and used throughout the world is inefficient and unsustainable economically, environmentally and socially*" [translated from 39], this concept proposes to apply a similar logic to what happened to information with the Internet. The solution is to create a "*global logistic system, open, based on physical, digital and operational interconnectivity through encapsulation, protocols and interfaces*" [translated from 39]. In practice, this entails increased collaboration between players in the logistics sector, which would make it possible, through modular containers and shared transportation networks, to achieve very significant efficiency gains. Both elements were considered (Table 7): i) overall reduction in energy service demands, and ii) modal switch from heavy trucks to light and medium-sized trucks (for which more carbon-free alternative options are available). A shift to the rail mode is also a very attractive option as trains are typically 90% less energy-consuming per ton-km than heavy trucks, but could not be explored due to lack of data.

Table 7: Reduced energy service demands in the freight transportation sector

Service demand	Unit	2015	2050 – REF	2050 – REF*	Comments
Road, Freight, Heavy trucks	Mt-km	42,351	81,822	42,797	About -50% in 2050 compared with the original reference. Portions of this decrease is transferred to smaller trucks.
Road, Freight, Medium trucks	Mt-km	4,086	6,759	13,519	About 2 times in 2050 compared with the original reference. For all truck segments, total service demand in 2050 is decreased by 25%.
Road, Freight, Light trucks	Mt-km	5,119	8,469	16,938	
Rail, Freight	Mt-km	48,855	79,161	79,161	Unchanged
Air, Freight	Mt-km	490	920	920	Unchanged
Marine, Freight	PJ	27	32	32	Unchanged

Passenger transport. For this segment, [40] proposes work axes and objectives to definitely change the way people travel in Quebec. The proposed actions are grouped in three areas: i) land-use planning reform, ii) better management of transport supply and demand, and iii) improved vehicle and fuel performance. The report sets out the following objectives by 2030: i) reduce distance traveled by 20% (limiting the number and length of trips, doubling the modal share of public and active transport, reducing the motorization rate), and ii) improve energy efficiency of vehicles by 50%. The first objective was used to develop the targets for 2050, while applying a logic of 'no increase compared to 2015' for the undocumented segments (Table 8).

Residential and commercial. Fewer references are available for these sectors. An ambitious scenario has, however, been developed for France in 2050 based on energy sobriety, energy efficiency, and use of renewable energies [41]. This scenario generates very significant reductions in energy consumption for most demand segments: -20% to -50% (sometimes -80%) in 2050 compared with 2010. Since the underlying assumptions are difficult to replicate in the Province of Quebec without a deeper analysis, we have used a consistent and a slightly less restrictive rule where all energy service demands are maintained at the 2015 level toward 2050. This translates into the following reduction in 2050 compared with the original reference: commercial (-20% to -29%), residential space heating (-1% to -17%), residential space cooling (-30% to -47%), residential water heating (-11% to -28%), residential appliances (-8% to -41%).

Table 8: Reduced energy service demands in the passenger transportation sector

Service demand	Unit	2015	2050 – REF	2050 – REF*	Comments
Road, Passenger, School buses	Mp-km	6,387	7,193	15,105	About 2 times in 2050 compared with the original reference.
Road, Passenger, Urban buses	Mp-km	3,354	3,782	10,063	About 2.5 times in 2050 compared with 2015.
Road, Passenger, Metros	Mp-km	1,438	1,621	4,313	
Rail, Passenger	Mp-km	196	256	393	About 1.5 times in 2050 compared with 2015.
Road, Passenger, Large cars, Long distance	Mp-km	18,104	27,640	18,104	Same as in 2015 or -35% in 2050 compared with the original reference.
Road, Passenger, Small cars, Long distance	Mp-km	20,925	31,948	20,925	
Road, Passenger, Motos	Mp-km	1,038	1,339	1,038	Same as in 2015 or -22% in 2050 compared with the original reference.
Road, Passenger, Light trucks	Mp-km	39,125	50,482	39,125	
Road, Passenger, Off-road	PJ	23	26	23	Same as in 2015 or -10% in 2050 compared with the original reference.
Road, Passenger, Large cars, Short distance	Mp-km	21,229	26,375	14,861	About -30% compared with 2015 or -44% in 2050 compared with the original reference. There is a greater reduction potential for shorter distances.
Road, Passenger, Small cars, Short distance	Mp-km	24,538	30,486	17,177	
Road, Passenger, Intercity buses	Mp-km	1,434	1,815	1,815	Unchanged
Air, Passenger, Domestic	Mp-km	10,365	11,409	11,409	Unchanged
Air, Passenger, International	Mp-km	11,769	19,259	19,259	Unchanged

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