Les Cahiers du GERAD ISSN: 0711–2440

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G–2017–98

November 2017

La publication de ces rapports de recherche est rendue possible grâce au soutien de HEC Montréal, Polytechnique Montréal, Université McGill, Université du Québec à Montréal, ainsi que du Fonds de recherche du Québec – Nature et technologies.

The publication of these research reports is made possible thanks to the support of HEC Montréal, Polytechnique Montréal, McGill University, Université du Québec à Montréal, as well as the Fonds de recherche du Québec – Nature et technologies.

Dépôt légal – Bibliothèque et Archives nationales du Québec, 2017
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The Canadian contribution to avoiding dangerous climate changes: An analysis of technological options and energy trade

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November 2017
Les Cahiers du GERAD
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Abstract: Canada was a proactive participant in developing the Paris Accord (COP 21; December, 2015), and committed to reduce its greenhouse gas (GHG) emissions by 30% below 2005 levels, by 2030. Canada also presented its Mid-Century Plan at the COP 22 meeting in Marrakech (November, 2016), which also included further reductions in GHG emissions of 70 to 90% below 2005 levels, by 2050.

In response to these very challenging commitments, we have carried out a series of analyses for deriving optimal solutions for progressive GHG mitigation to 2050, for all of Canada, while also reflecting impacts of a rapidly growing economy. These analyses have been carried out with the aid of the NATEM energy optimization model.

In this chapter, we describe the results of four separate sets of analyses, including reductions of up to 80% in GHG emissions from the energy sector, relative to 1990. The results of this study serve to demonstrate the magnitude, complexity and high cost for Canada for achieving the very ambitious GHG mitigation targets agreed at the COP 21 and 22 meetings. The results also serve to demonstrate the merits of using a comprehensive optimization model for demonstrating the overall mix of GHG mitigation options for achieving national mitigation at minimum cost for all of Canada.

1 Introduction

Canada participated proactively at the Paris Conference of the Parties (COP21) that led to the signing of the Paris Accord (UNFCCC 2015) on December 12, 2015. As part of this Accord, Canada committed to reduce its GHG emissions by 30% below 2005 levels, by 2030. The underlying goal of this Accord was to define a first step towards keeping global temperature rise "*well below*" 2 degrees Celsius (^{o}C) above pre-industrial levels. On October 3, 2016, the Government of Canada formally ratified the Paris Accord, which came into force on November 4, 2016. On November 18, 2016, Canada presented its Mid-Century Long-Term Low-Greenhouse Gas Development Strategy at the COP 22 meeting in Marrakech. In this report, Canada further defined its overall strategy for reducing climate change impacts, by committing to also achieving 70 to 90% reductions in GHG emissions by 2050, relative to 2005.

Canada is not a major contributor to the world's GHG emissions (only about 1.6% of the total in 2013). However, at 20.1 tCO2-eq per capita (2013), it is ranked as one of the highest per capita emitters in the world (World Resources Institute 2017). In 2015, total GHG emissions were 722 Mt CO_2-eq., with the energy sector accounting for 81% of this total (Environment Canada 2017). Emissions vary greatly between jurisdiction, with the highest per capita emissions being from jurisdictions with its economies having major dependence on production and delivery of fossil fuels. With its federal structure and based on constitutional allocation of responsibilities, each of the provinces and territories have primary responsibility for planning and development of resources within its jurisdiction, including energy. Following the signing of the Paris Accord by the Government of Canada, Canada's First Ministers issued a joint communique in the Vancouver Declaration, on clean growth and climate change. This communique builds on existing commitments and actions by the Provinces and Territories, as well as the momentum from COP 21, for clean growth and climate change. This commitment includes meeting or exceeding Canada's international emissions targets, and transitioning Canada to a low carbon economy. Some of the provinces, including Quebec, Manitoba and Ontario, have even committed to GHG mitigation targets within their respective jurisdictions, greater than Canada's 30% reduction commitment.(Boothe and Boudreault 2016).

These commitments require special consideration of the energy sector in Canada. The country is endowed with abundant energy resources. It is one of the world's main energy producers, with enormous proven reserves. In 2015, it ranked second in production of uranium (fourth for proven reserves), fourth for production of crude oil (third for proven reserves), fifth for production of natural gas (seventeenth for proven reserves), and twelfth for production of coal (fifteenth for proven reserves) (Natural Energy Canada 2017). However, these resources are not evenly distributed across the country. For example, most of the oil reserves are in Alberta, and the uranium reserves are in Saskatchewan. Because of long-distance transport, it is more cost efficient to import oil from the Middle East into Eastern Canada, while oil is being exported from Western Canada to the United States and the Far East. As a consequence, there is not only extensive trade between Canada and the rest of the world for energy commodities (both export and import); there are also major trade flows between the respective jurisdictions in Canada.

The main objective of this paper is to present results of cost-efficient strategies for Canada for achieving major reductions in GHG emission from the energy sector, consistent with its global obligations. More precisely, we identify several decarbonization pathways for the Canadian energy sector associated with different GHG reduction targets and defining premises. This is carried out primarily with a TIMES model for Canada, which is part of the NATEM (North American TIMES Energy Model) platform (Vaillancourt et al. 2017).

2 Approach

Our approach is based on the application of the NATEM-Canada optimization model. NATEM belongs to the TIMES family of models developed within the Energy Technology Systems Analysis Program (ETSAP) of the International Energy Agency (Loulou et al. 2016). As such, NATEM relies on the concept of a Reference Energy System (RES) that describes energy value chains from primary energy to useful energy.

For the energy supply side, two sectors are distinguished: electricity and heat production on the one hand (including combined heat and power); and supply of all other energy forms (in particular, primary fuels and derivatives from fossil and biomass sources. For energy demand, five sectors are considered: agriculture, commercial, industrial, residential, and transportation. At each point of the value chains, technologies are competing, not only existing ones but also new or improved ones. The model accounts for direct GHG emissions from fuel combustion as well as fugitive emissions from the energy sector. This enables NATEM to capture substitution of energy forms (e.g., switching to biofuels) and energy technologies (e.g., use of renewable power plants instead of fossil-fired facilities) to comply with GHG reduction targets. NATEM is a dynamic linear programming model. The objective is to minimize the net present worth cost of the energy system. The main outputs, in addition to the overall minimum present worth cost, include the selected decision variables and the magnitude of such variables for contributing to overall GHG mitigation for all of Canada. These variables also include transfers of energy commodities between jurisdictions, as well as international imports and exports.

NATEM-Canada models the RES of each of the 13 Canadian provinces and territories, as well as flows of energy and material commodities between these jurisdictions. For reporting purpose, Canada is sometimes divided into two broad regions: Western Canada, including the three prairie provinces, British Columbia and the three Territories; and Eastern Canada including Quebec, Ontario and the Atlantic provinces. The model includes representation of more than 4,500 specific technologies and 475 different commodities. NATEM-Canada is calibrated to a 2011 base year, and represents the 40-year period from 2011 to 2050. Costs are presented in 2011 Canadian dollars, with future costs being discounted at 5% per annum.

3 Scenarios

The results reported herein include four separate GHG mitigation scenarios, with comparison to the results of a reference scenario (REF) representing a business-as-usual case. In the REF, 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 (TEFP, 2016).

The CanESS model was calibrated with historical data from the Canadian Socio-Economic Information System (CANSIM) for the period 1978 to 2010, as well as projections from the National Energy Board (NEB, 2013). The main results include : i) 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, iii) an average GDP per capita growth rate of 1.86% (2010-2035) and 1.31% beyond 2035. The REF is also based on government policies already in place, such as Corporate Average Fuel Economy (CAFE) standards (NHTSA, 2011); federal and provincial regulations on minimum content of biofuels in gasoline (5%) and diesel (2%) (Government of Canada, 2010); coal-fired electricity standards (Environment Canada, 2013); and existing carbon market between Quebec and California through a floor price ranging from $9.9/tonne in 2012 to $24.9/tonne in 2030.

For comparison with this REF scenario, we analyze four separate GHG mitigation scenarios with increasing levels of mitigation efforts for Canada. The first scenario (GHG13) represents the intended national contribution of Canada with a 30% reduction by 2030 from 2005 levels (UNFCCC, 2016a). This target is then assumed to be held constant to 2050. It is noted that 30% reduction by 2030, relative to 2005, is equivalent to 13% reduction, relative to 1990The second scenario (GHG50) has a reduction target of 50% in 2050, compared with 1990 levels. This is a target derived from the MERGE model that allocates reduction efforts to the different world regions to limit global warming by 1.5 ^{o}C. The third scenario (GHG75) has a target reduction of 80% by 2050 from 2005 levels as generally proposed in the Canadian Mid-Century Strategy (Environment and Climate Change Canada, 2016). Compared with 1990 levels, this represents a 75% reduction. The fourth scenarios (GHG80) has a more ambitious reduction target of 80% by 2050, relative to 1990. Although this is a further reduction of only 5%, it serves to demonstrate several limits of what can be achieved with current assumptions.

These limits are applied to GHG emissions from fuel combustion in the energy sector. These emissions represent 71% of total emissions in Canada in 1990 (Environment Canada, 2016). The emission reduction targets and required reductions in 2050 are shown on Table 1.

Table 1: GHG emission reduction targets in Canada

Target	% reduction in 2050 from 1990	Cap in 2050	Absolute reduction in 2050 from the reference scenario
GHG13	- 13 %	378 Mt	- 371 Mt
GHG50	- 50 %	219 Mt	- 530 Mt
GHG75	- 75 %	108 Mt	- 641 Mt
GHG80	- 80 %	87 Mt	- 662 Mt

Special consideration was given to ensuring accurate representation of the electricity sector in the respective jurisdictions, and the potential for increasing electricity trade between jurisdictions. In Canada, each of the 13 jurisdictions is responsible for electricity self-sufficiency. This includes both guaranteed electrical energy and dependable generating capacity for meeting energy demand at all time, including especially during peak demand periods. While most jurisdictions provide guaranteed electricity supply from within its jurisdiction, there are three exceptions in Canada, resulting in reliance on neighboring jurisdictions; the Churchill Falls interconnection with Newfoundland & Labrador supplying Quebec through a contract to 2041; the relatively recent contract between Newfoundland & 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.

We assessed the potential for increasing trade of electrical energy and dependable capacity between neighboring jurisdictions. This included additional investment in high-voltage interconnections. There would be reduced investment in dependable capacity in the receiving jurisdiction and correspondingly increased investment in dependable capacity in the selling jurisdiction. One of the interesting low-cost options for dependable capacity was to add generating capacity at existing and future hydro sites, referred to as the "incremental hydro" option. This option applies for both inter-jurisdictional trade and for complementing electricity generation from intermittent renewable generating sources, which produce little dependable capacity. This option is included in these alternate scenarios for demonstrating the full potential of hydro systems to produce electrical energy and dependable capacity. These analyses were carried out as variants of the four basic Mitigation Scenarios, and are identified respectively with an "a": GHG13a, GHG50a, GHG75a and GHG80a.

4 Results

4.1 GHG emissions

For the REF scenario, combustion related emissions increase by 48% between 2013 and 2050. The breakdown of emissions by sector (Figure 1) shows that the transportation sector accounts for one third of total emissions, caused by a continued reliance on petroleum-based fuels. In 2050, emissions from energy supply (production of fossil fuels) and industries represent, respectively, 22% and 17% of total emissions. GHG emissions increase in all sectors. However, the overall increase (48%) is less rapid than the overall increase in GDP of more than 100%. This reflects the impact of full implementation of all cost efficient energy efficiency and energy conservation measures, including CAFÉ standards in the transportation sector.

Results for the four mitigation scenarios show dramatic changes from the REF scenario. First, the results suggest a fully decarbonized electricity supply by 2030. There is a progressive decarbonization of the other sectors to 2050. The residential and commercial sectors are fully decarbonized by 2050 for the three most stringent mitigation scenarios. The dominant remaining challengers in 2050 are in the transportation, industrial and fossil fuel supply sectors. The challenges for the transportation sector are associated with very high costs of non-fossil fuel options for heavy freight and long-distance transport, limits on availability of biofuels, and limits on electricity storage systems. For the industrial sector, there are limits of availability of proven conversion options for switching from use of fossil fuels. For fossil fuel supply, the limitations are associated with the high implicit GHG mitigation cost for production and delivery of fossil fuels, relative to its value in the global market.

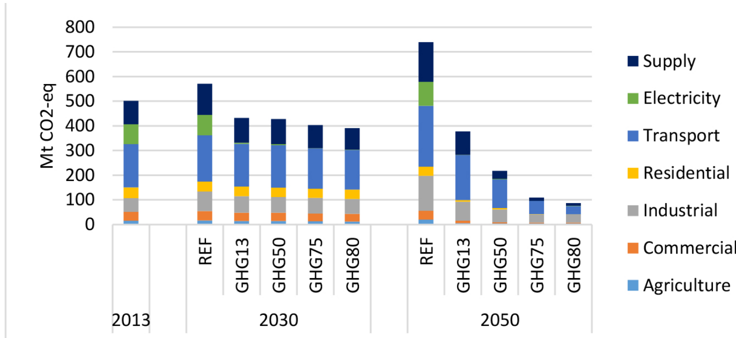

Figure 1: GHG emissions by sector in Canada

4.2 Final energy demand

Final energy consumption by fuel is shown on Figure 2. For the REF scenario, final energy demand is projected to increase by 45% between 2013 and 2050, with half of the additional demand coming from the industrial sector. In 2050, final energy is mainly consumed by industries (35%) and the transport sector (34%). The energy mix continues to be dominated by oil products and electricity in the long term, representing 47% and 26% of total consumption in 2050, respectively.

However, for all mitigation scenarios, there are major transformations in the energy system. These include: i) reductions in demands due to impacts of price elasticities, especially for heavy freight, as well as air and marine transport (up to 18% compared with their projected initial value for 2050); ii) significant energy efficiency improvements through technological substitutions; iii) greater penetration of electricity in all sectors (between 41% and 64% of total consumption in 2050), arising dominantly from reduced use of oil, from 47% in the REF scenario, to as little as 7% in the GHG80 scenario; iv) use of natural gas also reduces, from 18% in the REF scenario, to 6% in the GHG80 scenario; iv) increased use of bioenergy in 2050, from 5% in the REF scenario to 17% in the GHG80 scenario. These transformation trends are generally similar across jurisdictions.

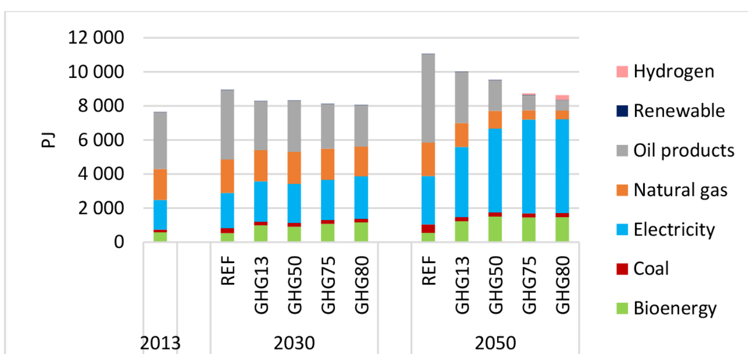

Figure 2: Final energy consumption by type in Canada

Significant transformations occur especially in the transport sector (Figure 3). We observe a gradual and substantial decrease in the total amount of energy consumed in 2050 compared with the REF scenario (i.e. 45% reduction for scenario GHG80). This is due dominantly by replacement of internal combustion engines (ICE) by electric motors for passenger road transportation which are more than three times more efficient in conversion of primary energy to motive power. Electrification represents a central option for + decarbonizing passenger road (cars, school and city buses and light truck), rail transportation (urban and interurban), and light-duty freight vehicles.

As for medium and heavy freight transportation, a portion of conventional diesel fuel is replaced with biofuels (e.g. FT diesel), compressed natural gas and renewable natural gas (included in the bioenergy category). Liquefied natural gas (LNG) is primarily used for marine transportation for replacing heavy fuel oil, also resulting in significant reductions in GHG emissions. Hydrogen is part of the optimal energy mix in 2050 under the most ambitious scenarios (GHG75 and GHG80) only, given the high cost associated with the development of its supply chain. Hydrogen from electrolysis of water provides a role as a reduction option for heavy freight when the amount of biomass feedstock available for biofuel production or other uses is constrained by limitations on overall resource availability.

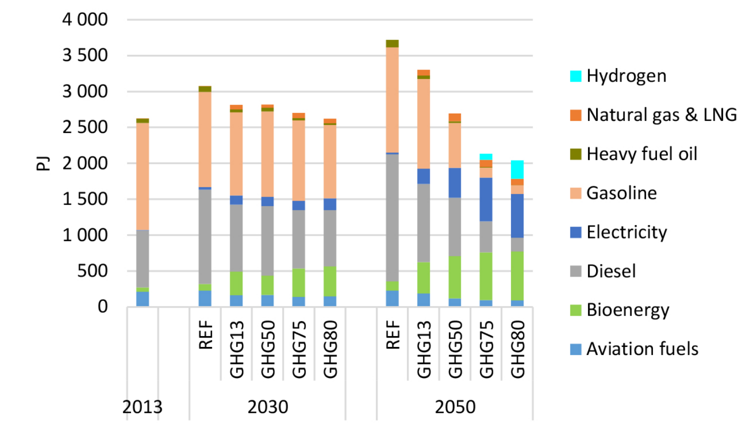

Figure 3: Final energy consumption in the transport sector in Canada

The evolution of energy consumption by type in the residential, commercial and agricultural sectors is shown on Figure 4. While electricity already accounts for a large proportion of the mix by 2050 in the REF scenario (54%), this proportion reaches 86%-87% in scenarios GHG50 to GHG80 as a replacement for oil products and natural gas. In addition, decentralized electricity generation through photovoltaic solar panels replace a significant portion of the electricity coming from the grid: from 35% (GHG13) to 40% (GHG50 to GHG80) of total electricity used in 2050. Decentralized production occurs initially in the commercial sector where costs are slightly lower than in the residential sector. Based on literature review, cost reduction assumptions for solar energy may be optimistic, with 60% decrease projected by 2020, with further 37% reduction projected from 2020 to 2050 (EIA, 2014; NREL, 2013). Energy conservation measures (programmable thermostats, duct sealing, window insulation, etc.) contribute to meeting a portion of the building heating requirements: 21% of total heating demand for the residential sector and 6% for the commercial sector. Solid biomass and renewable natural gas also meet a small portion of space heating requirements. The maximum potential is reached in all scenarios including the REF scenario. Energy conservation is therefore not limited by the costs of measures, but by the maximum potential savings that it is possible to achieve.

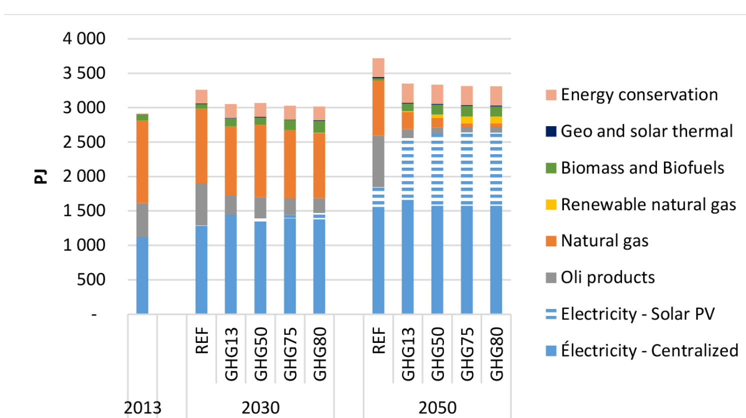

Figure 4: Final energy consumption in the residential, commercial and agriculture sectors in Canada

The evolution of the energy mix in the industrial sector is shown in Fig 5. Again, electrification represents a significant reduction option. While electricity meets 24% of industrial needs in 2050 in the REF scenario, this proportion reaches 56% in the GHG80 scenario. This electrification leads to a decline in oil products and natural gas consumption. In addition, a significant portion of natural gas is replaced with renewable natural gas (biogas) that represents up to 7% of the total consumption in 2050. This proportion of natural gas also includes 2% of LNG, mainly used in the mining sector in remote areas.

The role of biomass varies across time. There is a decrease of biomass consumption in the pulp and paper industry due to projected decline in demand, from 24 Mt in 2011 to 19 Mt in 2050 for the REF scenario, and even more in the GHG mitigation scenarios due to the price elasticity effects (17 Mt in GHG80). This reduction is offset by use of biomass as an alternative to coal in the cement and iron & steel industries in the least stringent scenarios (GHG13 and GHG50). However, by 2050, in the most stringent scenarios (GHG75 and GHG80), the use of biomass for the industrial sector is limited, due to competition for other uses, including massive production of second-generation biofuels.

There are other options for contributing to emission reductions in the industrial sector. There are significant energy efficiency gains in the most energy-intensive industries, including aluminum, chemicals, and iron & steel. There may also be reductions in other industrial sectors; however, reduction options are less well documented and are more difficult to represent in the optimization model. Energy efficiency gains include replacement of existing technologies with more efficient technologies, as well as increasing re-use of materials, including metal recycling. Efficiency gains for the aluminum sector are as high as 2.0% per annum over the period 2013 to 2050. With the recent Canadian regulation on coal-related emissions, coal could either be replaced by a less polluting source or combined with CCS (which has not been represented yet in the current version of the NATEM model). And lastly, a portion of coke used in the iron and steel industries remain in the mix as no option exists in the existing database to replace it.

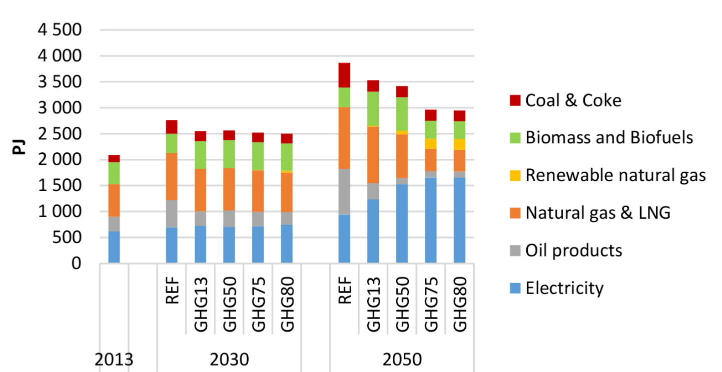

Figure 5: Final energy consumption in the industrial sector in Canada

4.3 Electricity generation

As noted above, massive electrification of end uses represents a consistent observation across sectors for the GHG mitigation scenarios, with the amount of electrification increasing with increasingly stringent GHG reduction targets. .Major investments are required to increase the supply of carbon free electricity generation, in both Western Canada (Figure 6) and Eastern Canada (Figure 7).

For the REF Scenario, electricity generation increases from 167,938 TWh in 2013, to 235,800 TWh in 2050. For the GHG mitigation scenarios, there are further increases in electricity generation, to as much as 401,386 TWh for the GHG80 Scenario. This represents 2.4 –fold increase in electricity generation from 2013 to 2050. Due to a very uneven distribution of primary resources in Canada (as described in section 4.4), the electricity generation mix varies between jurisdictions.

Electricity generation in Western Canada, currently, comes primarily from 19 GW of hydro projects in British Columbia and Manitoba, and 18 GW of thermal power plants. For the REF, the increasing demand for electricity by 2050 is dominantly from an additional 19 GW of gas-fired power generation, especially in Alberta, and including cogeneration for steam production in the industrial and fossil fuel supply sectors, especially for oil sands production. Thermal generation from existing coal-fired plants is decreasing, from 8 GW to 1 GW, due to planned phasing out (Environment Canada, 2013).

For the GHG mitigation scenarios, thermal generation is replaced with addition of hydro developments, primarily in Manitoba and the Northwest Territories (there is a moratorium on new large-scale hydro projects in British Columbia). The remaining portion of thermal generation, for instance in the scenario GHG80, includes the existing gas-fired power plants (12 GW) which are used to provide dependable electricity and refurbished coal-fired power plants with carbon capture and sequestration facilities (6 GW). Nuclear power plants are built in Alberta (19 GW) to achieve deep reduction levels by 2050 (GHG75 and GHG80). Renewable electricity comes largely from wind energy (46 GW supported with 18 GW of pumped storage) and development of the small geothermal potential in Alberta and British Columbia (2 GW).

Electricity generation in Eastern Canada is already close to being carbon free, with 89% of electricity generation from non-emitting sources. This is 55 GW of installed hydro capacity in Quebec, Ontario and Newfoundland & Labrador, with another 7 GW projected by 2050 for the REF. Projected growth in demand is also satisfied with greater use of gas-fired power plants, primarily in Ontario. Wind farms are projected to increase from 4 to 8 GW by 2050. The installed capacity from nuclear power is projected to slightly decrease with the already scheduled refurbishment program for only a portion of the existing reactors in Ontario. Finally, coal-fired plants are phased out as scheduled, and not refurbished with carbon capture and sequestration facilities Renewable electricity also includes generation from small scale solar plants in Ontario (0.5 to 0.9 GW) and one tidal plant in Nova Scotia (0.02 GW).

For the GHG mitigation scenarios, there is a need for additional electricity supply. For example, for the very ambitious scenario GHG80, there will be a requirement for 38 GW of additional hydro capacity, 18 GW of nuclear capacity (in Ontario) and 49 GW of wind capacity, with support from 26 GW of pumped storage capacity. While thermal generation already plays a marginal role in the REF scenario, it is almost non-existent in the GHG Mitigation Scenarios. Existing gas-fired plants are used only marginally and generation from diesel generators in remote regions remains very small. The technical potential for hydroelectric generation capacity is estimated at 125 GW in Eastern Canada, with 82 GW in Quebec alone [34], i.e. more than the double of the installed capacity in 2013. The hydraulic resource represents a major asset in meeting the growing demand for electricity for the very ambitious GHG mitigation scenarios.

In both regions, electricity generation from biomass remains small as the various types of biomass feedstocks are used primarily for liquid biofuel production, renewable natural gas production, space heating, and as a replacement of coal in some industries.

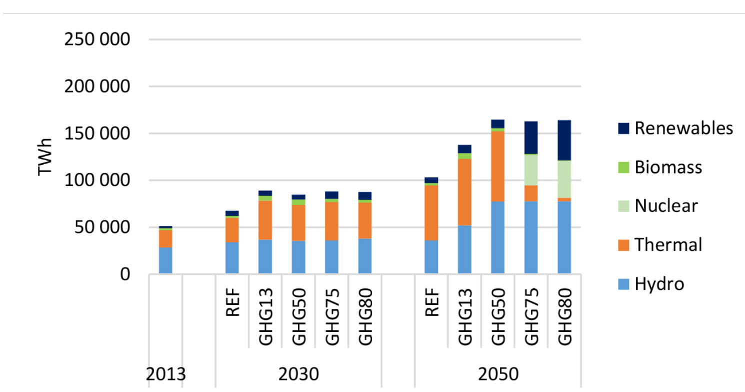

Figure 6: Electricity generation in Western Canada

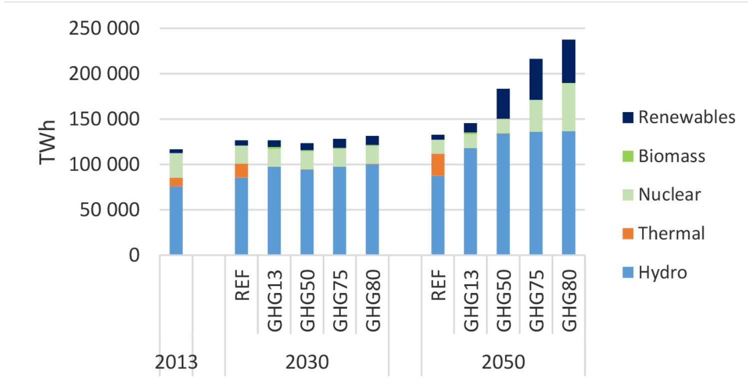

Figure 7: Electricity generation in Eastern Canada

4.4 Primary energy production

While the composition of the final energy mix in the end-use sectors is generally similar across jurisdictions as well as the selected reduction options for meeting the various climate targets, the primary resources are distributed very unevenly across the country. Primary energy production for both domestic consumption and exports is illustrated separately for Western Canada (Figure 8) and Eastern Canada (Figure 9).

In Western Canada, where most of conventional and unconventional fossil fuel reserves are located, the REF scenario shows the primary mix being dominated by an increase in oil and gas production: by 68% from 2013 to 2050. By 2050, fossil fuels (oil, gas and coal) represent 76% of the primary energy production mix.

However, for the GHG mitigation scenarios, there are major reductions in oil and gas production, with 66% reduction for scenario GHG80 from 2013 to 2050. Domestic needs are critically reduced with the electrification of end uses, and there are major reductions in international exports, especially oil. The system-wide costs for in-situ bitumen extraction in Alberta are greater than revenues from exports for this extreme scenario. Uranium reserves in Saskatchewan are huge, with most of the uranium extraction for supply to international markets, which are projected to further increase by 2050. In the most ambitious reduction scenarios, the uranium production increases to supply new nuclear power plants.

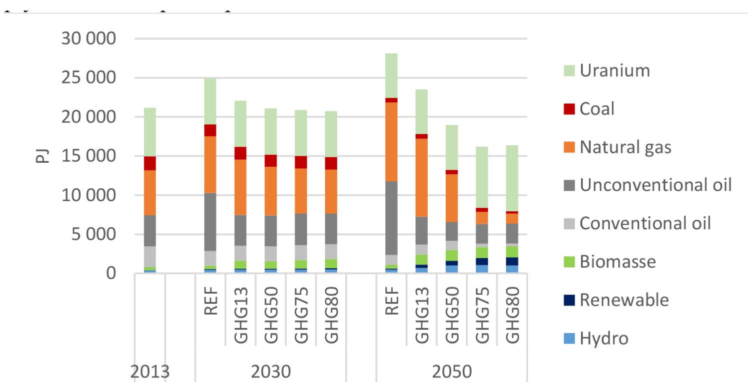

Figure 8: Primary energy production in Western Canada

By comparison, the primary energy production mix in Eastern Canada is strongly dominated by the exploitation of hydraulic, other renewables and biomass feedstock resources (Figure 9). Renewable resources include wind energy produced from existing wind farms or already scheduled for future construction, as well as new investments in decentralized solar energy. At the maximum, by 2050 in the GHG80 scenario, the mix includes 1,314 PJ of energy from biomass (amount equivalent to Western Canada), 1,824 PJ from hydraulic energy and 1,409 PJ from other renewables (mainly wind and solar, and a tiny amount of geothermal energy).

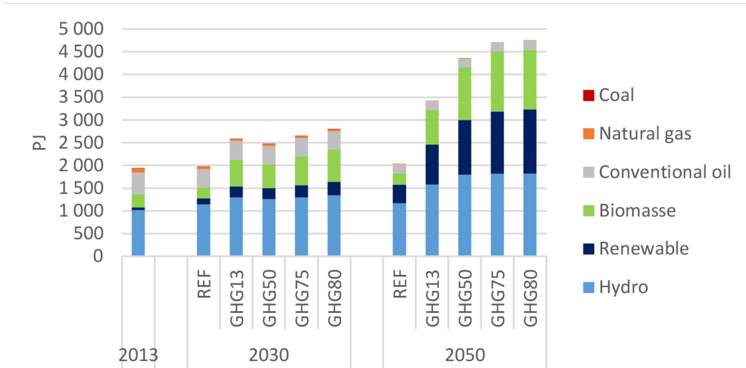

Figure 9: Primary energy production in Eastern Canada

4.5 Energy trade

Obviously, with fossil fuel and uranium reserves that greatly exceed domestic needs, Western Canada is a net exporter of energy to the rest of Canada, the United States and the rest of the World (Figure 10). While most of fossil fuel exports are currently destined to international markets (89% for oil, 78% for gas, 98% for coal), these shares are expected to decrease over the long term with increasing exports to Eastern Canada. For the REF Scenario, international exports are projected to decline to 68% for oil, 42% for gas, and 75%, for coal.

For the GHG mitigation scenarios, however, there are major reductions in production and delivery of fossil fuels. This arises due to reduced domestic demand, as well as reductions associated with the need for reducing emissions for supply and delivery of fossil fuels which are emissions intensive with high implicit costs, resulting in uneconomic production. It is assumed that the international community will reduce its demands for fossil fuels at the same ratio as Canada (the model is flexible to represent such assumed relationships). Production of uranium remains relatively constant across scenarios and time, dominated by exports. There is a slight decrease in exports by 2050 for the GHG80 scenarios, in response to increased projected domestic demand, primarily for additional nuclear reactors in Alberta and Ontario.

In contrast, Eastern Canada is a net importer of fossil fuels and uranium (Figure 11). While most of the crude oil imports come from international markets in 2013, these are progressively replaced with synthetic oil from Alberta in the REF scenario given the lower price for oil sands (although the Energy East pipeline project is on hold, transport by rail and heavy trucking remains).

For the GHG mitigation scenarios, all imports are decreasing, with associated reductions in refining activities. While natural gas comes from Alberta through existing pipelines, an increasing amount could come from shale gas deposits in the Eastern United States Uranium is imported exclusively from Saskatchewan. Eastern Canada is a net exporter of electricity to the United States through existing interconnections from Quebec (4.3 GW to 6.3 GW from 2020 with scheduled projects), Ontario (2.1 GW) and New Brunswick (1.1 GW) to New England, New York and the Midwest.

4.6 Mitigation costs

Marginal costs for GHG mitigation, for the four mitigation scenarios, are shown on Figure 12. These marginal costs increase significantly over time, and reach high values by 2050, especially for the most ambitious levels of mitigation. Marginal costs in 2050 are\$343/tCO_2-eq forGHG13), \$663/tCO_2-eq for GHG50, \$1,785/tCO_2-eq for GHG75, and \$2,130/tCO_2-eq for GHG80. The less stringent scenarios (GHG13 and GHG50) would require a doubling of the cost of gasoline to reflect such marginal costs. .

The analyses also showed that limiting GHG emissions below 200 MtCO_2-eq by 2050 represents a sensitive point, with abatement costs increasing exponentially due to the lack of reduction options, especially for the transportation, industrial and fossil fuel supply sectors. Additional reduction options are needed to explore

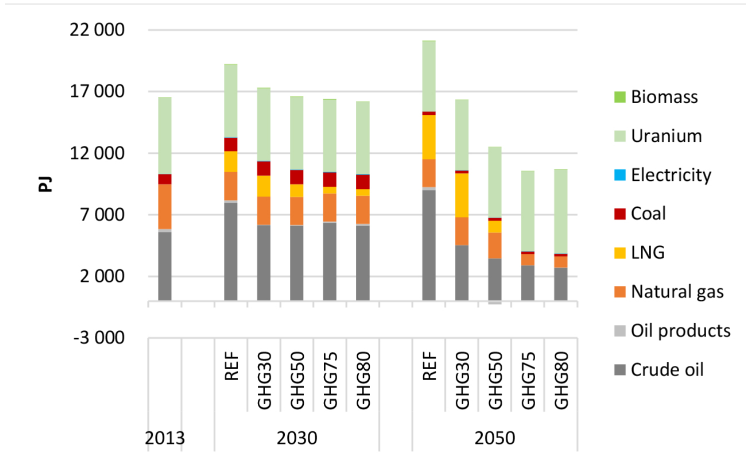

Figure 10: Net exports in Western Canada

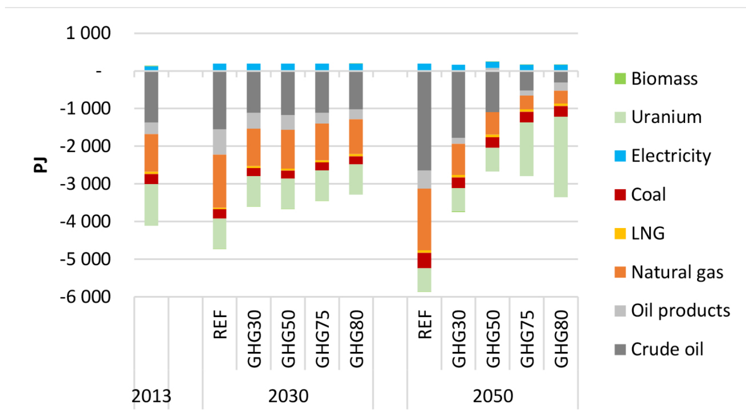

Figure 11: Net exports in Eastern Canada

more aggressive transformation pathways such as carbon capture and storage facilities in various industries, third-generation biofuels, CO2 trade between jurisdiction to allow a greater role for bioenergy with carbon capture and storage (which is not limited to jurisdictions with both biomass feedstock and sequestration potential), and additional options for long-distance and heavy freight transport. Moreover, it is possible that our price elasticity assumptions underestimate the reduction in service demands in such ambitious reduction contexts.

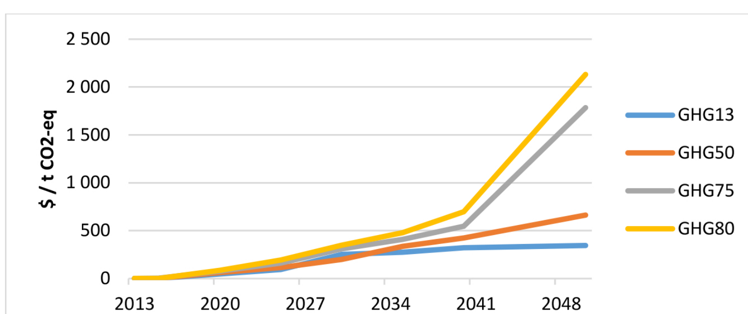

Figure 12: Marginal cost of abatement

5 Sensitivity analysis on dependable capacity

Decarbonization of end-use sectors is strongly dominated by electrification options, supplied by clean electricity sources, and by using a large variety of biomass feedstock. Since energy resources are not distributed evenly across the country, important trade movements and modifications in trade patterns occur in order to satisfy a growing demand both in a business-as-usual situation (REF scenario) and in GHG reduction scenarios. The role of incremental hydro capacity at existing hydro sites along with the option of purchasing dependable capacity from other jurisdictions reduces the need for investments in more expensive dependable capacity. These effects are illustrated in Figure 13 by comparing the installed capacity by type in the two most ambitious scenarios (GHG75 and GHG80) in 2030 and 2050 in Western Canada. Decarbonization of the electricity sector is indeed more difficult in this region due to the lack of clean energy source that can be used as dependable capacity. With these additional options, Alberta for instance, benefits from capacity imports from the Northwest Territories and the development potential of the hydro resources of the Mackenzie River. Globally for Western Canada, these options allow to reduce investments in thermal based capacity by 13% and in storage capacity by 43% to achieve a 80% reduction by 2050 from 1990 levels (GHG80 scenario). For slightly less stringent scenario (GHG75), this also contributes to reducing nuclear based capacity by 16% in 2050. The total energy system cost is reduced by 5% in both scenarios compared with their formal version. While our assumptions for these alternate scenarios were very conservative, namely in terms of potential, it would be interesting to further explore the role of incremental hydro as a cost-effective option to reduce GHG emissions and especially in nuclear phase-out scenarios.

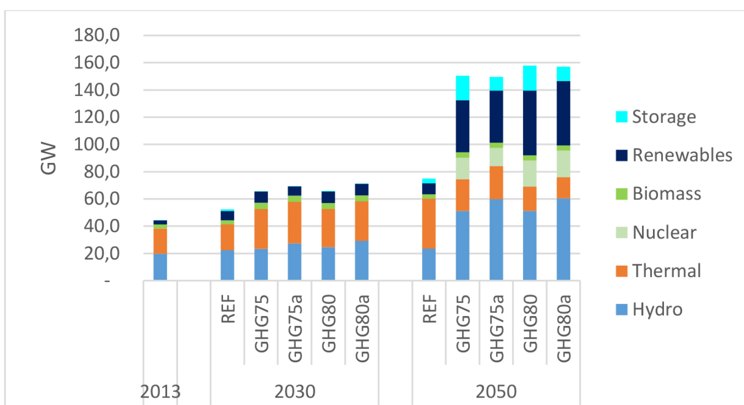

Figure 13: Installed capacity for electricity generation in Western Canada

6 Conclusion

In the context of the Paris Agreement, we have explored different decarbonization pathways that would allow Canada to participate in global mitigation efforts to prevent dangerous climate changes. The 13-region NATEM model was used to explore the main transformations needed in the energy sector for achieving four progressive GHG emission reductions up to 2050: 1) the intended national contribution of Canada with a 30 % reduction by 2030 from 2005 levels, 2) a 50% reduction target by 2050 from 1900 levels compatible with a warming limit of 1.5 ^{o}C (as derived from the global MERGE model), 3) the 80% target by 2050 from 2005 levels from the Canadian Mid-Century Strategy, and 4) a more ambitious target of 80% by 2050 from 1990 levels. The gradual increase in the emission reduction targets allow for a better understanding of the effects of climate policies on the penetration rates of different forms of fuel switches and technological options. In order to reach lower levels, more technological options would be necessary to consider as well as significant behavioural changes.

The main observations from our result analysis are as follows. i) There are very substantial reductions in energy demand and associated GHG emissions, with implementing cost efficient energy efficiency and energy conservation strategies. ii) For all mitigation scenarios, there are major reductions in the use of fossil fuels to meet energy-based demands, with correspondingly large increases in use of electricity (dominantly from non-emitting sources) and biomass/ biofuels. iii) Overall costs for GHG mitigation are high, with marginal costs being in the range of several hundred dollars per tonne, and increasing over time. These values define the implicit costs for GHG mitigation. iv) With increasingly stringent demands for GHG mitigation by 2050, there is increasing incidence of resorting to very expensive options to satisfy such reduction targets. These include, as examples, reaching resource supply limits on production of biofuels, use of expensive hydrogen in the transport sector, and implementing increasingly expensive energy efficiency and energy conservation options.

Defining pathways for achieving ambitious GHG reductions is a very complex task involving many uncertainties. This analysis did not consider all the factors that could impact the optimal solutions. Many factors could be explored further, such as the optimization of transport modal shifts, the adoption of reduction targets in the rest of the World, the integration of more advanced reduction options not commercially available today, etc. In addition, some limitations are inherent to the current version of the model and do not provide a full perspective on the problem such as GHGs from other sectors and non-GHG pollutants. Despite all these limits, however, the analysis of several scenarios illustrates that fact that optimization energy models such as NATEM are powerful tools for identifying robust trends and options.

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