Les Cahiers du GERAD

G-2016-125
December 2016

CITATION ORIGINALE / ORIGINAL CITATION

Vaillancourt, Kathleen; Bahn, Olivier; Frenette, Erik; Sigvaldason, Oskar, Exploring deep decarbonization pathways to 2050 for Canada using an optimization energy model framework, Applied Energy, 195, 774-785, 2017.
DOI: 10.1016/j.apenergy.2017.03.104

Les Cahiers du GERAD ISSN: 0711–2440

Exploring deep decarbonization pathways to 2050 for Canada using an optimization energy model framework

K. Vaillancourt, O. Bahn,
E. Frenette, O. Sigvaldason

G–2016–125

December 2016
Revised: March 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.

Dépôt légal – Bibliothèque et Archives nationales du Québec, 2016
– Bibliothèque et Archives Canada, 2016

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.

Legal deposit – Bibliothèque et Archives nationales du Québec, 2016
– Library and Archives Canada, 2016

GERAD HEC Montréal
3000, chemin de la Côte-Sainte-Catherine
Montréal (Québec) Canada H3T 2A7

Tél. : 514 340-6053
Téléc. : 514 340-5665
info@gerad.ca
www.gerad.ca

Exploring deep decarbonization pathways to 2050 for Canada using an optimization energy model framework

Kathleen Vaillancourt [a]
Olivier Bahn [b]
Erik Frenette [a]
Oskar Sigvaldason [d]

[a] *ESMIA Consultants, Blainville, Montréal (Québec) Canada*

[b] *GERAD & Department of Decision Sciences, HEC Montréal (Québec) Canada*

[c] *SCMS Global, Toronto (Ontario) Canada*

`olivier.bahn@hec.ca`

December 2016
Revised: March 2017

Les Cahiers du GERAD

G–2016–125

Abstract: The main objective of this paper is to explore deep decarbonization pathways for the Canadian energy sector that would allow Canada to participate in global mitigation efforts to keep global mean surface temperatures from increasing by more than 2° Celsius by 2100. Our approach consists in deriving minimum cost solutions for achieving progressive emission reductions up to 2050 using the North American TIMES Energy Model (NATEM), a detailed multi-regional and integrated optimization energy model. With this model, we analyze a baseline and two 60% reduction scenarios of combustion related emissions by 2050 from 1990 levels, with different assumptions regarding projected demands for energy services and availability of technology options for carbon mitigation. The first reduction scenario includes only well-known technologies while the second one considers additional disruptive technologies, which are known but are not fully developed commercially. Results show that three fundamental transformations need to occur simultaneously in order to achieve ambitious GHG emission reduction targets: electrification of end-use sectors, decarbonization of electricity generating supply, and efficiency improvements. In particular, our results show that electricity represents between 52% and 57% of final energy consumption by 2050, electricity generating supply achieves nearly complete decarbonization by 2025 and final energy consumption decreases by 20% relative to the baseline by 2050.

Keywords: GHG emissions, decarbonization pathways, optimization, TIMES model, canadian energy systems

---

Acknowledgments: The results presented in this paper are from the Trottier Energy Futures Project (TEFP). The initiative and funding for this project came from Lorne Trottier, through the Trottier Family Foundation. The project was jointly sponsored by the Canadian Academy of Engineering (CAE) and the David Suzuki Foundation (DSF). Olivier Bahn also acknowledges financial support from the Natural Sciences and Engineering Research Council of Canada (NSERC individual grant).

1 Introduction

1.1 Context

The international scientific community has stated the need for deep decarbonization of the global economy in order to avoid irreversible damage from anthropogenic climate change. The Intergovernmental Panel on Climate Change (IPCC) has determined that atmospheric GHG concentrations should not exceed 450 parts per million of carbon dioxide equivalent (CO_2e) in order to keep global mean surface temperatures from increasing by more than 2° Celsius by 2100, thus, minimizing dangerous anthropogenic interference with the climate. This translates to an emission reduction target range between 23% and 63% of global 1990 levels by 2050, and 71% to 124% by 2100[1] [1].

In 2014, total Canadian emissions were 732 Mt of CO_2e with around 81% being energy-related and the rest being attributed to industrial processes and product use, agriculture, and waste [2]. Canada has recently announced a national GHG emission reduction goal of 30% reduction from 2005 levels by 2030 [3]. However, this target places it last (tied with Japan) concerning emission targets amongst the G7 countries. One major obstacle impeding more ambitious reduction policies is Canada's role as one of the largest fossil fuel-exporting countries. In 2013, oil and gas production accounted for around 10% of Canadian GDP [4]. By comparison, in the United States, the share of oil and gas production in GDP was around 1.6% in 2011.

1.2 Objectives

The main objective of this paper is to explore possible deep decarbonization pathways and identify priority actions for the Canadian energy sector which would allow Canada to participate in these global mitigation objectives. Our approach is to derive minimum cost solutions for achieving progressive reductions in total greenhouse gas (GHG) emissions, from 2011 to 2050, for all of Canada. This is done using the North American TIMES Energy Model (NATEM), which is a highly detailed multi-regional optimization model [5]. NATEM is part of The Integrated MARKAL-EFOM System (TIMES) family of models supported by the *Energy Technology Systems Analysis Program* of the *International Energy Agency* [6].

A series of GHG reduction targets for 2050, varying from 30% to 70% reduction (in 10% increments) below the 1990 level, were first analyzed. The 60% reduction target was selected as the maximum realizable target for the combination of possible reduction options included in the model database. Any substantive increase in the target was not economically feasible with current technologies. For this paper, the goal of 60% reduction is set in order to delineate the most efficient mitigation measures and optimize the timing of their implementation.

Another objective of this paper is to show the impacts of considering disruptive technologies, which are known but are not fully developed commercially, on the optimal solutions and their costs. A series of scenarios were analyzed where additional disruptive technologies were included incrementally. This paper compares the two extreme cases: one scenario where only commercially proven technologies are included, and the other, where multiple disruptive technologies are also included in the model database.

1.3 Optimization of decarbonization scenarios

Optimization models provide a rigorous analytical basis for defining decarbonization pathways and deriving minimum cost solutions that meet both growing demands for energy-related services and progressive reductions in combustion emissions. At a global level, the *Global Energy Assessment* [7] explores three alternative sets of transformation pathways using two integrated assessment modeling frameworks including the Model of Energy Supply Strategy Alternatives and their General Environmental Impacts (MESSAGE). In addition, every two years the *Energy Technology Perspectives* [8] of the *International Energy Agency* provides a comprehensive analysis of possible energy futures to 2050, including more than 500 technology options, using the TIMES cost-optimization model and stock

---

[1] Emission target range was converted from a 2010 base year to a 1990 base year using the fact that 2010 global emissions were 31% higher than 1990 emissions, data is taken from Table 3.1 in [1].

accounting simulation models. Finally, the *World Energy Scenarios* of the *World Energy Council* [9] presents three exploratory scenarios representing alternative energy transition futures to 2060 using the Global Multi-Regional MARKAL (GMM) energy model.

At a national or regional level, numerous decarbonization studies have been carried out using cost-optimization models, in a stand-alone manner or in combination with other models. In particular, scenarios achieving an 80% GHG reduction goal of 1990 levels by 2050 employing the TIMES methodology were analyzed, for instance, in California [10,11], Ireland [12], Scotland [13] and the United Kingdom [14]. Some studies rather focus on pathways directly compatible with meeting the 2 °C target and their impacts on the energy system of various regions such as China and India [15, 16] or globally [17, 18]. Other studies on emission reduction pathways using similar tools include analysis for Macedonia [19], Austria [20] and Taiwan [21]. Comparable studies look at sector-specific decarbonization pathways such as for the electricity sector in Portugal [22] and Switzerland [23], and for the cement [24], steel [25] and building sector [26] in China. Finally, several studies propose decarbonization pathways through renewable penetration targets rather than emission targets such as for the power sectors in France [27] and Greece [28].

Based on the literature review, the work presented in this paper brings significant new information on this topic. Indeed, this is the first time in Canada that such a comprehensive integrated multi-jurisdictional approach, in a multi-time period context, has been undertaken for deriving minimum cost solutions for meeting ambitious GHG mitigation targets [5]. While global optimization models handle Canada as an aggregated region or even as part of the North American region, no other studies have been carried out for Canada specifically using a cost optimization, multi-regional and technology-rich approach. The *Deep Decarbonization Pathways Project* [29] looks at substantial reduction targets for fifteen different countries including Canada. The Canadian chapter of the project looks at an 88% reduction from 2015 levels by 2050, excluding agriculture, using a simulation model and a computable general equilibrium model [30, 31]. However, it does not explicitly take cost minimization into consideration as part of a complete energy system approach. Similarly, two more studies carried out at *Environment and Climate Change Canada* [31] reports on a net 80% GHG emission reduction from 2005 levels using the Global Change Assessment Model (GCAM), a dynamic-recursive computable general equilibrium model.

Consequently, the work presented in this paper can: i) provide more detailed Canadian-specific insights to global studies on deep decarbonization and their impacts on other regions; and ii) help the Canadian authorities in defining long-term GHG strategies that are aligned with international agreements with a minimum impact on the energy system cost.

The remainder of this paper is organized as follows. Section 2 presents our methodological approach. Section 3 presents the different scenarios and their underlying assumptions. Section 4 consists of an overview of the main results as well as more detailed results by sector. Section 5 proceeds with a discussion of policy implications and limitations of the study. Section 6 concludes with a summary of key points and lessons learned.

2 Methodology

Our approach consists in deriving minimum cost solutions that satisfy both growing demands for energy-related services and progressive reductions in GHG emissions up to 2050. For this, we use the Canadian portion of the NATEM multi-regional energy model (NATEM-Canada) [5]. It offers a comprehensive representation of the energy system of each of the 13 Canadian provincial and territorial jurisdictions. It also models inter-jurisdictional and international flows of energy commodities, as well as the various options for meeting the prescribed GHG mitigation targets in 2050. NATEM has been soft-linked with a detailed simulation model of the Canadian energy systems (CanESS) [32] to provide consistency checks in particular for the turnover of the energy technology stocks.

2.1 The NATEM optimization energy model

NATEM was developed based on the TIMES optimization model generator [6]. A TIMES model is a representation of one or multiple region's entire integrated energy system through specific technologies with different techno-economic parameters and emission coefficients. The model is demand-driven and must meet exogenously specified end-use demands over the determined time horizon (NATEM include 70 end-use demand segments).

TIMES is cast as a dynamic linear programming model. Such a model consists of 3 elements: 1) an objective function, expressing the decision criterion to be minimized or maximized; 2) decision variables, the unknowns to be determined by the optimization; and 3) constraints, i.e. equations expressing the logical relationships that must be satisfied by the optimal solution to adequately portray the energy system. In TIMES, the objective function corresponds to maximizing net total surplus (the sum of consumer and producer surpluses) [6]. This maximization is operationally achieved by minimizing the net total cost of the energy system which includes investment costs, operation and maintenance costs, plus the costs of imported fuels, minus the income from exported fuels, minus the residual value of technologies at the end of the model's time horizon, plus welfare losses due to endogenous demand reductions. The model is based on the assumption that energy markets are under perfect competition; therefore, searching for the maximal net total surplus simulates market equilibrium. The main decision variables are technology specific investment and activity levels for each specified time period, quantity of energy consumed or produced by technology, energy imports and exports in each jurisdiction. Other model outputs are the shadow price of each energy, material and emission commodity and the reduced cost of each technology. Alongside, TIMES must satisfy numerous constraints all described in [6]. These constraints deal in particular with the scarcity of resources and the obligation both to satisfy useful demands and to balance energy within the system. 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.

NATEM is used to systematically search though all possible combinations of decision variables for satisfying the objective function (minimum net total cost of the energy system) while respecting all the model constraints.

2.2 Soft-link framework with a simulation model

The NATEM-Canada optimization model was used as the main tool for generating results from the scenario analysis. However, it was used in a soft-link framework with the *Canadian Energy Systems Simulator* (CanESS) model. CanESS is a detailed simulation model of the Canadian energy systems that is calibrated with historical data from 1978 and enables projection of scenarios forward to 2050 and beyond in one-year steps.

The soft link framework works in both directions as illustrated in Figure 1: i) projections concerning key macroeconomic drivers and service demands were supplied by the simulation model to the optimization model so that both models use the same set of demand for energy services compatible with national sources [33]; and ii) decision variables produced from the scenario analysis with the optimization model were integrated in the simulation model for a more detailed analysis of system responses and further refinements to input variables for the optimization model. Significant efforts were dedicated to technology mapping between the two models and multiple iterations were necessary to ensure that results were consistent and credible.

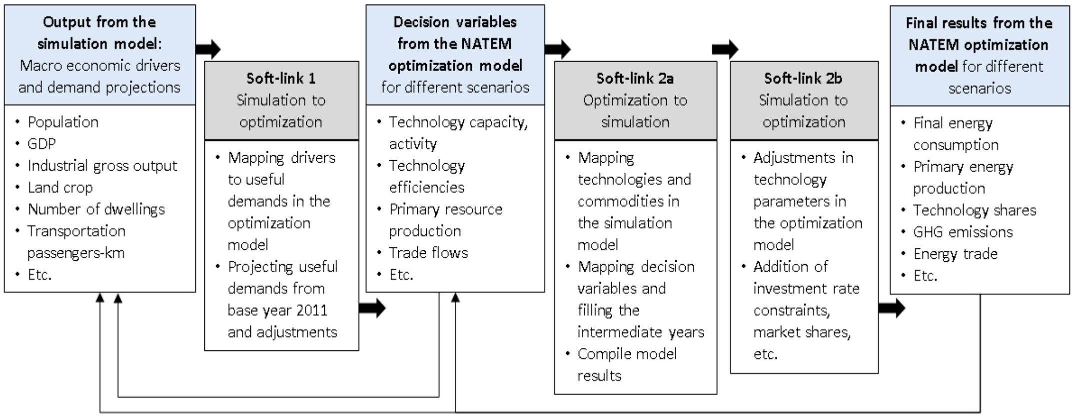


Figure 1: Soft-link framework between the optimization and simulation models

One particular area where this soft link framework added value to the study compared with an approach based only on the standard TIMES optimization approach is the use of the simulation model algorithms for representing principles of optimum system dispatch for electricity supply and refining techno-economic representation of power plants in the optimization model [5]. This was required for ensuring that the amount of generation for each of the various classes of generating facilities in each jurisdiction was being represented appropriately in terms of its respective operating mode, and that associated evaluations of energy production were accurate and compatible with actual recorded results.

An additional feature was added to NATEM concerning the electricity sector: dependable capacity constraints [5] to ensure that, for each jurisdictional electricity supply system, the total demand for electricity was met at all times including during peak periods. This was required as there are several classes of generating facilities that provide little or no guaranteed capacity such as intermittent renewables. Special formulations were developed to ensure that the sum of guaranteed capacity contributions (referred to as dependable capacity) for each class of generating facilities was equal to or greater than system peak demand in all jurisdictions at all times. Additionally, the feature of interjurisdictional dependable capacity was added; jurisdictions can use neighboring jurisdictions' electricity transfers to satisfy part of their peak demand. In other words, interjurisdictional imports of electricity can be counted on as dependable capacity.

3 Scenarios

We define a baseline and two 60% reduction scenarios with a 2050 time horizon, in order to provide the necessary insight for determining pathways for achieving deep decarbonization in a Canadian context and to identify priority actions:

- **Baseline:** This is a business-as-usual scenario which represents a future in which no GHG reduction targets are imposed by new energy policies or governmental regulations agreements.

- **R60%A:** This is a 60% reduction scenario of combustion related emissions by 2050 from 1990 levels. Reduction is measured against the original set of end-use demands for energy services. A conservative approach was employed when selecting which options would be included: mitigation options are limited to technologies which are proven and commercially viable. This allows for results which point to a benchmark in terms of feasible pathways.

- **R60%B:** This is a 60% reduction scenario of combustion related emissions by 2050 from 1990 levels. Reduction is measured against a new set of end-use demands for energy services assuming improved urban forms and consequently lower demand for some services in the residential, commercial and transport sectors due to densification, integrated multi-modal transportation systems, etc. Additional disruptive technologies were added in the model database to run this scenario, which are known, but are not fully developed commercially. These include namely second generation biofuels (cellulosic ethanol, biodiesel from biomass gasification, etc.), coal-fired and biomass-fired generation with carbon capture and storage, and biojet fuel.

All input data and assumptions are fully described in [5].

4 Results

This section presents the final results generated with the NATEM optimization model, the main tool used for the scenario analysis, after an extensive calibration phase involving the valuable support of the simulation model.

4.1 GHG emission reductions

Total Canadian GHG emissions have increased from 613 Mt of CO2e in 1990 to 731 Mt in 2013. Combustion related emissions, which represented 72% in 1990 and 70% in 2013, are projected to increase from 504 Mt in 2013 to 763 Mt in 2050 in the baseline scenario. For both reduction scenarios, combustion related emissions decrease to 171 Mt in 2050. Figure 2 shows the projected emissions for the baseline and the targeted reduction trajectory for the R60%B scenario. The emission reduction trajectory was defined as an essentially linear relationship from the actual value in 2013 to the prescribed 60% reduction target in 2050. This approach was used for simplicity reasons and future works would help understanding the impacts of setting different trajectories on the optimal solutions. The intermediate resulting targets are as follows: 6% reduction from 1990 levels by 2025, 18% by 2030, 29% by 2035, 39% by 2040 and 60% by 2050.

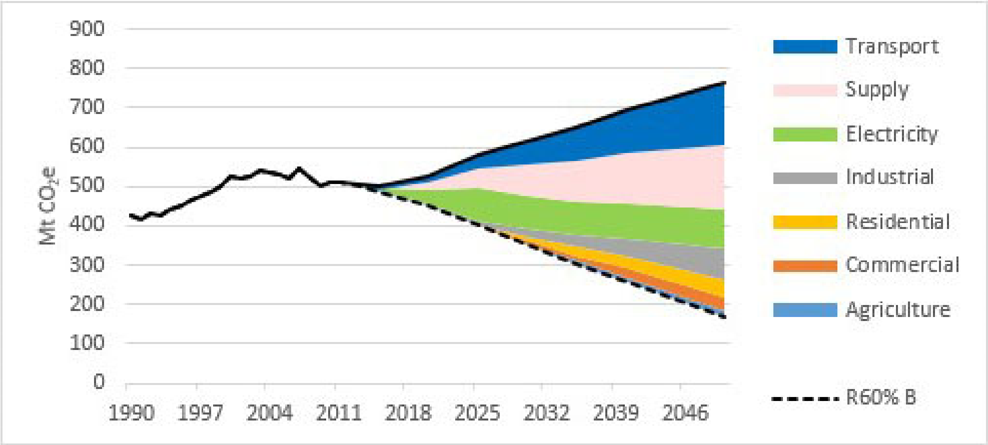
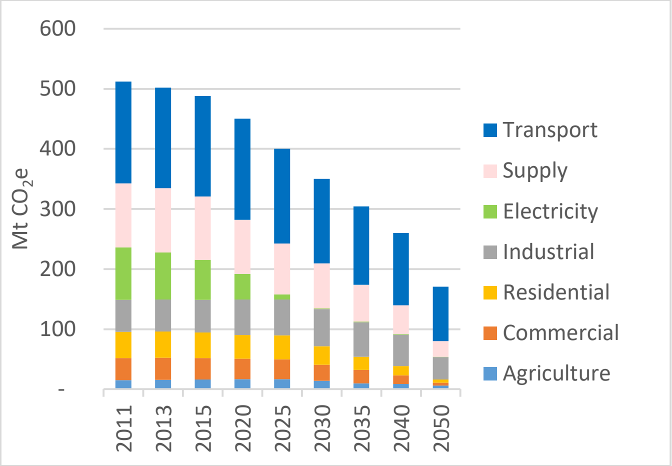


Figure 2: **GHG reductions by sector in the R60%B scenario**

Figure 2 also shows the contribution of each sector to the reduction target which represents a total decrease of 592 Mt CO_2e in 2050. In 2050, results show that 27% of the reduction is achieved in each of the fossil fuel supply sector and the transport sector, 17% in electricity generation, 13% in industries, 14% in residential and commercial sectors, and 2% in agriculture. The electrification of the transport sector and reduction in production of fossil fuels represent thus a majority of the reductions.

Figure 3 shows remaining GHG emissions by sector for the R60%B scenario totalizing 171 Mt CO_2e in 2050. The contribution of each sector to the total reduction is shown in % on the right side (i.e. the absolute emission reduction in each sector in MtCO2-eq divided by the total amount of reductions in MtCO2-eq). Emissions from the transportation sector decrease from 170 Mt in 2011 to 91 Mt in 2050. This reduction is achieved principally through electrifying road vehicles, electrifying rail transport and massive use of both first and second generation biofuels for heavy freight transportation. The fossil fuel supply sector sees emissions decrease from 106 Mt in 2011 to 26 Mt, a decrease which is attributable to reduced production volume. Industry emissions decrease from 54 Mt in 2011 to 37 Mt in 2050. The decrease in industry is explained by some electrification of technologies and investments in more efficient processes. The electricity sector undergoes a rapid decarbonization, with emissions decreasing from 87 Mt in 2011 to 1 Mt by 2030 and less than 1 Mt in 2050. This rapid decarbonization is obtained by massive investments in renewable electricity generation: hydro, wind and pumped storage. Substantial investments in nuclear are also made. The residential and commercial sectors have emissions decreasing from 80 Mt to 10 Mt in the same period. This decrease is caused by investments in conservation technologies for buildings, in more efficient technologies and in electricity-based technologies. Agricultural emissions decrease from 15 Mt to 6 Mt; a decrease which is due to electrification.

The changes discussed above can by grouped into three main strategies which will be referred to as the three fundamental transformations necessary for decarbonizing the Canadian economy.



Contribution of each sector to the total reduction

	2020	2035	2050
Transport	21%	24%	27%
Supply	27%	31%	27%
Electricity	41%	25%	17%
Industrial	7%	9%	13%
Residential	2%	7%	8%
Commercial	2%	3%	6%
Agriculture	0%	2%	2%
	100%	100%	100%

Figure 3: **GHG emissions by sector in the R60%B scenario**

4.2 Transformation options

The three transformations needed to achieve deep decarbonization are: electrification of end-use sectors, decarbonization of electricity generating supply, and efficiency improvements.

First, massive electrification is needed to displace the consumption of fossil fuels in end-use sectors. Figure 4 highlights the results for final energy consumption by showing the share of electricity consumption over total final energy consumption. For both reduction scenarios, starting around 2025, there is a sharp increase in electrification of end-uses which persists until 2050 where electricity represents more than half of final energy consumed. The increase in electricity consumption is mainly used for space and water heating, road transportation and industrial and agricultural processes. The availability of additional reduction options in the R60%B scenario compared with R60%A (e.g., use of next-generation biofuels to replace diesel) is the prime reason for reduced electrification.

In order for electrification of end-uses to be an effective mitigation, it must be coupled with the decarbonization of the power generation supply for producing increased amounts of electricity. Figure 5 shows the combustion related emission intensity of produced electricity in both the baseline and reduction scenarios. The sharp decline in emission intensity in the reduction scenario is obtained by massive investments in renewable and nuclear generation, combined with a significant decrease in generation from existing thermal plants. Investments start early and by 2025 there is approximately 34 GW of new hydro capacity, 7 GW of new pumped storage capacity and around 3 GW of new wind capacity in the scenario R60%A. Additional reduction options in R60%B result in these investments being reduced to, respectively 11 GW, 8 GW and 1 GW. Furthermore, thermal electricity generation in 2025 declines from 154 TWh in the baseline to respectively 2 TWh and 64 TWh in the reduction scenarios. It is important to mention that, for the baseline scenario, the observed decrease in emissions is primarily due to the planned phasing out of coal fired generation [34], with associated replacement of gas-fired generation. As may also be observed from comparison of Figures 4 and 5, the sharp increase in electricity consumption occurs immediately after major decarbonization of electricity supply.

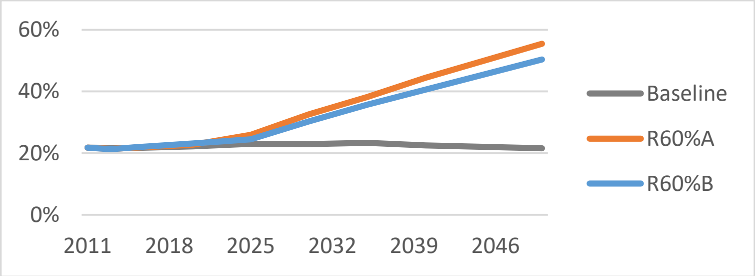


Figure 4: **Share of electricity consumption over total final energy consumption**

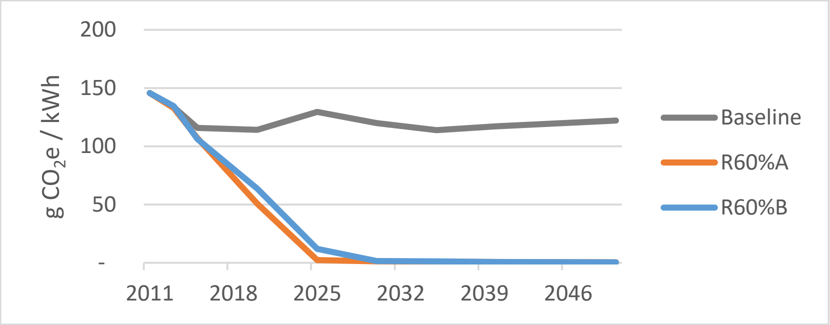


Figure 5: Electricity generation emission intensity

The third transformation is energy efficiency improvements, which allows for reduced final energy consumption to meet energy service demands. As electrification increases throughout the years, increases in energy efficiency translate to less strain on the electricity generation sector. Figure 6 presents the different efficiency gains achieved in the baseline and reduction cases respectively. Efficiency gains are measured by how much demand can be satisfied by 1 unit of energy input in terms of useful energy. The biggest gains in energy efficiency are achieved in the transport sector by replacing internal combustion engines by electric engines for a majority of road transportation. The switch from an internal combustion engine to an electric one allows for around a 3-to-4-fold gain in efficiency [35]. The second most important gains in energy efficiency are achieved in residential and commercial buildings, by investing in more efficient technologies such as energy star appliances and light-emitting diode (LED) lighting, and by investing in conservation methods such as improved building envelopes.

These three fundamental changes each offer considerable mitigation potential on their own, however, it is their synergistic quality which explains their effectiveness; massive electrification must be coupled with a decarbonized electricity supply which produces clean electricity and significant efficiency gains which allow for less strain on the electricity sector.

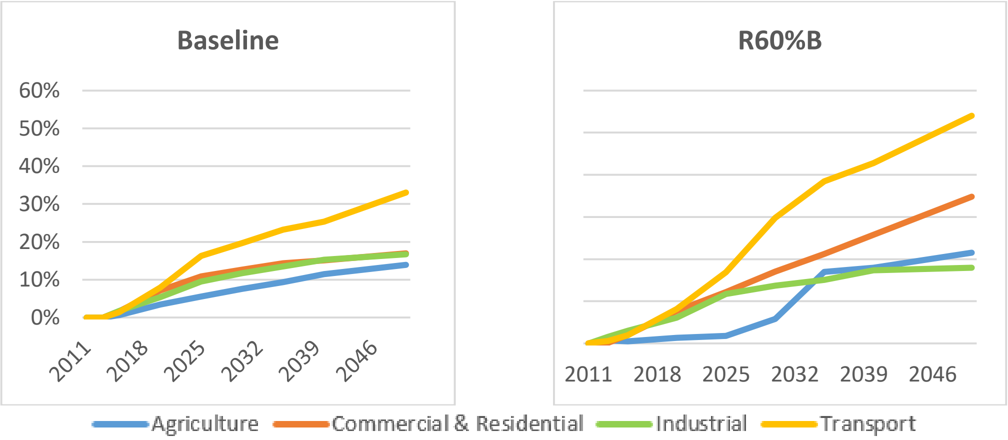


Figure 6: Energy efficiency improvements

4.3 Primary production and final consumption

The three transformations presented above have a significant effect on primary energy production and final energy consumption for the reduction scenarios.

Figure 7 shows primary energy production in the baseline and reduction scenarios. The baseline sees primary production increasing from 23,683 PJ in 2011 to 32,148 PJ in 2050, a 36% increase. On the other hand, the reduction scenarios show a 16% and 5% decrease (respectively) in the same period. These opposing trends correspond in 2050 to a 38% and 30% decrease (respectively) in the reduction scenarios compared to the baseline. The key difference is in the future role of fossil fuel production in the primary production mix. While the baseline shows steady increases in both gas and oil production, the reduction scenarios show a steady decline of both. There are two main causes for the decline in fossil fuel production for the reduction scenarios. First, end-use consumption of fossil fuels is replaced by electricity consumption and this trend is amplified in the S60%A scenario compared to S60%B. Second, exports of fossil fuels are reduced in the reduction scenario as it is more cost effective to reduce exports than to electrify the fossil fuel supply sector. The increases in uranium, hydro and renewable energy production stem from the decarbonized and increased electricity generating capacity observed in the reduction case.

Figure 8 illustrates next the main difference in final energy consumption between the baseline and reduction scenarios. First, energy consumption increases at a much lower rate in the reduction scenarios (19% and 15% respectively between 2011 and 2050) when compared to the baseline (46% for the same period). This difference of more than 2,000 PJ in 2050 between the baseline and reduction scenarios is explained by significant efficiency gains in end-use sectors. Second, there is massive electrification in the end-use sectors. Electricity consumption in the reduction scenarios increases from 1,375 PJ in 2011 to 5,363 PJ and 4,708 PJ (respectively) in 2050, a threefold increase. Electricity and heat represent 57% and 52% (respectively) of the energy mix in 2050. In the baseline, electricity consumption increases only to 2,615 PJ in 2050 (23% of the energy mix).

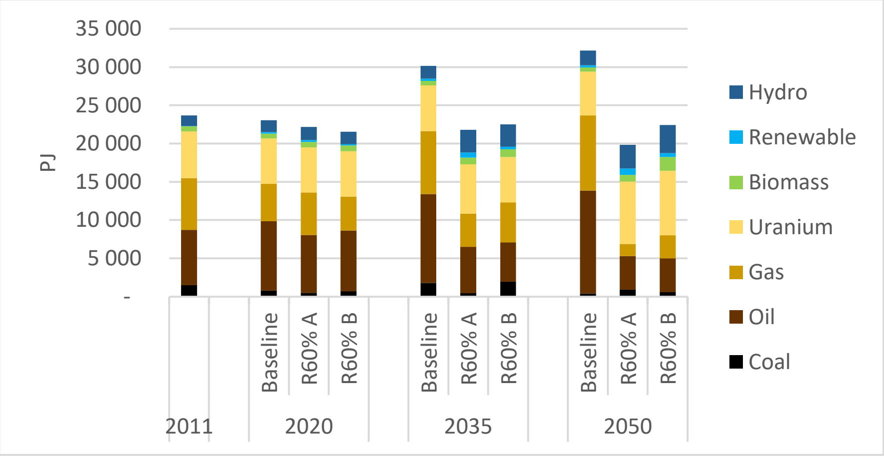


Figure 7: Primary energy production

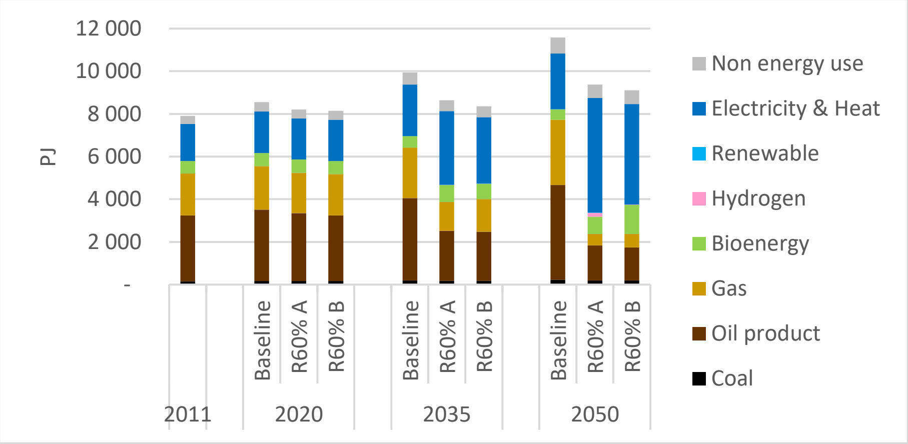


Figure 8: Final energy consumption

4.4 Sector analysis

The following sections present more detailed results, further highlighting the fundamental transformations for the electricity, transport, residential and commercial, and fossil fuel supply sectors. The omission of a more detailed assessment of the industrial and agricultural sectors is primarily due to the lack of specific reduction options.

4.4.1 Electricity

The electricity sector undergoes massive infrastructure changes in order to provide the increased amounts of electricity needed for the electrification of end-uses and to produce this electricity in a non-emitting manner. Figure 9 shows electricity production by source for the baseline and reduction scenarios.

Electricity production increases from 2,150 PJ in 2011 to 2,988 PJ in 2050 for the baseline and to 6,228 PJ and 5,606 PJ (respectively) in 2050 for the two reduction scenarios. Major differences between these scenarios for the year 2050 are: i) the cessation of thermal-based power generation in the reduction scenarios; ii) significant increase in nuclear-based power generation, from 199 PJ in the baseline to 2,603 PJ and 1,402 PJ (respectively) in the reduction scenarios; iii) a significant increase in renewable power generation (mainly wind), from 148 PJ in the baseline to 598 PJ and 365 PJ (respectively) in the reduction scenarios; and iv) an increase in hydro power, from 1,858 PJ in the baseline to 3,011 PJ and 3,572 PJ (respectively) in the reduction scenarios.

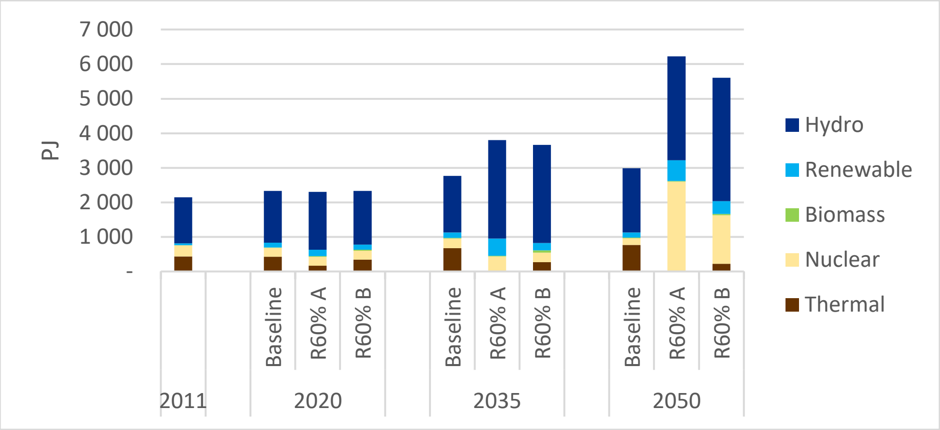


Figure 9: Electricity generation

Figure 10 shows the corresponding installed capacity. It is especially worth noting that 17 GW and 15 GW, respectively, of pumped storage capacity is required in 2050 for the reduction scenarios. This is to provide dependable capacity contribution to complement wind generation, provides virtually no dependable capacity, for meeting peak electricity demand.

Massive electrification of end-use sectors coupled with rapid decarbonization of electricity generating supply implies massive infrastructure changes in the electricity sector. These changes require substantial investment costs, which, in turn affects the cost of electricity. Figure 11 presents the total electricity sector investment cost for all scenarios. For the baseline scenario, investment costs for new electricity generating capacity start at around 169 million $ in 2020 and increases to around 5.7 billion $ in 2050 (in 2011 $CAD). In the reduction scenarios, investments in new capacity start earlier and increase respectively to around 73.5 and 58.0 billion $ in 2050, which is over ten times the amount for the baseline. Historically, investment levels have never gone above the 18 billion $ mark in any given year; investments reached peak levels of around 15 billion $ in 1991 and close to 18 billion $ in 2009 and 2010 [36].

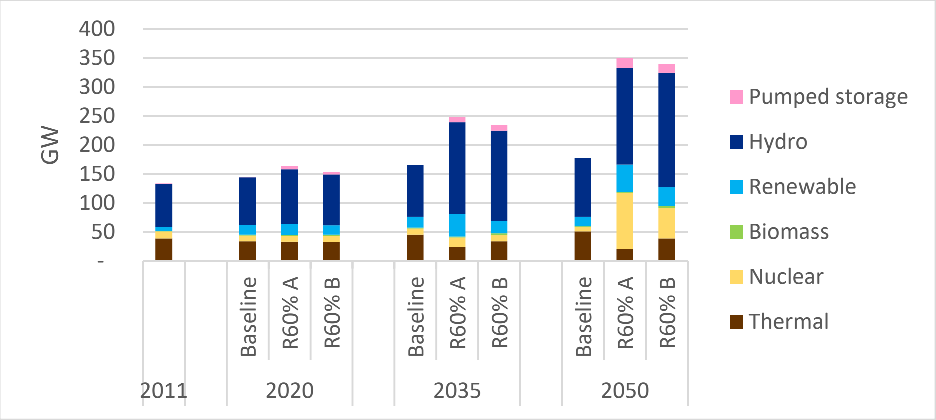


Figure 10: **Electricity installed capacity**

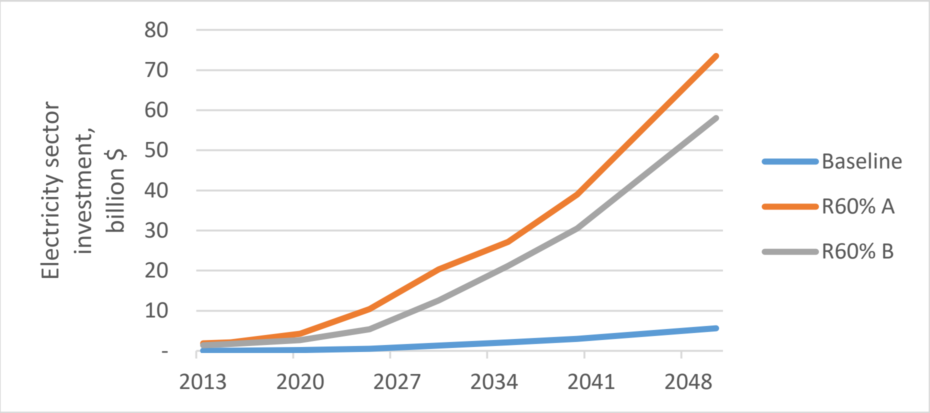


Figure 11: **Total investment costs in the electricity sector**

4.4.2 Transportation

The transportation sector is responsible for more than 150 Mt of reductions in GHG emissions by 2050 (around 20% of the total reduction) when comparing the baseline to the reduction scenarios. A majority of this reduction is achieved through the electrification of road transportation leading to significant efficiency gains from converting internal combustion engines to electric motors.

Figure 12 shows final energy consumption in the transportation sector where the result of these efficiency gains is apparent. In 2050, total energy consumption is 3,679 PJ for the baseline compared with 2,156 PJ and 2,447 PJ (respectively) for the reduction scenarios, and the increase in electricity consumption for massive electrification is limited to 324 PJ and 286 PJ respectively. Electrification of road transportation also yields a decrease in gasoline consumption: in 2050, gasoline consumption is 460 PJ and 380 PJ (respectively) in the reduction scenarios compared to 1,343 PJ in the baseline. In a lesser manner, biofuel blends with conventional fuels also contribute to reducing emissions from road transportation.

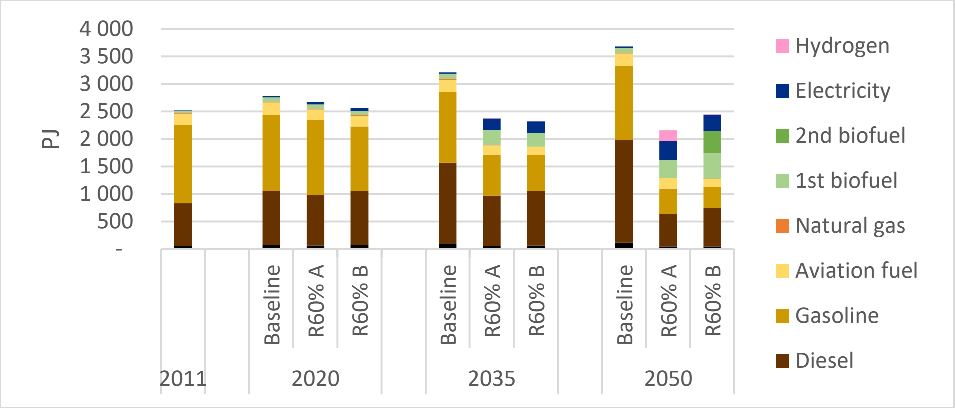


Figure 12: **Transportation sector energy consumption**

Electrification is definitely the most cost-effective option for road passenger transport and light and medium freight transport. However, heavy freight transportation is more difficult to electrify due to the volume and weight of the cargo it carries. Therefore, different technologies are used when compared to the rest of the transportation sector.

In the R60%A scenario, there is an increase in first-generation biodiesel consumption which acts as a substitute for traditional diesel. Biodiesel consumption is 250 PJ in 2050 compared with 32 PJ in the baseline. Biodiesel is a straightforward solution to substituting diesel, however, its potential is limited by feedstock supply limits (food crops) and the technical feasibility of using a large share of biodiesel in a truck fuel mix. The latter was (optimistically) limited to 30% for this study, as high mix levels are considered problematic due to low cloud point property of biodiesel [5]. Since feedstock and fuel mix restrictions on first generation biodiesel limits how much diesel consumption can be displaced in this manner, investments in more costly hydrogen based trucks are made in later years in order to reduce heavy freight truck related emissions. Hydrogen consumption in 2050 for the reduction scenario is 190 PJ compared with no hydrogen consumption in the baseline. The result of increased biodiesel and hydrogen consumption for heavy freight transportation is a 68% reduction in total diesel consumption by 2050 compared to the baseline. Consumer demand, measured in passenger and ton kilometers, also decreases via demand elasticity by round 12% as a reaction to high prices of some transportation options. The main reductions in demand are from the heavy freight, air transportation and rail freight subsectors, which have limited cost-effective mitigation options.

In the R60%B scenario, the availability of second-generation biofuels releases the pressure not only on the transportation sector but on the overall energy system, as biodiesel from biomass gasification can act as a direct substitute (100%) for diesel in all sectors. Two observations are worth mentioning here: i) these substitutions release a quantity of first-generation biodiesel from other sectors to be used in the transportation sector (biodiesel consumption increases from 250 PJ in R60%A to 400 PJ in R60%B); and ii) a significant amount of second-generation biofuels, namely biodiesel from biomass gasification, is also available as a mitigation option for all sectors including transport (with 290 PJ in 2050). Another 110 PJ of cellulosic ethanol is part of the fuel mix in 2050. The role of biofuels increases very substantially with corresponding reductions in use of hydrogen which is a more expensive option.

4.4.3 Residential and commercial buildings

Emissions in the residential and commercial sectors decrease by 48 Mt when comparing the reduction scenarios to the baseline in 2050. This decrease represents 8% of the total combustion-based emissions reduction attained in 2050. The main transformation in these sectors is the electrification of space heating and water heating technologies.

Figure 13 shows residential and commercial energy consumption. Electrification starts around 2025, once the electricity generation sector is decarbonized. In 2050, electricity consumption in the baseline represents 48%, while this proportion reaches 90% in the reduction scenarios. The share of natural gas, mainly for space and water heating, goes from 42% in the baseline to about 5% in the reduction scenarios.

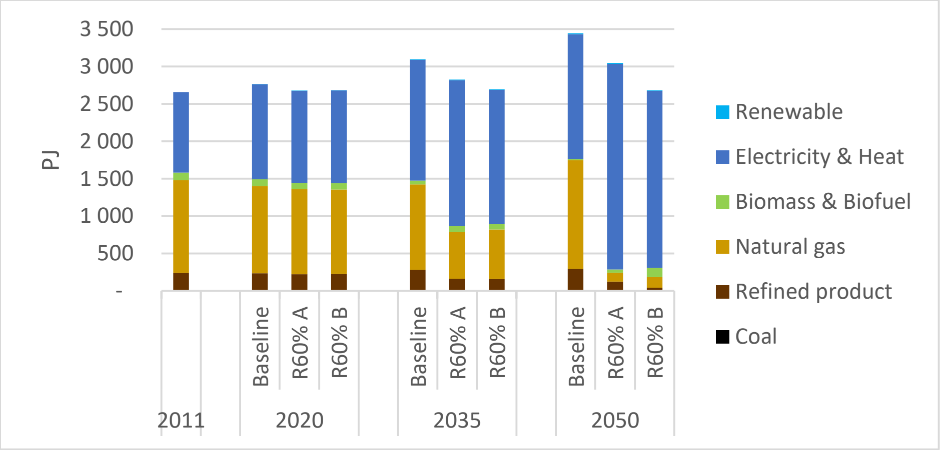


Figure 13: Residential and commercial sector energy consumption

Another contributor to GHG reductions in these sectors is the reduced total energy consumption, which is achieved through investments in conservation methods and more efficient technologies. Total energy consumption in 2050 for the baseline is 3,446 PJ compared to 3,050 PJ and 2,687 PJ (respectively) in the reduction scenarios. This corresponds to a respective decrease of 12% and 22% in energy consumption.

Most of this reduction is due to investments in more efficient technologies and reduced consumer demand via price elasticity, while 17% of the reduction is tied to investments in conservation methods. More efficient technologies include, for example, energy star appliances, LED lighting, improved heat pumps, etc. Conservation methods include technologies such as programmable thermostats for more efficient indoor temperature management and improved building shells.

4.4.4 Fossil fuel production

The contrast between official projections [33] on which baseline fossil fuel production is based and results for fossil fuel production in the reduction scenarios highlights the difficulty of maintaining projected levels in the context of deep decarbonization. Figure 14 shows oil production for different scenarios. Production grows from 7,027 PJ in 2011 to 13,446 PJ in 2050 in the baseline, and decreases to 4,384 PJ and 4,418 PJ (respectively) in 2050 for the reduction scenarios, levels are nearly three times less.

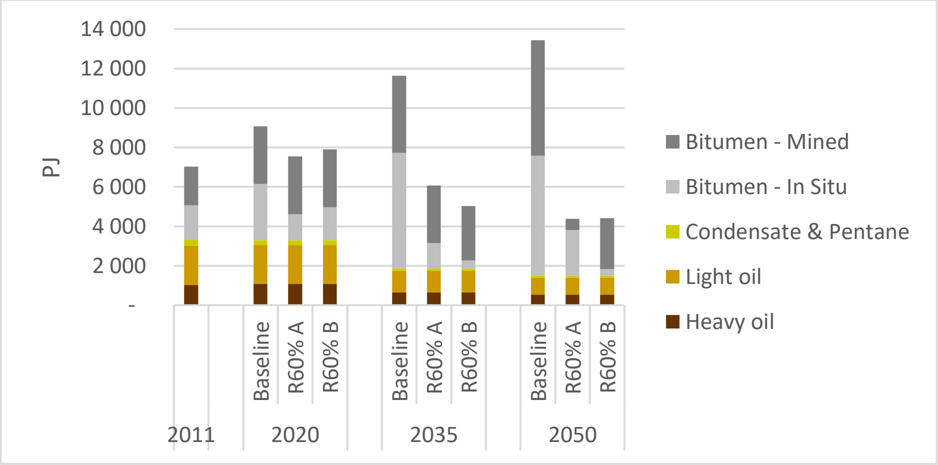


Figure 14: Oil production

There are two main reasons for this decline. First, domestic consumption of fossil fuels is substituted by the massive electrification of end-use sectors. Second, the cost of electrifying oil sands (electrifying steam generation of in-situ bitumen) in order to produce bitumen with fewer emissions is considerable and this results in in-situ bitumen production in the reduction scenarios representing only a fraction of production levels seen in the baseline. The revenues from exports do not compensate for the cost of reduction. It follows that a significantly lower amount of oil is exported in the reduction scenarios in order to reduce emissions from production volume. Exports decrease from 8,168 PJ in the baseline in 2050 to 2,595 PJ in both reduction scenarios.

4.5 Marginal cost

Figure 15 presents the evolution of the marginal cost of reducing GHG emissions. It is important to highlight the timing of the different cost levels. Until 2025, a carbon price under 200$ per ton of CO_2e is estimated for both reduction scenarios. However, for subsequent time periods, where there is an increase in uncertainty surrounding available reduction technologies, carbon prices climb to levels which could be more difficult to implement. Prices in the range of 400-500 per ton are estimated for 2040, with a faster increase in the scenario that includes less reduction options (R60%A). Since the technologies which were included in this scenario are limited to proven and commercially viable technologies, high prices in the long-term (by 2050) also highlight the difficulty of achieving deep decarbonization with current technologies and the need for the development of new, more cost-effective, technologies (such as the ones assumed for R60%B).

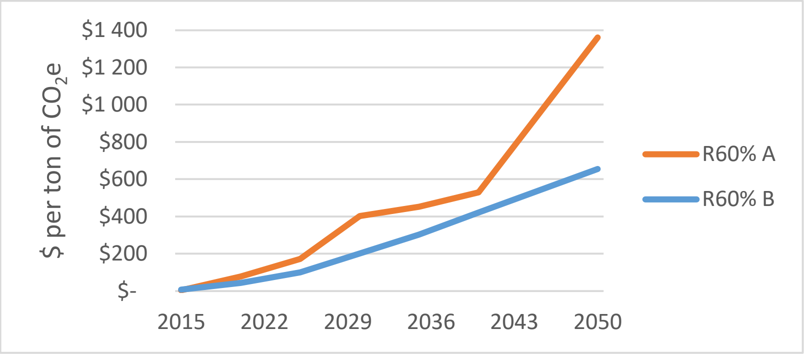


Figure 15: **Marginal cost of GHG emission reduction**

5 Discussion

5.1 Comparison of results

There is consensus in the literature that electrification of end-uses, decarbonization of electricity supply, and energy efficiency are fundamental to deep decarbonization [7, 8, 10]. The Canadian chapter of the *Deep Decarbonization Pathways Project* [30] shows similar results concerning these three transformations. First, they show similar levels of electrification of end-use sectors resulting in 43% of final energy consumption being electricity compared to 52% in the present study. Second, they also show a nearly entirely decarbonized electricity supply by 2050 with emissions intensity of generation (in gCO_2/kWh) reduced by 97% compared to 99% in the present study. Lastly, they show energy efficiency gains through energy intensity of GDP, which decreases from 6.95 MJ/$ in 2010 to 3.13 MJ/$ by 2050; similarly, we see a decrease to 2.98 MJ/$. However, they do not present model results for marginal costs of GHG emission reduction.

Marginal costs of reduction cannot be compared with those obtained in global studies which are normally on the lower range for several reasons, including: i) the target is met globally (and not necessarily in each country) with more reductions occurring in countries with the most cost-effective options; and ii) global models do not account for the investments required in trading infrastructures within a region or a country (for a large country like Canada, these costs can be significant). As for national studies, marginal costs are difficult to compare, when available, due to the specifics of each national energy system. However, it is worth mentioning that the marginal abatement cost curve for California, obtained with a TIMES model [10], shows costs approaching 2,000$ per ton for a 72% GHG reduction in 2050, with a sharp increase at 7,000$ per ton for an 80% reduction. Similarly, marginal costs of 1,200$ per ton and over by 2050 are reported for the United Kingdom [37].

5.2 Limitations

The overall viability of implementing such massive changes depends on many factors which are outside the scope of what our model can provide. This section addresses the main limitations of our study by looking at the viability of the proposed mitigation measures for each sector and by addressing model restrictions.

End-use sectors. A limiting factor to the transformations seen in these sectors is the pace at which they need to be electrified. In reality, it might be difficult to incentivize such a rapid switch of technologies for consumers, such as devices for space heating or passenger transport vehicles which will also require massive infrastructure changes (from fuel pumping stations to electric charging stations). There are also important limitations of feedstock availability for production of bioenergy, as well as social acceptability issues for expanding such supplies.

Electricity sector. The level of infrastructure change required in the electricity sector represents a huge challenge, both for the size of the capacity requirement and the speed at which it would need to be installed. In reality, it will be virtually impossible to undertake such rapid development rates for new generating capacity, especially considering the major role hydro projects play in the solution, which have development times of at least 10 years [38]. Additionally, large amounts of nuclear capacity will be difficult to implement considering societal concerns over this type of electricity generation. A sensitivity analysis was performed to represent a future where no additional nuclear resource was allowed. Reduction targets can then be attained by substituting nuclear resource by a combination of wind and pumped storage capacity at relatively small cost difference [5]. It is important to appreciate, however, that this is a preliminary observation: the viability of such options also needs to be addressed in the respective jurisdictions, especially where there are major additions of pumped storage generation.

Energy storage. The study would also benefit from more modeling efforts about storage options and the integration of more intermittent renewables in the network. Although the pumped storage option is available in the model database, there is very little site-specific information available. In addition, there are several other energy storage options that were not included such as smaller storage devices for decentralized renewable generation (for instance, in the residential and commercial sectors).

Fossil fuel sector. The results for oil production are very dependent on the cost of electrifying steam generation for in-situ bitumen extraction. If new, more cost-effective, technology is discovered which allows for emission-free (or low emissions) steam generation at a low cost, this could potentially lead to higher exports of oil (and gas) as part of a deep decarbonization pathway.

Non-combustion GHG. In 2013, combustion emissions represented around 70% of total emissions versus 30% for non-combustion emissions [2]. Non-combustion emissions are disaggregated into four different categories: industrial processes, agricultural processes (enteric fermentation, manure management, nitrous oxide from nitrogen-based fertilizers, etc.), waste management and fugitive emissions from the oil and gas sector. It is possible to attain deep reduction levels by concentrating on combustion emissions, as seen in the present study. However, it is not clear whether including mitigation options for non-combustion emission sources could potentially reduce abatement costs.

Behavioural. In this study, consumer reaction is solely captured through the own price elasticity of demand for end-use services and exogenous reduction of some end-use demands in the building and transport sectors. However, the optimization of behavioral modifications, such as modal shifts in the transportation sector, could add significant GHG mitigation options by providing endogenous demand substitutions for end-use services that are more difficult to decarbonize, for example, switching from heavy freight to freight train transportation.

6 Conclusion

In this study, we use the NATEM model to illustrate possible pathways to a deeply decarbonized Canadian economy.

We have shown that there are three dominant fundamental transformations which underlie these pathways and which need to occur simultaneously in order to achieve ambitious GHG emissions reduction targets: electrification of end-uses, decarbonization of electricity supply, and energy efficiency improvements. Indeed, we have shown electricity representing between 52% and 57% of final energy consumption by 2050, electricity generating supply achieving nearly complete decarbonization by 2025 and final energy consumption decreasing by 20% relative to the baseline by 2050.

Additionally, although the choice of mitigation strategies for some sectors seem relatively clear, other sectors present a more ambiguous situation due to the uncertainty of technological advances which may affect them. For instance, the future of heavy freight transportation is sensitive to new developments in second-generation biodiesel, and projected levels of fossil fuel production could be significantly altered if cost-effective low-carbon intensity oil sand extraction technologies are developed.

By using an optimization model, we have also shown that deep decarbonization, although presenting an enormous challenge, is technologically feasible for Canada. Achieving a 60% reduction relative to 1990 level emissions by 2050 could be possible for carbon prices of around 40\$/tCO_2e by 2020, 300\$ by 2035 and 650\$ by 2050 when considering disruptive technologies. For the scenario R60%A, the total reduction cost would represent about 3.0% of the Canadian GDP in 2035 and 5.7% in 2050. For the scenario R60%B, these percentages go down to 1.2% in 2035 and 2.6% in 2050. Without disruptive technologies, the impact on the energy sector cost would be more than doubled. However, the use of a general equilibrium model would be necessary to measure the overall impact on the whole Canadian economy accounting for all costs and benefits (e.g. the lost in fossil fuel export revenues compared with new opportunities associated with large hydro development and job creation in the renewable energy sector).

In all cases, these marginal price levels could also be lowered if other new mitigation options were developed, especially for heavy freight transportation and if non-combustion-related emissions were considered. Indeed, there is a considerable need for research and development for new abatement technologies that would increase the feasibility of a pathway to such targets by 2050 and also to ensure that sufficient additional options are available for the eventual pathway to 2100.

References

[1] Intergovernmental Panel on Climate Change (2014). Climate Change 2014 Synthesis Report: Summary Chapter for Policymakers. 32 p. Retrieved from https://www.ipcc.ch/pdf/assessment-report/ar5/syr/AR5_SYR_FINAL_SPM.pdf

[2] Environment Canada (2016). National Inventory Report: Greenhouse Gas Sources and Sinks in Canada 1990-2014. Executive Summary. Canada's Submission to the United Nations Framework Convention on Climate Change, 15 p. Retrieved from https://www.ec.gc.ca/GES-GHG/default.asp?lang=En&n=662F9C56-1

[3] Government of Canada (2015). Government of Canada announces 2030 emissions target. News Release, May 15, 2015, Retrieved from http://news.gc.ca/web/article-en.do?nid=974959.

[4] Natural Resources Canada (2015). Energy Markets Fact Book 2014-2015. Retrieved from http://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/energy/files/pdf/2014/14-0173EnergyMarketFacts_e.pdf

[5] TEFP - Trottier Energy Futures Project (2016). Canada's challenge & opportunity – Transformations for major reductions in GHG emissions. Retrieved from http://iet.polymtl.ca/en/tefp/.

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

[7] Johansson T.B. Nakicenovic N. Patwardhan A. Gomez-Echeverri L. Arent D. J. Banerjee R. … Yeager K. (2012). Global Energy Assessment: Toward a Sustainable Future. Key Findings, Summary for Policymakers, Technical Summary. International Institute for Applied Systems Analysis (IIASA). Retrieved from http://www.iiasa.ac.at/web/home/research/Flagship-Projects/Global-Energy-Assessment/GEA-Summary-web.pdf

[8] International Energy Agency (2014). Energy Technology Perspectives 2014. Energy Technology Perspectives 2014. Paris, International Energy Agency, 376 p. Retrieved from https://www.iea.org/etp/etp2014/

[9] World Energy Council (2016). World Energy Scenarios 2016 – The Grand Transition. In Collaboration with Accenture Strategy and the Paul Scherrer Institut. Retrieved from https://www.worldenergy.org/publications/2016/world-energy-scenarios-2016-the-grand-transition/

[10] Yang C. Yeh S. Zakerinia S. Ramea K. McCollum D. (2015). Achieving California's 80% greenhouse gas reduction target in 2050: Technology, policy and scenario analysis using CA-TIMES energy economic systems model. Energy Policy 77: 118–130.

[11] McCollum D. Yang C. Yeh S. Ogden J. (2012) Deep greenhouse gas reduction scenarios for California – Strategic implications from the CA-TIMES energy-economic systems model. Energy Strategy Reviews 1 (1): 19–32.

[12] Chiodi A. Gargiulo M. Rogan F. Deane J.P. Lavigne D. Rout U.K., Ó Gallachóir B.P. (2013) Modelling the impacts of challenging 2050 European climate mitigation targets on Ireland's energy system Energy Policy 53: 169–189.

[13] McDowall W. A. S. Anandarajah G. Ekins P. (2012). Insights into Scotland's energy and climate policies from energy systems modeling. Fraser Economic Commentary, Special Issue 3: 5–8.

[14] Ekins P. Anandaraiah G. Strachan N. (2011). Towards a low-carbon economy: scenarios and policies for the UK. Climate Policy 11 (2): 865–882.

[15] Lucas P.L. Shukla P.R. Chen W. van Ruijven B. J. Dhar S. den Elzen M. G.J. van Vuuren D.P. (2013). Implications of the international reduction pledges on long-term energy system changes and costs in China and India. Energy Policy 63: 1032–1041.

[16] Gambhir A. Napp T.A. Emmott C. J.M. Anandarajah G. (2014). India's CO2 emissions pathways to 2050: Energy system, economic and fossil fuel impacts with and without carbon permit trading. Energy 77: 791–801.

[17] Ystanes Føyn T.H. Karlsson K. Balyk A. Grohnheit P.E. (2011) A global renewable energy system: A modeling exercise in ETSAP/TIAM. Applied Energy 88: 526–534.

[18] Haurie A. Babonneau F. Edwards N. Holden P. Kanudia A. Labriet M. Pizzileo B. Vielle M. (2015). Fairness in Climate Negotiations: a Meta-Game Analysis Based on Community Integrated Assessment. In Willi Semmler and Lucas Bernard, eds., The [Oxford] Handbook of the Macroeconomics of Climate Change. Oxford University Press: 170–203.

[19] Dedinec A. Taseska-Gjorgievska V. Markovska N. Pop-Jordanov P. Kanevce G. Goldstein G. Pye S. Taleski R. (2016). Low emissions development pathways of the Macedonian energy sector. Renewable and Sustainable Energy Reviews 53: 1202–1211.

[20] Kalt G. Baumann M. Lauk C. Kastner T. Kranzl L. Schipfer F. Lexer M. Rammer W. Schaumberger A. Schriefl E. (2016). Transformation scenarios towards a low-carbon bioeconomy in Austria. Energy Strategy Reviews 13–14: 125–133.

[21] Tsai M.-S. Chang S.-L. (2015). Taiwan’s 2050 low carbon development roadmap: An evaluation with the MARKAL model. Renewable and Sustainable Energy Reviews 49: 178–191.

[22] Amorim F. Pina A. Gerbelová H. Pereira da Silva P. Vasconcelos J. Martins V. (2014). Electricity decarbonisation pathways for 2050 in Portugal: A TIMES (The Integrated MARKAL-EFOM System) based approach in closed versus open systems modeling. Energy 69 (1): 104–112.

[23] Pattupara R. Kannan R. (2016). Alternative low-carbon electricity pathways in Switzerland and it’s neighboring countries under a nuclear phase-out scenario. Applied Energy 172: 152–168.

[24] Li N. Ma D. Chen W. (2016). Quantifying the impacts of decarbonisation in China’s cement sector: A perspective from an integrated assessment approach. Applied Energy, In Press, Available online 15 January 2016.

[25] Ma D. Chen W. Yin X. Wang L. (2016). Quantifying the co-benefits of decarbonisation in China’s steel sector: An integrated assessment approach. Applied Energy 162: 1225–1237.

[26] Shi J. Chen W. Yin X. (2016). Modelling building’s decarbonization with application of China TIMES model. Applied Energy 162: 1303–1312.

[27] Krakowski V. Assoumou E. Mazauric V. Maïzi N. (2016). Feasible path toward 40–100% renewable energy shares for power supply in France by 2050: A prospective analysis. Applied Energy 171: 501–522.

[28] Tigas K. Giannakidis G. Mantzaris J. Lalas D. Sakellaridis N. Nakos C. Vougiouklakis Y. Theofilidi M. Pyrgioti E. Alexandridis A.T. (2015). Wide scale penetration of renewable electricity in the Greek energy system in view of the European decarbonization targets for 2050. Renewable and Sustainable Energy Reviews 42: 158–169.

[29] Deep Decarbonization Project Pathways (2015). Pathways to deep decarbonization. Published by the Sustainable Development Solutions Network (SDSN) and the Institute for Sustainable Development and International Relations (IDDRI). Retrieved from http://deepdecarbonization.org/about/

[30] Bataille C. Sawyer D. Melton N. (2015). Pathways to deep decarbonization in Canada. 47p. Retrieved from http://deepdecarbonization.org/wp-content/uploads/2015/09/DDPP_CAN.pdf

[31] Environment and Climate Change Canada (2016). Canada’s Mid-Century Long term Low Greenhouse Gas Development Strategy. Report submitted to the United Nations Framework Convention on Climate Change (UNFCCC), 87 p.

[32] What If? Technologies (2014). Canadian Energy System Simulator - CanESS. http://www.caness.ca

[33] National Energy Board (2013). Canada’s energy future 2013: energy supply and demand projections to 2035. Ottawa. Retrieved from http://www.neb-one.gc.ca/clf-nsi/rnrgynfmtn/nrgyrprt/nrgyftr/2013/nrgftr2013-eng.pdf

[34] Government of Canada (2015). Canada’s 2030 emissions target. News Release, September 29, 2015, Retrieved from http://news.gc.ca/web/article-en.do?nid=974949

[35] US Department of Energy (2015). All-electric vehicles. Energy Efficiency and Renewable Energy. Retrieved September 29, 2015, from https://www.fueleconomy.gov/feg/evtech.shtml

[36] Conference Board of Canada (2011). Canada’s Electricity Infrastructure Building a Case for Investment. Retrieved from http://www.electricity.ca/media/ReportsPublications/11-257_ElectricityInfrastructure[1].pdf

[37] Pye S. Anandarajah G. Fais B. McGlade C. Strachan N. (2015). Deep Decarbonization Pathways: UK. Retrieved from http://unsdsn.org/what-we-do/deep-decarbonization-pathways/

[38] Association québécoise de la production d’énergie renouvelable (2015). *Hydro Power*. Retrieved September 29, 2015, from http://www.aqper.com/en/how-long-does-it-take-to-build-a-hydroelectric-power-station