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Implications of EMF 34 scenarios on renewable deployment and carbon abatement in Canada: Insights from a regionalized energy model

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Abstract: This paper proposes a detailed analysis of the evolution of Canadian energy systems under some selected EMF (Energy Modeling Forum) 34 scenarios. Our analysis is based on NATEM, an energy model that follows the TIMES approach of the International Energy Agency to represent in detail the energy sector of each of the 13 Canadian provinces and territories. NATEM shows that imposing different renewable penetration constraints for electricity generation has limited impacts outside the electricity sector. In particular, greenhouse gas (GHG) emissions continue to increase over time. Conversely, the imposition of a carbon tax has broader impacts on Canadian energy systems and on GHG emissions that are almost stabilized. However, the level of the carbon tax envisions by the EMF 34 study (increasing to a maximum level of $130 per tonne by 2050) is not high enough, in a Canadian context, to trigger a decrease of GHG emissions over time as mandated by Canadian climate policies.

Keywords: Low-carbon energy system, renewable electricity, climate change mitigation, TIMES optimization model, prospective analysis

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1 Introduction

The aim of this paper is to provide a detailed Canadian perspective for the Energy Modeling Forum[1] (EMF) on its EMF 34[2] scenarios that deal with the issue of North American energy trade and integration.

Canada is among the world's top energy producers, ranked at the sixth place for the total amount of primary energy produced in 2016 (NRCAN, 2019). Canada is indeed endowed with an abundance of non-renewable energy resources, in particular crude oil (ranked third in the world for its proven reserves), uranium (third rank), but also coal (sixteenth rank) and natural gas (seventeenth rank). However, these resources are not uniformly distributed across Canada. For instance, 96% of its proven oil reserves correspond to oil sands found in the province of Alberta. Likewise, most of its uranium reserves are located in the province of Saskatchewan.

In terms of renewable energy, Canada is also among the world's top producers, with the seventh rank for its primary energy production from renewables, which contributed to about 17% of its total primary energy supply in 2016 (NRCAN, 2019). Here also, Canada benefits from a diversity of sources, such as hydropower, biomass, but also wind and solar. Hydroelectricity (that provided 60% of electricity generation and accounted for 67% of Canada's total renewable energy use in 2017) is well developed, with a total capacity close to 81 GW and hydro plants located in several provinces (in particular, Quebec, British Columbia, Newfoundland and Labrador, Ontario, and Manitoba). Biomass is the second-largest source of renewables in Canada, with 23% of Canada's total renewable energy use in 2017. It mainly comes from wood waste. There is a large potential for wind energy across Canada. In 2017, the total installed capacity was close to 13 GW, the provinces having the most installed capacities being Ontario and Quebec. Together with wind, solar photovoltaic energy is the fastest-growing source of electricity in the country, with a total installed capacity of about 3 GW in 2018, located mostly in Ontario.

Canada (through its federal government) and its provinces have several energy policies that set targets for renewable penetration in energy systems, see Langlois-Bertrand et al. (2018) for a detailed review. Most notably, targets relate to minimum contents of renewable fuels in gasoline and diesel, and to minimum shares of renewables in electricity generation mixes. For the electricity sectors, targets can also be expressed as (minimum) shares or installed capacities for clean (non-emitting) electricity generation. The province of Quebec also has targets for bioenergy production. Such objectives, together with targets on electrification and energy efficiency improvements that some provinces have adopted, shall help Canada reach greenhouse gas (GHG) emission reduction levels, in particular its commitment, under the UNFCCC Paris Agreement, to abate emissions by 30% from 2005 levels by 2030. Note that beyond energy policies, Canada has also adopted, under its Pan-Canadian Framework on Clean Growth and Climate Change (PCF), flexible approaches (taxes or systems of emission permits) to impose prices on GHG emissions (Canada, 2016). Besides, the federal government will impose a minimum carbon tax in provinces that do not regulate GHG emissions. However, this federal legislation is currently (2019) challenged by several provinces (Alberta, Quebec, Ontario, and Saskatchewan). Finally, on the longer term, it is worth mentioning that Canada ambitions to reduce its GHG emissions by 80% by 2050 from the 2005 level (Environment and Climate Change Canada, 2016).

The EMF 34 scenarios we consider in this study also deal with renewable penetration targets, with a focus on the power generation sector, and with carbon pricing. However, there are some notable differences with Canadian legislation. With a power sector relying in 2018 for about 80% on non-emitting GHG sources (StatCan, 2019), in particular hydro (59%), nuclear (15%), and wind (5%), the federal government's objective is to achieve a level of 90% by 2030 and 100% in the longer term. By contrast, EMF 34 scenarios only set targets for the penetration of solar photovoltaic and wind. In terms of carbon pricing, the federal government shall start in 2019 imposing its backup carbon tax at $20 CDN per tonne, with a yearly increase of $10 until 2022, at which year the policy will be revised.

[1] See: https://emf.stanford.edu
[2] See: https://emf.stanford.edu/projects/emf-34-north-american-energy-trade-and-integration

By contrast, the EMF carbon policy scenario envisions a carbon tax starting only in 2022, of $35 USD per tonne, with a yearly increase of 5%.

For the EMF 34 study, we rely on NATEM (Vaillancourt et al., 2017), a detailed bottom-up (BU) energy model that follows the TIMES approach (Loulou et al., 2016) of the International Energy Agency. NATEM offers a unique perspective on Canadian energy markets, as it is the only BU optimization model to detail, within the EMF 34, the whole energy system of each of the 13 Canadian provinces and territories. NATEM enables thus to analyze impacts on all energy markets of achieving renewable penetration targets (for the power generation sector), while accounting for Canadian regional disparities.

Beyond NATEM, several other models used for the EMF 34 study enable to analyze the Canadian energy sector, most notably: EC-MSMR (Zhu et al., 2018), Energy 2020 (Systematic Solutions, 2017), GCAM (Calvin et al., 2019), IPM (U.S. Environmental Protection Agency, 2020), MARKAL (developed by the U.S. National Energy Technology Laboratory–NETL; see for instance Balash et al., 2013) MUSE (Kerdan et al., 2019), NANGAM (Feijoo et al., 2016), NA-REGEN(an extension of the US-REGEN model, Electric Power Research Institute, 2020), and ReEDS (Cohen et al., 2019).

The North American Natural Gas Model (NANGAM) is a long-term partial-equilibrium model of the United States, Canadian, and Mexican gas markets. Its analysis is thus limited to the gas sector. Likewise, the Integrated Planning Model (IPM) and the Regional Energy Deployment System (ReEDS) only analyze North American electricity sector. The North American Regional Economy, Greenhouse Gas, and Energy (NA-REGEN) model also has a detailed view of the electric sector through a dispatch and capacity expansion model of the electric sector and combines it with a dynamic computable general equilibrium (CGE) model of the rest of the economy. United States jurisdictions are explicitly modeled, but not Canadian ones. Energy 2020, used in particular by the Canadian National Energy Board (NEB) to produce its *Canada's Energy Future* (see for instance: NEB, 2019), provides detailed simulations of Canadian energy markets, but does not derive optimal (energy) policies. Conversely, the MARKet ALlocation (MARKAL) model developed by NETL computes optimal configuration for the North American energy systems but consider Canada as a single jurisdiction. The ModUlar energy systems Simulation Environment (MUSE) model is a world energy systems model that provides detailed energy perspectives for 28 regions but does not distinguish among the different Canadian jurisdictions. Likewise, The Environment and Climate Change Canada's Multi-Sector Multi-Region (EC-MSMR) model is a world CGE model. It allows considering a broad economic perspective but aggregates all Canadian jurisdictions into a single region. Finally, the Global Change Assessment Model (GCAM) is an integrated assessment model that offers broad perspectives on energy and climate issues but considers Canada as a stand-alone region.

Despite its own limitations, NATEM offers a unique and complementary view to enrich the EMF 34 study, with its TIMES modeling paradigm. This paper aims thus to provide a deeper analysis of the whole Canadian energy systems for several EMF 34 scenarios, to complete inter-model comparisons that focus on selected results only. Besides, this paper ambitions to contribute to the ongoing Canadian debate on how to proceed in the energy sector to abate GHG emissions.

The remainder of this paper is organized as follows. Section 2 briefly recalls the TIMES approach and the main characteristics of NATEM. Section 3 details the EMF34 scenarios that we consider and the specific assumptions we have made for Canada. Section 4 details our Canadian regional specific results. Section 5 contains a brief discussion, while Section 6 concludes.

2 Modeling approach

TIMES follows a bottom-up approach to describing the whole energy system of a given jurisdiction (e.g., a city, a region or a country). It is based on reference energy system (RES) concept to represent the various energy carriers and energy technologies, from supply of primary energy to consumption of final energy to satisfy useful energy demands (energy services). Actually, a TIMES model is driven by a set of exogenously assumed demands for energy services (e.g., demand for personal transportation), mobilizing different types of end-use technologies (e.g., vehicles with an internal combustion engine or battery electric vehicles) that consume different forms of final energy (e.g., fossil fuels, biofuels or electricity). In turn, TIMES envisions different production or conversion technologies (e.g., refineries, biorefineries or power plants) that use primary energy (e.g., crude oil, biomass or hydropower) to deliver the needed (final) energy. The model finally tracks supply of primary energy, as well as trade of the various energy forms. It also tracks air contaminant emissions as well as GHG emissions[3].

TIMES is mathematically cast as a dynamic, linear programming (optimization) model. Decision variables correspond in particular to energy flows throughout the whole energy sector, as well as installed capacities and activity levels of energy technologies. Numerous constraints ensure for instance that energy balances are maintained throughout the energy systems and that useful energy demands are satisfied. Note that these demands are elastic to their own prices. The objective function corresponds to maximizing producer and consumer surpluses but is implemented as the minimization of the overall energy system cost. Under some assumptions, such as perfect information and perfect foresight for economic agents, a single optimization describes a potential evolution of the energy systems that would be socially desirable and where energy markets would be in equilibrium.

NATEM (North American TIMES Energy Model) uses the TIMES approach to model the energy sector of each of the 13 Canadian provinces and territories, as well as flows of energy and material commodities between them. The model contains a rich database that details 475 such commodities, and more than 4500 explicit technologies with their economic and technical parameters. Hypotheses on the evolution of key technologies come from different Canadian and international sources, for instance CanSIA (2016), Fu et al. (2017), and Wiser et al. (2016) for intermittent renewables. NATEM also distinguishes between 70 demands for energy services. It is calibrated to a 2011 base year and extends to a 2050 horizon. Between 2011 and 2050, NATEM considers 10 time periods and 16 annual time slices (4 seasons a year and 4 intraday periods). Costs are in 2011 Canadian dollars, with future costs being discounted at 5% per year. The model has already been applied to analyze Canadian energy issues (Levasseur et al., 2017; Vaillancourt et al., 2018a, 2019) as well as Canadian climate policies (Vaillancourt et al., 2018b).

3 Scenarios

Among the different EMF34 scenarios, we have selected the following five ones to be extensively analyzed in a Canadian context:

REF: Our reference scenario that represents a counterfactual business-as-usual case, without any renewable penetration targets or GHG emission reduction targets.

INT: A high intermittent renewable penetration scenario, that considers an increase by 20% (by 2030) and 30% (by 2050) of the penetration of centralized solar and wind generation compared to the REF case. This increased penetration could be achieved through cost reductions. However, in our model that follows a linear programming approach, we have simply imposed market penetration constraints to achieve the required penetration levels.

RNW1: A scenario where renewable penetration targets are imposed at the Canadian level, such that the contribution of all renewables (including hydro power) to satisfy electricity demand is at least 30% in 2020, 40% in 2030, 50% in 2040, and 60% in 2050, with linear ramps between years. This is again achieved in NATEM through market penetration constraints.

RNW2: A scenario with the same renewable penetration targets as in RNW1, but where the penetration goals should be achieved individually in each of the 13 Canadian jurisdictions. This is again implemented in NATEM using market penetration constraints.

[3] Note that, to compute emissions in CO2-eq., we have used a GWP factor of 25 for methane and 298 for nitrous oxide, so as to be compatible with the Canadian GHG national inventory (Environment and Climate Change Canada, 2018).

TAX: A climate policy scenario where a carbon tax is (only) imposed in Canada as follows: $33.25/tonne (in 2011 CAD, or equivalently $35/tonne in 2015 USD) starting in 2022 and increasing at 5% per year until 2050.

The version of NATEM used here only models Canadian energy systems. All energy trade movements between Canadian jurisdictions are modeled endogenously, i.e., NATEM computes the relevant additional investments (if any), optimal energy flows, and energy prices. However, international trade movements are modeled exogenously through fixed quantities and prices, since NATEM does not optimize the US energy systems nor the rest of the world. This translates into optimistic assumptions regarding the size of international markets for Canadian exports which are not restricted to a large extent. This concerns for instance the exports of clean electricity from Eastern provinces to New England, or the exports of liquefied natural gas to the rest of the world through the Canadian West Coast. The integration of certain policies in the reference case is another aspect that was not harmonized between modeling teams and that could lead to significant differences between scenario results. There are two policies in particular that were recently announced by the federal government but faces important oppositions from some provinces or implementation challenges. These are the federal carbon tax and the clean-fuel standard which is still in a consultation phase. We have chosen not to include these two policies in our baseline.

4 Result analysis

This next section presents our numerical results that correspond to optimal trajectories computed by NATEM for the different Canadian jurisdictions. For simplicity, we will mostly report either on Canadian (overall) values or on two groups of jurisdictions: Eastern Canada (Quebec, Ontario, and the Atlantic provinces), and Western Canada (the three prairie provinces, British Columbia and the three Territories). Note that in the forthcoming graphs, results are reported on a per annuum basis.

4.1 Primary energy production

Figure 1 displays the evolution of primary energy production by type in the different scenarios. In 2015, primary energy supply comes mostly from fossil fuels (for 67%) and uranium (24%). In REF, primary energy production increases by 34%, between 2015 and 2050, to reach a level about 35 EJ. This increase is mostly due to fossil fuels: unconventional oil (77% increase), conventional oil (56%), and natural gas (49%), that compensate for a decrease in coal production (70% decrease). By 2050, these fossil fuels (except a tiny fraction of conventional oil) are all produced in Western Canada, where most of the reserves are located. There is also a notable increase in the exploitation of biomass resources (by 41%, between 2015 and 2050) that concerns both regions (Eastern and Western Canada), but the amount involved (285 PJ) is comparatively quite small.

For the above-mentioned energy types, the evolution is similar in the scenarios INT, RNW1, and RNW2. However, the category 'other renewables' (solar and wind energy) sees in these scenarios a progressive increase (up to a factor 3.5) that mostly takes place in Eastern Canada. But, again, the amounts concerned (in PJ) are relatively small. The TAX scenario introduces further differences. On the one hand, total primary energy production increases less between 2015 and 2050 (only 22%) due in particular to a reduction overtime in the production of natural gas. On the other hand, the exploitation of other renewables (solar and wind) as well as biomass resources is on a larger scale.

4.2 Electricity generation

Figure 2 displays next the evolution of electricity generation by sources in the different scenarios. In 2015, electricity is mostly generated from hydro power plants (for 60%), but also from thermal (19%) and nuclear (15%) power plants. Due to a very uneven distribution of primary resources in Canada (Vaillancourt et al., 2018b), the electricity generation mix is, however, quite different across jurisdictions, as indicated in Figure 3 (Eastern Canada) and Figure 4 (Western Canada). Whereas

Eastern Canada relies primarily on hydro (57.5 GW of installed capacity) and nuclear (13.7 GW, in Ontario), Western Canada mix is dominated by hydro (22.3 GW, located mainly in British Columbia and Manitoba) and thermal power plants (18.5 GW, mostly in Alberta and Saskatchewan).

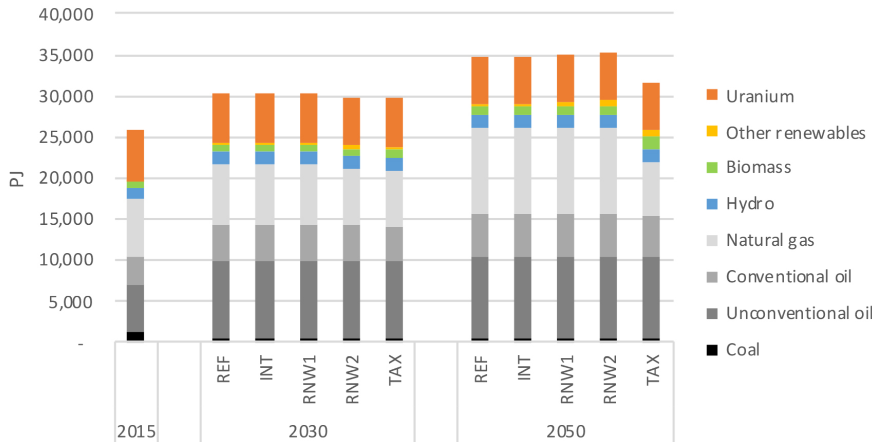

Figure 1: Primary energy production by type in Canada (in PJ)

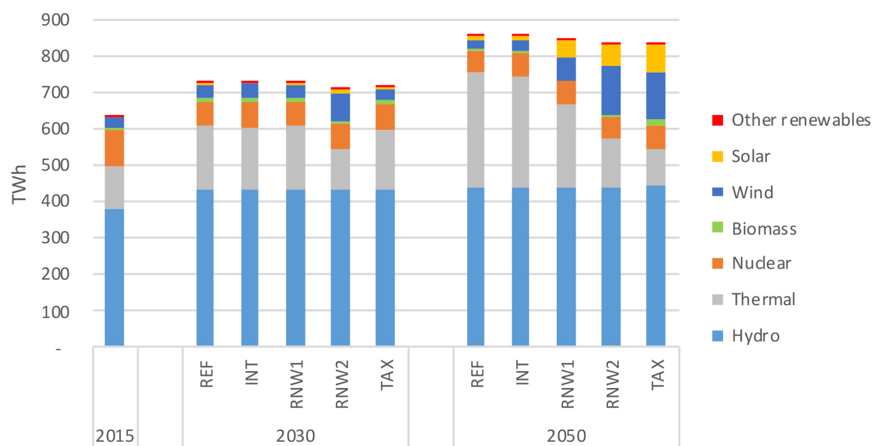

Figure 2: Electricity generation by source in Canada (in TWh)

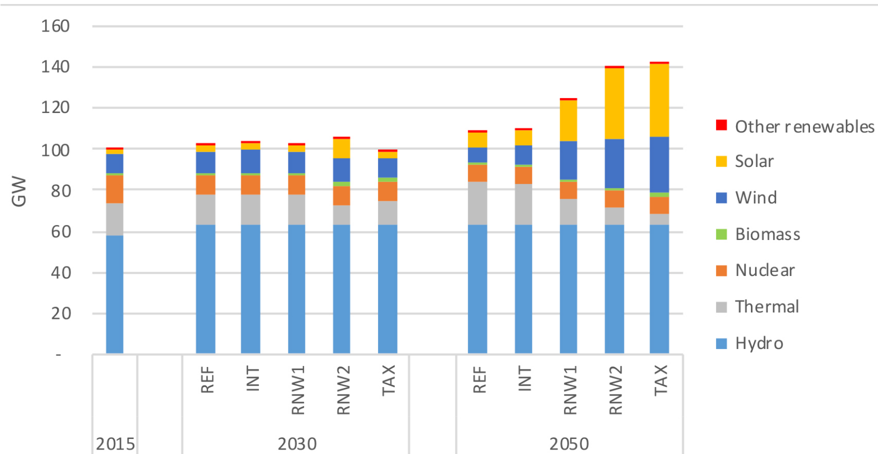

Figure 3: Installed capacity by type in Eastern Canada (in GW)

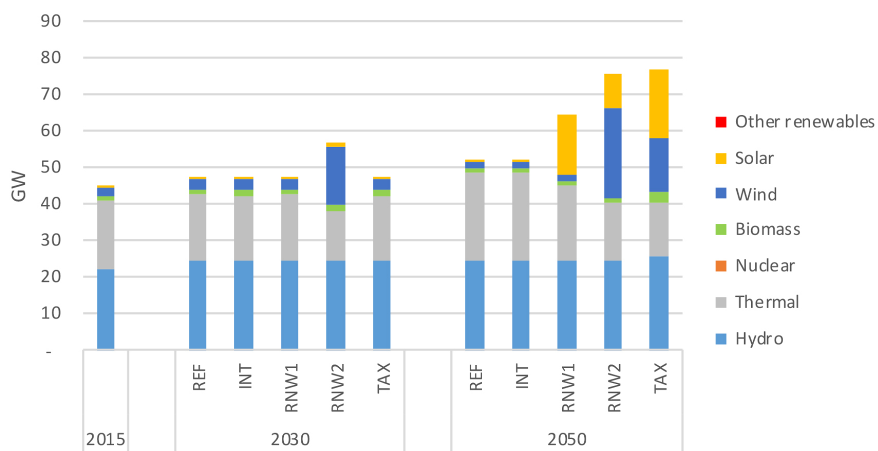

Figure 4: Installed capacity by type in Western Canada (in GW)

In the REF scenario, Canadian electricity generation increases by 35% by 2050. This increase is met with 10.8 GW of additional (gas-fired) thermal capacity and 7.4 GW of additional hydro capacity (mostly in Eastern Canada), while nuclear capacity (in Ontario) loses 5.3 GW since not all existing reactors are covered by a scheduled refurbishment program.

The INT scenario, that imposes penetration constraints on centralized solar and wind generation, only benefits wind power that gains an extra 2.6 GW of installed capacity (compared to the 2050 REF situation). Wind farms are mostly installed in Eastern Canada (for 2.3 GW).

In the RNW1 scenario, compared to the 2050 REF situation, the electricity mix changes notably with a decrease of thermal generation mostly in favor of decentralized solar generation (with an additional 28.8 GW of installed capacity, 16.7 GW in Western Canada, the remaining in Eastern Canada) and wind generation (plus 11.1 GW, again almost exclusively in Eastern Canada).

In the RNW2 scenario, that imposes renewable penetration constraints for each of the 13 Canadian jurisdictions, the decrease of thermal generation is more pronounced. Here, wind is the largest beneficiary, with an additional 40.1 GW of installed capacity (compared to the 2050 REF situation) followed by decentralized solar (plus 35.8 GW). But compared to the RNW1 case, this additional capacity is better distributed between the two regions: Western Canada gets 23.0 GW additional wind capacity and 9.2 GW of solar, whereas Eastern Canada gets 17.1 GW additional wind capacity and 26.6 GW of solar.

Finally, in the TAX scenario, thermal generation is further reduced as it loses its second position in terms of 2050 market shares (with 12%) to wind (16%). Beyond wind, solar, biomass and hydro all get additional installed capacity compared to the 2050 REF situation. Solar benefits the most, with 45.8 additional capacity (60% of which is in Eastern Canada). Biomass generation increases by 1.9 GW (69% of which is in Western Canada). Hydro generation increases by 1.3 GW, exclusively in Manitoba (Western Canada).

While large-scale wind farm projects are attractive for meeting renewable target policies or in reaction to a carbon tax, solar penetration in the electricity mix is rather explained by the availability of distributed generation and storage options. Investment costs for solar rooftops on residential and commercial buildings have indeed been declining dramatically in the recent past.

4.3 Final energy consumption

Figure 5 displays next the evolution of final energy consumption by type in the different scenarios. In 2015, fossil fuels are dominant (69% of the total), together with electricity (23%). In our baseline (case REF), final energy consumption increases by 33% between 2015 and 2050. The additional 2582 PJ of final energy consumed mainly comes from the industrial sector (for 62%) and the transport sector (for 29%). Besides, in 2050, final energy is mainly consumed by the transport sector (39% of the total) and by the industrial sector (35% of the total). In terms of energy mix, fossil fuels remain predominant (70% of the total by 2050, compared to 69% in 2015), but natural gas replaces oil products as the main final energy consumed.

The evolution is very similar in the scenarios INT, RNW1, and RNW2 that impose renewable penetration targets for electricity generation. However, some notable differences appear with the introduction of a carbon tax (scenario TAX). On the one hand, final energy consumption increases less between 2015 and 2050 (only 29%). This is the result of a lower increase in demands for energy services due to price elasticity, and of energy efficiency improvements through technological substitutions. On the other hand, the consumption of bioenergy and electricity is larger, at the expense of fossil fuels whose share is only 66% by 2050.

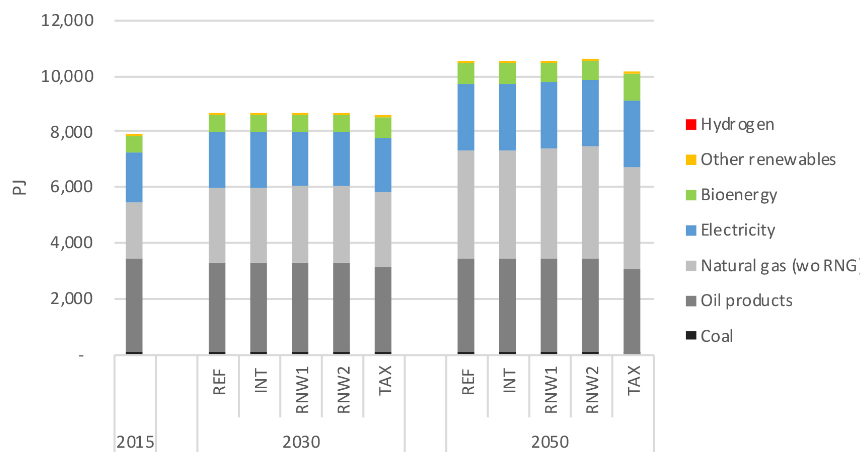

Figure 5: Final energy consumption by type in Canada (in PJ)

In the commercial and residential sectors, natural gas (without accounting for renewable natural gas–RNG) is the main type of final energy consumed overtime in the REF case, with a share reaching 57% by 2050. Electricity is a solid second, with a share of 41% by 2050. The commercial sector relies mainly on natural gas systems, while the residential sector includes a mix of natural gas systems with electric resistance (and air-source heat pump in a lesser manner). It remains so for the other cases, with the notable difference that a fraction of the electricity consumed is generated from (decentralized) solar PV, up to 23% in the TAX case by 2050, about ten times more than in the REF case. Similar patterns can be observed overtime in both Eastern and Western Canada, but in the latter region there is a stronger reliance on natural gas (with shares around 66% in the different scenarios) compared to the former where shares of natural gas are about 51%.

In the industrial sector, the main types of final energy consumed overtime in the REF case are natural gas (including liquified natural gas) with a share of 49% by 2050, electricity (32%), and bioenergy (14%). In the INT, RNW1, and RNW2 cases, shares are rather similar. However, in the TAX case, both bioenergy (share of 16% by 2050) and electricity (33%) register some gains at the expense of natural gas (47%). Similar patterns can be observed overtime in both Eastern and Western Canada, but again, in the latter, there is a stronger reliance on natural gas (with shares varying between 53% in the TAX case and 59% in RNW2) compared to the former region where shares of natural gas are about 44% in the different scenarios.

In the transport sector, one should distinguish between passenger and freight transportation. For the former, gasoline is the main type of final energy consumed in the REF case (62% by 2050), but it loses overtime market shares in favor of biofuels (10% by 2050) and electricity (8%). One observes the same for the policy scenarios, but trends are slightly more pronounced in the TAX case. Based on previous studies (Vaillancourt et al., 2017, 2018b), a much higher carbon price is indeed necessary to trigger a significant electrification of the passenger transportation segment. In 2050, light-duty vehicles still account for 70% of the total consumption in this segment. For freight transportation, diesel and gasoline are the main fuels consumed in the REF case (respectively 57% and 23% by 2050), but their market shares decrease overtime in favor of natural gas (17% by 2050) for heavy trucking and marine transport. These trends are about the same for the other policy scenarios, but again trends are more pronounced in the TAX case. Besides, in the latter case, biofuels reach a market share of 8% by 2050 (vs. 2% in the other cases). For each transportation category (passenger and freight), similar patterns can be observed overtime in both Eastern and Western Canada for the different scenarios. For freight transportation, however, Western Canada relies significantly more on natural gas (with 2050 shares varying between 20% and 23% across scenarios) than Eastern Canada (shares are between 11% and 12%).

4.4 Overview of energy trade

Figure 6 displays next the evolution of net energy exports by type in the different scenarios. This corresponds to the difference between exports and imports on international energy markets. In 2015, Canada is a net exporter of around 7.7 EJ of fossil fuels (mostly crude oil and natural gas) and 5.1 EJ of uranium. Exports originate from Western Canada (Alberta and Saskatchewan), whereas Eastern Canada imports around 2 EJ of fossil fuels. In the REF case, net exports increase by a factor 1.4 between 2015 and 2050, driven mainly by the increase of crude oil exports (in particular unconventional oil from Alberta). One can also notice that by 2050 Canada imports around 0.9 EJ of natural gas (to satisfy Eastern Canada needs), while it exports about twice that amount as LNG (originating again from Western Canada). Note that the natural gas production profile of NATEM follows projections from the National Energy Board (2019) with optimistic assumptions on the access of North American natural gas to markets outside North America. There is also an increase in exports of electricity (by an overall factor 1.2, between 2015 and 2050) from both regions (Eastern and Western Canada), but the amount involved (an increase of around 9.3 TWh) is comparatively quite small.

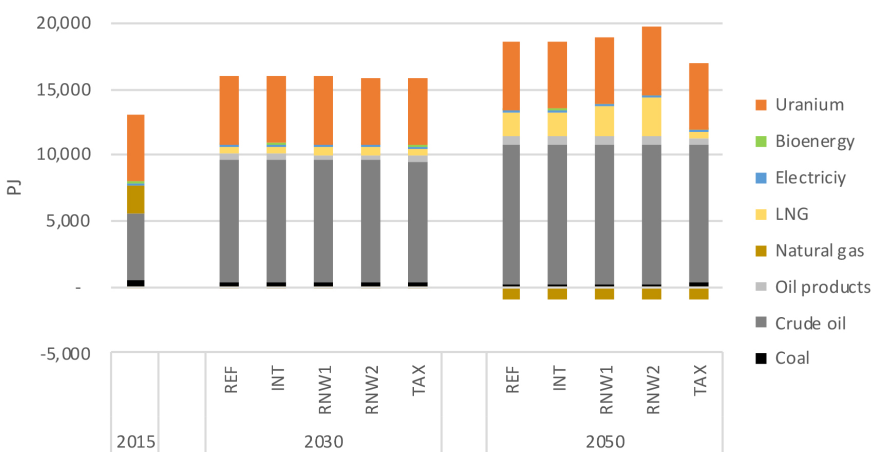

Figure 6: Net energy exports by type in Canada (in PJ)

In the INT scenario, net energy exports are almost identical to the REF situation. In the RNW1 and RNW2 cases, the evolution over time is similar but involves some higher levels (3% to 7% higher, from the 2050 REF level). These cases impose renewable penetration targets on electricity markets. The resulting decrease in thermal electricity generation makes an additional amount of fossil fuels (mainly natural gas) available for export to international markets. In the TAX case, there is still an increase in net exports between 2015 and 2050 but only by a factor 1.2. In 2050, the main difference from the REF case is the reduction in the next export of LNG, consecutive to the reduction of natural gas production (see again Figure 1).

4.5 GHG emissions

Figure 7 finally displays the evolution over time of Canadian GHG emissions in the different scenarios. In the REF case, emissions increase by 32% between 2015 and 2050, with a higher increase in Western Canada (37%) driven in particular by emissions from fossil fuel extraction in Alberta and Saskatchewan, and a lower increase in Eastern Canada (24%). The impact of renewable penetration targets on GHG emissions (in cases INT, RNW1 and RNW2) is rather limited. Conversely, the carbon tax imposed (in scenario TAX) enables to control emission growth, with an increase of only 6% between 2015 and 2050. However, the emission level by 2050 (794.2 Mt CO_2-eq.) is far above the Canadian ambition to abate its GHG emissions by 80% by 2050 relative to 2005.

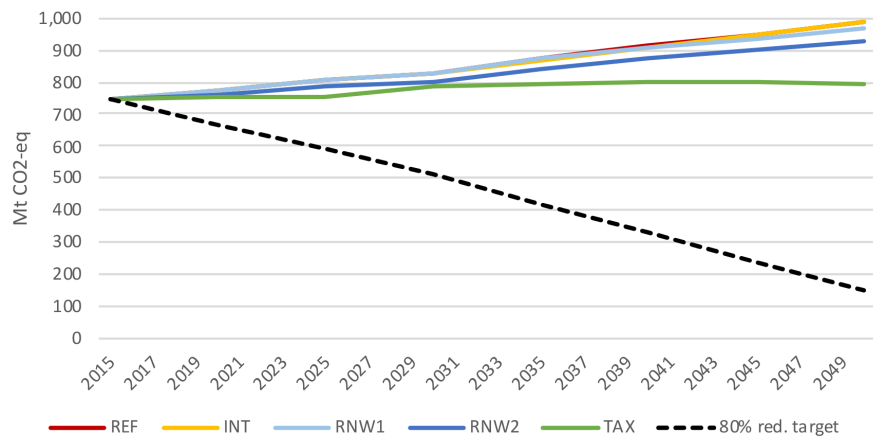

Figure 7: GHG emissions in Canada, with the Canadian 2050 reduction target (in Mt CO_2–eq.)

5 Discussion

In 2015, the Canadian electricity sector is already rather decarbonized, with thermal generation accounting for only 19% of the total electricity generated, whereas wind and solar account for 4% an 1%, respectively.

The INT scenario, that imposes penetration constraints on centralized solar and wind generation, yields in 2050 an additional 8.4 TWh of electricity generated from wind power (relative to the baseline). However, there is no effect on solar generation and thermal generation in 2050 is only reduced by 7.9 TWh compared to the REF case. Besides, there is no notable effect outside the electricity sector. As a result, the impact on Canadian GHG emissions is very limited, with a decrease of only 2.2 Mt CO_2-eq. by 2050 (compared to the baseline where emissions reach 987.5 Mt CO_2-eq., an increase of 32% from 2015 levels).

The RNW1 scenario includes all renewables in the penetration targets imposed on electricity generation at the Canadian level. However, these targets benefit only to intermittent renewables. In 2050, an additional 38.8 TWh is generated from solar and an additional 34.2 TWh from wind power, compared to the REF levels. In the meantime, thermal generation is reduced by 85.8 TWh by 2050 from the baseline. But again, there is no significant effect outside the electricity sector. And the impact on Canadian GHG emissions remains limited, with a decrease of 22.9 Mt CO_2-eq. by 2050 compared to the baseline.

The RNW2 scenario imposes the same renewable penetration targets as in RNW1, but these levels have to be reached in each of the 13 Canadian jurisdictions (provinces and territories) individually. In the electricity sector, trends are similar to the RNW1 case, only stronger. In 2050, an additional 48.3 TWh is generated from solar and 108.1 TWh from wind power, while thermal generation is reduced by 180.8 TWh, compared to the baseline. As in the RNW1 case, there is no significant effect outside the electricity sector. The energy policy envisioned slows down a little GHG emission growth to a level of 928.6 Mt CO_2-eq., an increase of 24% from 2015 levels.

On the electricity sector, the imposition of the carbon tax envisioned in the TAX case has stronger and broader impacts than our energy policy cases (INT, RNW1, and RNW2). It favors not only the penetration of intermittent renewables (solar and wind) but also hydro and biomass that all gain market shares (by 2050, compared to the REF case) at the expense of thermal generation. In terms of electricity generated, this corresponds to an additional 61.7 TWh from solar, 107.3 TWh from wind, 11.9 TWh from biomass, and 8.3 TWh from hydro, while thermal generation is reduced by 215.3 TWh, compared to the 2050 baseline levels. Beyond electricity, the final consumption of bioenergy and other renewables also increases. Consequently, of all policy scenarios considered, the TAX case has the strongest impact on GHG emissions that are 'almost' stabilized, with an increase of only 6% from 2015 levels. However, the 2050 emission levels (794.2 Mt CO_2-eq.) is 'far above' the level (146.4 Mt CO_2-eq.) that would correspond to the 80% reduction target (from 2005 levels) that Canada ambitions to reach by 2050, see again Figure 7. As shown in Vaillancourt et al. (2017, 2018b), such an ambition would indeed require much higher taxation levels. The gap in GHG emissions to reach the target could be achieved in particular through: i) a full decarbonization of electricity generation, whereas thermal generation retains by 2050 a 12% market share in our TAX case; and ii) a strong electrification of end-use sectors, with share of electricity consumption (over total final energy consumption) going beyond 50%, whereas this share is only 24% in our TAX case.

6 Conclusion and policy implications

This paper analyzes the impact of selected EMF 34 scenarios on the Canadian energy systems, taking into account regional diversities between the 13 Canadian provinces and territories. Imposing renewable penetration targets for electricity generation (in our scenario INT, RNW1, and RNW2) favors mostly wind and decentralized solar generation. But effects remain mostly contained to electricity markets and GHG emission increase over time is only (slightly) reduced. An economy-wide carbon tax, however, targets not only the electricity sector but all energy systems relying on fossil fuels. The carbon tax envisioned in this study (in our scenario TAX) not only has a stronger impact on renewable penetration but also enables to better control GHG emissions. Given the current concern of the Canadian federal government to abate significantly GHG emissions, a carbon tax appears to be a relevant policy. However, in the current context (2019) where several provinces are challenging in court the introduction of a federal carbon tax, the political acceptability of such a measure has yet to be determined.

As in any modeling exercise, results are strongly linked to model structures, solution approaches, level of disaggregation and assumptions. For this paper, we have used a very detailed TIMES optimization model, but for Canada only. Including the energy systems of the United States and Mexico with the same level of detail would certainly show different perspectives, namely regarding the Canadian exports to the rest of the continent. Future works will allow completing the modeling of the energy systems of the United States and Mexico in NATEM, and consequently, to have a better overview of the integration potential for achieving high renewable penetration rates and carbon mitigation targets.

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