Les Cahiers du GERAD ISSN: 0711–2440

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G–2013–70

October 2013

CITATION ORIGINALE / ORIGINAL CITATION

K. Vaillancourt, Y. Alcocer, O. Bahn, C. Fertel, E. Frenette, H. Garbouj, A. Kanudia, M. Labriet, R. Loulou, M. Marcy, Y. Neji, J.-Ph. Waaub, A canadian 2050 energy outlook: Analysis with the multi-regional model TIMES-Canada, Applied Energy, 132, 56–65, 2014, https://doi.org/10.1016/j.apenergy.2014.06.072.

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, 2013
– Bibliothèque et Archives Canada, 2013

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.

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A Canadian 2050 Energy Outlook: Analysis with the Multi-Regional Model TIMES-Canada

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Abstract: In terms of energy resources, Canada is an important player on the world scene. However, the energy systems of the Canadian provinces and territories are much diversified and a national energy strategy is missing in order to optimize the management of energy systems.

The objective of this paper is two-fold. First, we introduce TIMES-Canada, a new multi-regional energy model that has been developed using the most advanced TIMES optimization modeling framework, while keeping a very high level of details in the database (5,000 specific technologies; 400 commodities) compared with other Canadian energy models. Second, we define and analyze possible futures for the Canadian integrated energy system on a 2050 horizon, under five different baselines: a Reference scenario as well as four alternate scenarios corresponding to different oil prices (Low and High) and socio-economic growth trends (Slow and Fast).

In our Reference scenario, we show that the Canadian final energy consumption is expected to increase by 43% between 2007 and 2050. The Fast scenario leads to the maximum increase compared with the Reference scenario (21% in 2050). In all scenarios, oil products will continue to dominate on the long term, although in a decreasing proportion over time (from 43% in 2007 to 29% in 2050) in favour of electricity (31% of the additional demand in 2050) and biomass/biofuels. Regarding the corresponding optimal energy production paths, we illustrate two main trends: 1) a gradual replacement of onshore conventional oil & gas sources by unconventional and offshore sources (oil sands is expected to represent half of the production in 2050), and 2) a significant penetration of renewables in the electricity mix is shown after 2035 due to increases in oil import prices and decreases in renewable technology costs. The development and calibration of such a detailed technology-rich model represent an important contribution for Canada: TIMES-Canada is the only optimization model covering in details the large diversity of provincial energy systems on a long term horizon.

Key Words: Bottom-up energy modeling, energy systems, baseline scenarios, policy analysis.

Acknowledgments: The authors wish to acknowledge financial support from the Natural Sciences and Engineering Research Council of Canada (NSERC individual and strategic grants), from the Quebec Ministry of Economic Development, Innovation and Export Trade (MDEIE) and from the Canadian Government Post-Doctoral Research Fellowships. Natural Resources Canada and Environment Canada were partners of our NSERC strategic grant. The REACCESS project (Seventh Framework Program of the European Union) and Hydro-Québec were partners of our MDEIE funded project.

1 Introduction

The objective of this paper is two-fold. First, we introduce the new multi-regional energy model TIMES-Canada, an application of the TIMES model generator [1], a bottom-up optimization model that represents, in details, the whole integrated energy sector from primary to useful energy. Second, we define and analyze possible futures for the Canadian integrated energy system on a 2050 horizon, under different baselines corresponding to different socio-economic growth trends.

In terms of energy resources, Canada is an important player on the world scene. Indeed, the country is the second largest supplier of natural uranium [2], a leader in hydroelectricity generation and an important producer of oil, gas and coal [3], in particular from unconventional (oil) resources. However, given the global concerns about climate change, the unconventional oil industry is facing important environmental and reputational risk challenges. At the same time, a large proportion of the energy consumed in Canada is imported, especially oil products for transportation and natural gas for industries, in Central and Eastern provinces [4]. Consequently, energy security has become a priority on political agendas for non-producing provinces even though Canada is an important energy producer. In other words, the energy systems of the Canadian provinces and territories are diversified leading to different future challenges, in particular: environmental issues for fossil fuel producing provinces and energy security issues for importing and exporting provinces. In addition to this diversity of existing situations and future challenges, a national energy strategy is missing in order to optimize the management of energy systems and the conception of consistent energy policies [5].

To study possible futures for the Canadian energy sector, and help Canada meet its various energy challenges, we propose TIMES-Canada, a new multi-regional energy model that has been developed using the most advanced TIMES optimization modeling framework, while keeping a very high level of details in the database compared with global energy models. TIMES-Canada represents the outcome of a three-year research project realized with support from the Office of Energy Research and Development (OERD) of Natural Resources Canada.

The development and calibration of such a detailed technology-rich model represent an important contribution for Canada: TIMES-Canada is the only optimization model covering in details the large diversity of provincial energy systems on a long term horizon (up to 2100). In particular, the development of a consistent energy supply sector database represents an important contribution to energy analysis in Canada due to the fast growing trends and data confidentiality issues. In particular, the unconventional oil & gas sectors have been evolving rapidly in recent years and significant data gathering (from governments, associations and companies) as well as modeling efforts were needed to adequately model an accurate evolution of these industries in Canada. Similarly for electricity generation capacity and annual activity, the modeling implied taking into account thousands of plant units for which techno-economic data are not publicly available.

This paper is organized as follows. Section 2 gives an overview of existing energy models that underlie international and Canadian official energy outlooks. Section 3 presents the TIMES modeling approach in general and gives the main characteristics of TIMES-Canada in particular with an overview of the database structure and content. Section 4 details our calibration approach. Section 5 provides detailed analysis of baselines, namely: Final energy demand by fuel, energy supply such as oil production and electricity generation. In Section 6, we compare some of our results with the ones from existing outlooks before concluding in Section 7.

2 Literature review

In this section, we look at different outlooks covering Canadian trends as well as the underlying models behind these projections.

2.1 International outlooks

The two main institutions producing global energy outlooks annually are the U.S. EIA (Energy Information Administration) in Washington D.C. and the IEA (International Energy Agency) in Paris. The *IEO (International Energy Outlook)* of the EIA [6] examines 16 international energy markets, including Canada, under different socio-economic growth scenarios through 2035. Their projections are generated using the WEPS+ (World Energy Projections Plus) econometric model, a system of individual energy supply/demand modules that communicate through a central database [7]. The WEO (*World Energy Outlook*) of the IEA [8] contains an assessment of future energy trends in 25 world regions, including Canada, under different policy scenarios through 2035. Their projections are produced using WEM (World Energy Model), a partial-equilibrium simulation model [9]. The IEA [10,11] provides also *Energy Technology Perspectives* (ETP) that corresponds to long-term assessment of optimal energy strategies under existing WEO scenarios. The primary tool for these analyses is ETP, a technology-rich model that optimizes the energy system of 15-region, including Canada, and extends the WEO scenarios to a 2075 horizon. ETP belongs to the MARKAL and TIMES family of models (see Section 3.1).

2.2 Canadian outlooks

At the Canadian level, three main federal entities deal with energy models for internal analysis or outlook publication. The NEB (National Energy Board), an independent federal agency, is currently the most active entity in providing energy outlooks. Their latest outlook [3] contains a business-as-usual scenario as well as four sensitivity scenarios projecting Canadian energy supply and demand to 2035 according to different oil prices and economic growth rates. They are developed using a two-component modeling framework: 1) Energy 2020, a North American multi-region, multi-sector model that simulates supply and demand for all fuels, and 2) TIM (The Informetrica Model), a dynamic econometric model of the Canadian economy used to generate macroeconomic projections [12]. Both models run simultaneously and communicate in an iterative process for each year in the modeling horizon. Since 2011, the same modeling framework is used by Environment Canada, under the following name: The Energy, Emissions and Economy Model for Canada (E3MC). Their second annual report on GHG emission projections presents a reference baseline scenario as well as alternative scenarios resulting in a range of plausible emissions growth trajectories through 2020 [13]. Finally, Natural Resources Canada has published their latest Canadian Energy Outlook (CEO) in 2006. The report [14] presented a reference scenario for Canadian energy supply, demand and emissions for 2020 using MAPLE-C (Model to Analyze Policies Linked to Energy in Canada). MAPLE-C is a modular system similar to the NEMS (National Energy Model System) model [15] used for the US Annual Energy Outlook [16], where each supply/demand component communicates through the integrating module and is linked to a macroeconomic module. However, the model is currently not used for providing public outlooks.

2.3 Canadian mitigation studies

Although policy studies are not the focus of our paper, it is worth noting that bottom-up models have also been developed within academic research centers and used to provide governmental institutions with useful insights for designing energy or climate change mitigation strategies. In particular, two Canadian models have been developed in the past for costing GHG abatement policies in the Canadian National Climate Change Implementation Process [17]: The CIMS (Canadian Integrated Modeling System) model developed by the Energy and Materials Research Group at Simon Fraser University and the Canadian MARKAL (MARKet ALlocation) optimization model developed by the Energy Modeling Group at GERAD (Group for Research in Decision Analysis) in Montreal. CIMS is a simulation model that includes a representation of technologies that produce goods and services throughout the economy as well as equilibrium feedbacks. More recently, the CIMS model has been calibrated to Environment Canada baselines to analyse carbon pricing policies to meet a 65% emission reduction target by 2050 (below 2006 levels) for the National Round Table on the Environment and the Economy [18,19][1]. As for the original 11-region Canadian MARKAL [20], it has been used for numerous studies in the past [21,22,23], but it is not being used anymore. Indeed, the modeling

[1] The NRTEE has ceased operation as of March 31, 2013.

activities have evolved toward the construction of the next generation TIMES (The Integrated MARKAL-EFOM Systems) model generator destined to replace MARKAL [1].

3 Modeling approach

3.1 Overview of TIMES models

The TIMES model generator combines all the advanced features of the MARKAL models [24] and to a lesser extent the ones of the EFOM (*Energy Flow Optimization Model*) model [25], as well as various new features developed over time; see [1]. Within the Energy Technology Systems Analysis Program [26] of the International Energy Agency, MARKAL and TIMES models are currently used by more than 80 institutions in nearly 70 countries for various purposes including economic analysis of climate and energy policies.

A TIMES model represents the entire energy system of a country or region. Such a system typically includes extraction, transformation, distribution, end-uses, and trade of various energy forms and (some) materials. Each stage is described by means of specific technologies characterized by economic and technological parameters. The model also tracks GHG and criteria air contaminant (CAC) emissions from fuel combustion and processes. In baseline scenarios, end-use demands are exogenously specified in terms of socio-economic needs (e.g., transportation, expressed in vehicle-kilometres) over a future horizon.

A TIMES model is cast as a dynamic linear programming model. Under the assumption that energy markets are under perfect competition, a single optimization, which searches for the maximal net total surplus, simulates market equilibrium. Maximizing the net total surplus (i.e. the sum of producers' and consumers' surpluses) is operationally done by minimizing the net total cost of the energy system that includes investment costs, operation and maintenance costs, plus the costs of imported fuels, minus the incomes of exported fuels, minus the residual value of technologies at the end of the model horizon, plus welfare losses due to endogenous demand reductions (see below). The main model outputs are future investments and activities of technologies at each period of time. Important additional outputs of the model are the implicit (shadow) price of each energy material and emission commodity, as well as the reduced cost of each technology.

In addition, TIMES models in general acknowledge that demands are elastic to their own prices contrary to traditional bottom-up models. Although not required in our current baseline analysis, this feature makes possible the endogenous variation of demands in constrained scenarios (e.g., a nuclear phase-out policy) compared to the baseline, thus capturing the vast majority of structural changes in demands and their impacts on the energy system.

3.2 The TIMES-Canada model

Although an 11-region MARKAL model of the Canadian energy system has been developed at GERAD in the past, a completely new database has been built to reflect the current situation on Canadian energy markets and to fit into the new TIMES modeling paradigm. TIMES-Canada covers the energy system of the 13 Canadian provinces and territories with their own reference energy system (RES), and linked together through energy, material as well as emission permit flows. For reporting purposes, four geographical regions have been created: i) WEST: Alberta (AB), British Colombia (BC), Manitoba (MB) and Saskatchewan (SK); ii) CENT: Ontario (ON) and Quebec (QC); iii) EAST: New Brunswick (NB), Newfoundland (NL), Nova Scotia (NS) and Prince Edward Island (PE); and iv) NORTH: Northwest Territories (NT), Nunavut (NU) and Yukon (YT).

TIMES-Canada spans 44 years (2007 to 2050). Shorter time periods (1 to 2 years) are defined at the beginning of the horizon, while longer time periods (5 to 15 years) are considered afterwards, as uncertainties related to data are increasing. For each period, 12 time slices are defined uniformly across Canada, with four seasons a year (spring, summer, fall and winter) and three periods a day (day, night and peak hours). All costs are in 2007 Canadian dollars ($). The global annual discount rate has been set to 5% for this study, while future works would be relevant in order to assess the impact of higher discount rates on the future evolution of the energy system. Additional hurdle rates can be specified on a technology basis; they vary from 10% to 18% depending on the uncertainties related to their development [27].

Overall, the model database includes more than 5,000 specific technologies and 400 commodities in each province and territory, logically interrelated in a reference energy system. Figure 1 gives a simplified representation of the reference energy system common to all provinces and territories. Each box comprises a group of technologies or more specifically representations of physical devices that transform commodities into other commodities in a particular sector or module (e.g. biomass conversion plants). All energy flows are tracked in petajoules (PJ). Besides, the model tracks carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) emissions from fuel combustion and industrial processes.

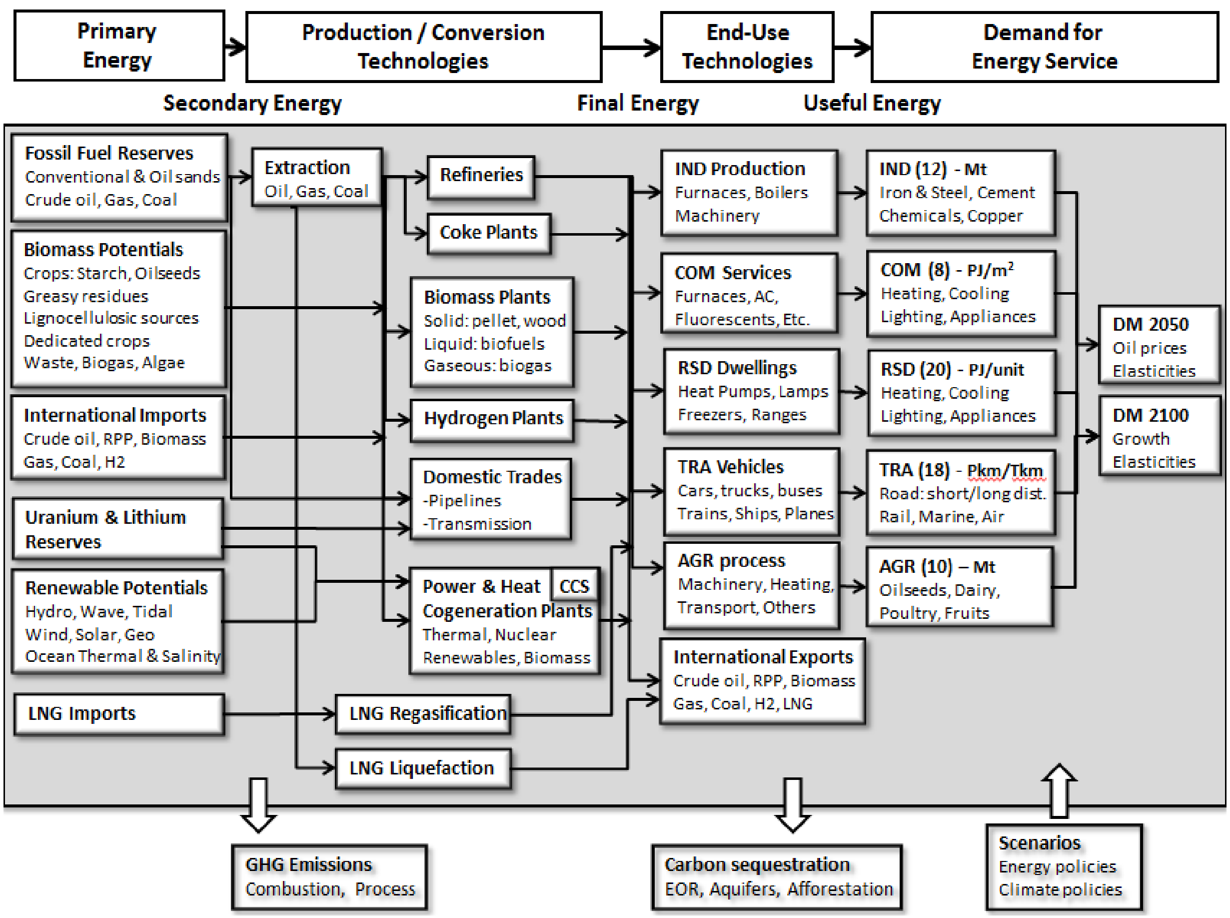


Figure 1: Simplified representation of the reference energy system of each province and territory

The remaining part of this section aims to illustrate the uniqueness and richness of the model database by providing some details regarding the content of each box. This description is structured according to different parts of the reference energy system: final energy (Section 3.2.1), secondary energy (Section 3.2.2) and primary energy (Section 3.2.3). Energy trade is covered in an additional section (Section 3.2.4).

3.2.1 Final energy consumption

The TIMES-Canada model is driven by a set of 67 end-use demands for energy services in five sectors: agriculture (AGR), commercial (COM), industrial (IND), residential (RSD) and transportation (TRA) (see Table 1).

In each of the five sectors, a number of existing technologies are modeled to calibrate each end-use demand for a 2007 base year (see Section 4). In order to replace existing technologies at the end of their lifetime, a repository is created in each sector with a large number of new technologies that are in competition to satisfy each end-use demand after the base year. This repository includes identical or improved versions of existing technologies, as well as totally new technologies not existing in the base year. For instance, the new technology repository for residential lighting comprises standard fluorescents, fluorescents with improved efficiency and new electron stimulated luminescence (ESL) devices.

Table 1: End-use demand segments within five consumption sectors

Sectors	Number of segments	Units	End-use demand segments
AGR	9	Million tons	Grains and Oilseeds, Dairy, Beef, Hog, Poultry, Eggs, Fruit, Vegetables, Others
COM	8	PJ	Space heating; Water heating; Space cooling; Lighting; Street lighting; Auxiliary equipments; Auxiliary motors; Others
IND	12	Millions tons	Iron and steel; Pulp and paper (Low quality, High quality); Cement; Non-ferrous metals (Aluminum, Copper, Others); Chemicals (Ammonia, Chlorine, Others); Other manufacturing industries; Other industries
RSD	20	PJ	Space heating (Detached houses; Attached houses; Apartments; Mobile homes); Space cooling (Detached houses; Attached houses; Apartments; Mobile homes); Water heating (Detached houses; Attached houses; Apartments; Mobile homes); Lighting; Refrigeration; Freezing; Dish washing; Cloth washing; Cloth drying; Cooking; Others
TRA	18	Millions passenger-km Millions ton-km	– Road / Passenger: Small cars (Short distance, Long distance); Large cars (Short distance, Long distance); Light trucks; Urban buses; Intercity buses; School buses; Motorcycles; Off road – Road / Freight: Light trucks; Medium trucks; Heavy trucks – Rail: Freight; Passenger – Air: Freight; Passenger – Marine

3.2.2 Conversion to secondary energy

This section of the reference energy system covers all energy conversion technologies such as power plants, fossil fuels transformation plants (refineries, coke plants) and biomass plants. In addition, there are separate modules for a potential future hydrogen economy and liquefied natural gas (LNG) industry (these energy forms are not consumed in the base year but available for future uses). All data sources are detailed in [28].

Coke plants. The model considers the existing commercial scale plants (in Ontario) where the production of coke and coke oven gas is used by the manufacturing industries.

Refineries. The model considers the existing 19 refineries that produces a full range of petroleum products: liquefied petroleum gas (LPG), still gas, motor gasoline, kerosene, stove oil, diesel fuel oil, light fuel oil (nos. 2 and 3), heavy fuel oil (nos. 4, 5 and 6), petroleum coke, aviation gasoline, aviation turbo fuel, non-energy products.

Liquefied natural gas (LNG). In addition to the existing projects proposed on the west and east coasts for the near future, different types of generic terminals are included in the database to allow flexibility in the model for potential growth of this industry: small and large regasification terminals, as well as onshore and offshore liquefaction terminals.

Power plants. The model database depicts in much details all existing electricity, heat and cogeneration plant units in Canada, as well as units already planned for construction or refurbishment in future years. It totalizes over 3,500 existing power units including decentralized generation units (i.e. diesel generators used in remote regions). Moreover, a repository of over 150 types of new power plants has been created to analyze the replacement of existing capacity at the end of their lifetime or the addition of new capacity to meet the additional demand for electricity. The repository includes all the different types of thermal (with and without carbon capture options), nuclear and renewable power plants that can potentially be built in

Canada in the near future (e.g. more efficient version of the existing plants), or that will become available on a longer time frame (e.g. fourth generation nuclear reactors, offshore wind and wave integrated system, etc.).

Biomass. Existing technologies include the 10 ethanol plants and the 7 biodiesel plants producing biofuels which meet Canadian standards at a commercial scale, as well as pellet producers in six provinces for energy and heating purposes. A new technology repository includes also more advanced options for biomass conversion.

Hydrogen. This module covers the whole potential hydrogen economy, i.e. with future technologies for hydrogen production, gasification/liquefaction, distribution and sector fuel consumption. Production technologies are grouped into two main categories: large-scale production plants connected to a distribution network and decentralized small-scale units at end-use locations. They can produce hydrogen in many different ways: from fossil fuels (steam methane reforming, coal gasification, adiabatic reforming, plasma dissociation), from water electrolysis, from solar power and from biomass gasification and pyrolysis. Hydrogen can be distributed in two different forms (as a compressed gas or a cryogenic liquid) and transported via four modes (pipeline, trucks, trains, ships). Finally, hydrogen can be used mainly for electricity generation (fuel cells) and road transportation (internal combustion engine and fuel cells), but also in small-scale units in the industrial, commercial and residential sectors.

3.2.3 Primary energy supply

TIMES-Canada compiles all Canadian primary energy sources, such as fossil fuels reserves (oil and gas, coal), renewables potentials, uranium reserves and biomass. We detail some of them below.

Fossil fuels. Reserves are classified into three categories (located reserves, enhanced recoveries and new discoveries) which are modeled through a three-step supply curve for the cumulative amounts in the ground. Each step corresponds to a given amount of resources that can be extracted at a given cost. Primary production or extraction technologies are modeled for each type of fuel and reserves: coal, conventional oil and gas, as well as unconventional oil and gas. Afterwards, fossil fuels can be transported by pipelines and other means (trucks and trains) from primary production plants to secondary transformation plants.

Biomass. There are several types of solid, liquid and gaseous biomass that can be used to produce a large variety of energy products. They have been documented by province. In the calculation of biomass potentials, ranges were calculated using different sets of assumptions and only the most conservative ones have been retained for their implementation in the model database.

Renewable potentials. The model considers also different renewable sources for electricity generation. Technical potentials have been estimating for hydro, geothermal, tidal and wave power computing the total quantity of energy that could be produced using current technologies over the model horizon. As for solar and wind, ‘accessible’ potentials refer to maximum amounts of electricity that can be generated annually and have been computing considering several aspects: geographical aspects (e.g. competition for land use, population density, vegetation, and climate), technical constraints (e.g. integration to the current network, minimal wind speed) and social acceptability.

3.2.4 Energy trade

All primary and secondary forms of energy can be traded within and outside Canada. The domestic trade module deals with energy exchanges between the Canadian provinces and territories, where trade movements are modeled endogenously (the model computes energy prices and determines the optimal quantities up to the current infrastructure capacities). The international trade module covers all energy exchanges between Canada and other countries, including USA. Imports and exports are modeled exogenously (i.e. using fix prices and lower/upper limits on quantities) by origins and destinations as TIMES-Canada is not linked with the rest of the world. New technologies (electric interconnection, oil & gas pipelines) are available in the database to allow future increases in importing and exporting capacities between provinces and outside Canada.

4 Model and baseline calibration

4.1 Base year

TIMES-Canada has been calibrated on a 2007 base year using energy balances available at [29]. In addition, numerous data sources were used to model energy flows in more details, including the *Comprehensive Energy use Database* of the Office of Energy Efficiency [30]. As a result of our calibration process, TIMES-Canada yields for 2007 energy production and consumption consistent with official statistics for the different province and territories.

4.2 Projection of energy service demands

The estimation of future demands for energy services has been done using growth rates for various socio-economic drivers applied on the base year demand, together with coefficients capturing demand sensitivity to these drivers. These drivers are related to economic (GDP) and well as demographic (number of households, population) trends.

More precisely, we have developed five different baselines using five coherent sets of growth rates [3]: a *Reference* scenario, as well as four alternate scenarios characterized by different assumptions for oil prices (*Low* and *High* scenarios) or for economic growth (*Slow* and *Fast* scenarios). As [3] provides data until 2035 only, we have used a regressive approach to determine drivers between 2035 and 2050. Main assumptions are shown in Table 2 for 2035.

Table 2: Main assumptions in our five baseline scenarios [3]

Scenario	**WTI Oil Price (2010 US$/barrel)**	**GDP Growth (%)**
	2035	**2010–2035**
Low	85 $	2.3%
High	155 $	2.3%
Reference	115 $	2.3%
Slow	112 $	1.8%
Fast	121 $	3.2%

The socio-economic growth rates we use in each scenario are thus consistent with a particular oil price forecast, a major driver of energy demand. Besides, the range we consider for 2050 oil prices (from 96 to 166 US$/barrel) cover a large part of the projections available in the literature (see for instance: [3,6,8,14,31]).

4.3 Existing policies

Energy and environmental policies have also a clear influence on energy supply and demand trends. Our baselines implicitly take into account the energy and environmental regulations already in place at the federal or provincial levels (but exclude non-official targets that have been proposed but not implemented yet). The most impacting regulations that have been taken into account in the baselines are [3,31]: Fuel efficiency standards for new vehicles; standards setting minimal renewable content in conventional fuels; and energy efficiency improvement targets.

5 Numerical results

5.1 Final energy consumption

In the Reference scenario, Canadian final energy consumption is expected to increase by 43% on the 2050 horizon. The breakdown by fuel type is given in Figure 2.

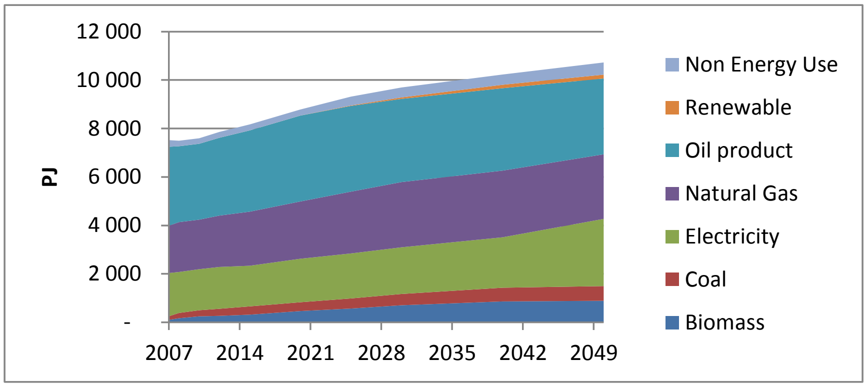


Figure 2: Final energy consumption by fuel type in the Reference scenario, 2007–2050

Figure 2 illustrates that oil products will continue to dominate on the long term due mainly to the reliance of the transportation sector on gasoline and diesel consumption, although in a decreasing proportion over time (from 43% in 2007 to 29% in 2050). Oil demand is reduced in favour of electricity *&* heat and biomass in particular, due to the assumed increases of oil prices on international markets on one hand, and the large variety of options available for electricity generation and biomass production (including biofuels for transportation) on the other hand. Indeed, a study specific to the transportation sector performed with TIMES-Canada shows that biofuels and electricity play a significant role for passenger transportation in baseline scenarios from 2040 [32]. Finally, the largest increase is coming from electricity with 31% of the additional energy consumption up to 2050. While biomass also counts for an important part of the additional consumption (25%), its share in the total consumption remains small (8% in 2050).

Figure 3 compares next the breakdown of final energy consumption by fuel for our five baselines in 2050. The variation of results across the different baselines is consistent with our assumptions regarding the significant influence of socio-economic trends. The Fast scenario leads in particular to a 21% increase in 2050 compared to the Reference scenario, with the commercial, industrial and transportation sectors being the most sensitive sectors to economic growth assumptions. Looking at fuel type, the main impacts relate to electricity consumption that accounts for one third of the additional demand compared to the Reference scenario. Further increases are associated with natural gas (20%), biomass (15%) and oil consumption (11%). At the other end of the range, the Slow scenario leads to an 8% decline in total energy consumption by 2050.

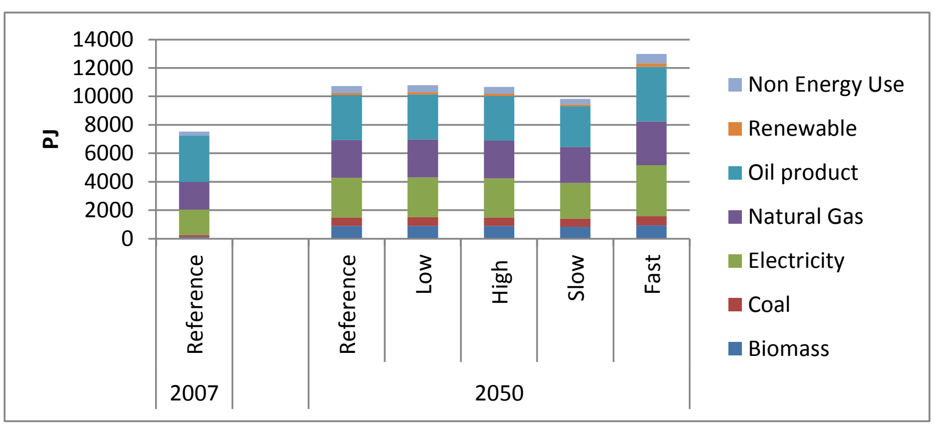


Figure 3: Final energy consumption by fuel type in our five baselines, 2007 & 2050

5.2 Primary and secondary energy supply

This section presents optimal energy production paths required to meet final energy demand (domestic consumption) and international exports. Results are presented for three main scenarios: Reference, Fast and Slow. We choose not to report any further on the Low and High scenarios, as they are very similar to our Reference scenario.

Figure 4 shows energy production by type in the Reference baseline. Oil production increases by 42% between 2007 and 2030 before declining by 10% between 2030 and 2050. Due to significant reserves of gas and coal, their production remains rather stable on the 2050 horizon with only a smooth decline of 9% for gas and 15% for coal. Uranium extraction follows a decreasing trend (-45% between 2007 and 2050) with the rarefaction of the reserves. On the same period, hydro follows a moderate increase (38%, mainly before 2030). Finally, although other renewable and biomass production show huge increases, with respectively 50 times and 4 times their 2007 level in 2050, their proportion of the overall production mix remains very small: 4% of total production each.

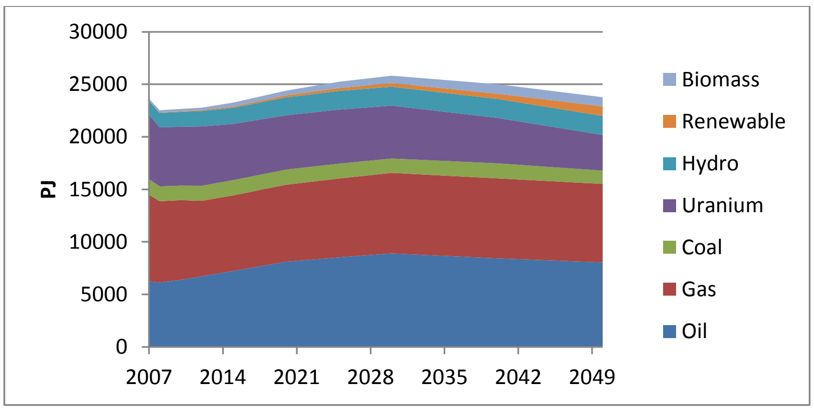


Figure 4: Energy production by type in the Reference scenario, 2007–2050

We detail next two particular sectors: oil production and electricity generation.

5.2.1 Oil production

The results presented in this section show the evolution of the total oil production by type through 2050 to meet both domestic demands and international exports. Since TIMES-Canada is currently not connected to global markets implicitly, assumptions have been made on future trade: oil exports from Alberta are expected to increase by 2.5 times between 2007 and 2050 in all baseline scenarios. Note that the development of the oil sector database has involved a very comprehensive and detailed documentation of all Canadian offshore (by water-depth) and oil sands (mining and in-situ) projects that are of growing importance in national oil production [33]. The resulting production profile takes into account well counts, (international) oil prices and oil production.

Figure 5 gives first the breakdown of crude oil production by type in the Reference scenario: oil production peaks at 10,760 PJ in 2030 (a 74% increase from 2007 levels) before declining to 8,160 PJ in 2050. Since domestic oil demand remains quite constant over time (as illustrated in Fig. 2), most of the additional production is exported. Note that Figure 5 reflects clearly the impact of the global economic recession between 2008 and 2010 that delayed many oil sands projects. In 2007, most of the oil production is coming from the WCSB (*Western Canadian Sedimentary Basin), a* mature basin *where* conventional oil *production* declines by 89% between 2030 and 2050, representing only 2% of the total oil production in 2050. The softer decrease between 2007 and 2030 is due to the availability of enhanced oil recovery options extending the life of some wells. The two sources of new project developments come from Western oil sands and Eastern offshore production. Due to the recent increase in oil prices as well as the further increasing trends predicted for the

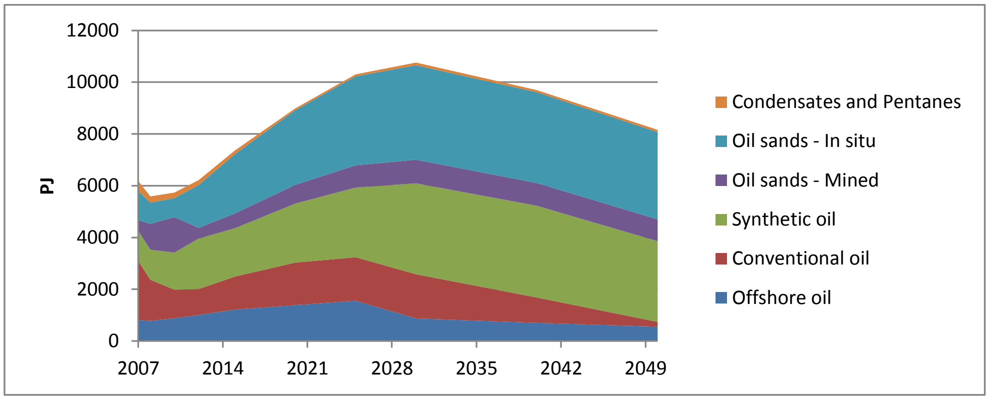


Figure 5: Oil production by type in the Reference scenario, 2007–2050

next decades [3], it has become profitable to exploit these new conventional and unconventional oil sources. The offshore production is expected to peak around 2020 in Eastern Canada, considering current trends and decay rate from offshore wells as well as new projects, while it is expected to start by 2025 in Western Canada. While oil sands (mined and in situ extraction) represented only a quarter of the total oil production in 2007, it is expected to represent half of the production in 2050. The proportion of oil sands extracted via in situ techniques is expected to represent 41% of the overall production in 2050, as the mined activities for oil sands extraction should remain quite constant over time. In addition, synthetic oil production from oil sands upgrading will provide another 38% of the total production in 2050.

Figure 6 compares next the breakdown of crude oil production by type for our three main baselines in 2030 and 2050. In relation with the stability of the domestic demand for oil over time, it is not surprizing to see that domestic economic trends have very little impacts on oil production across the different baselines. As most of the production is exported, the international demand for Canadian crude oil and refined products is the main driver for oil production levels. However, international trade conditions remain similar in all baselines. Future works will assess the impacts of various international exports levels on the Canadian oil production. The total oil production increase by only 121 PJ in 2030 and 194 PJ in 2050 to satisfy the additional domestic demand in the fast economic growth scenario (about 1% of the production). This increases come essentially from synthetic oil.

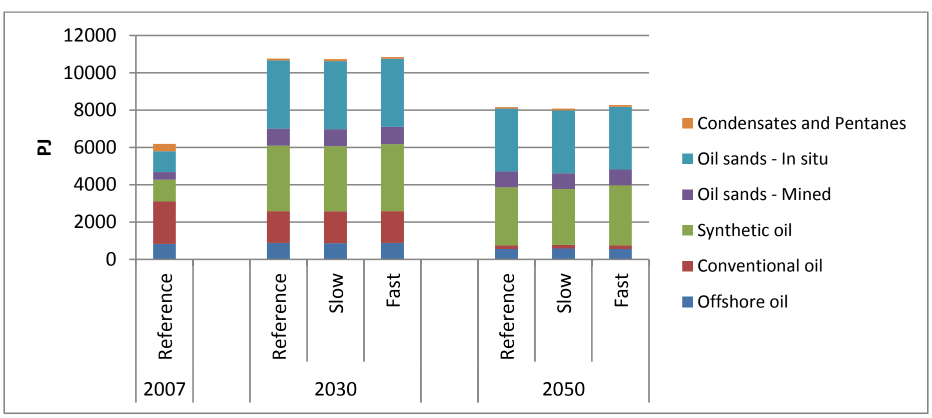


Figure 6: Crude oil production by type in our three main baselines, 2007, 2030 & 2050

5.2.2 Electricity generation

Figure 7 reports first on the breakdown of electricity generation by type in the Reference scenario. It is useful to recall that our baselines include ongoing projects as well as projects planned after our 2007 base year (e.g., coal phase out in Ontario, nuclear plant closure in Quebec, new hydro dams in Quebec and Newfoundland, new wind farm projects in many provinces, etc.) From 129 GW in 2007, these existing plants and scheduled projects will already bring the generation capacity to 151 GW in 2050. The model sets up new investments for an additional 66 GW of generation capacity in order to satisfy total demand in 2050. Overall, electricity generation increases thus by 57% between 2007 and 2050.

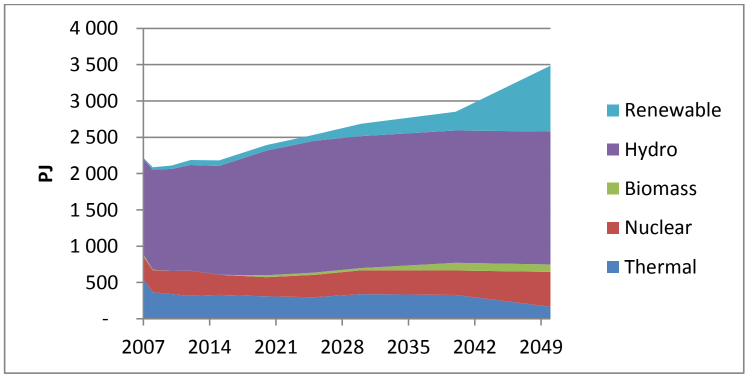


Figure 7: Electricity generation by type in the Reference baseline, 2007–2050

Hydro power remains the main source of electricity, although its share in the total generation slightly decreases from 59% in 2007 to 42% in 2050, due to the generation increase from other renewables. Nevertheless, a significant proportion of the additional generation is coming from hydro power in 2050 (41%), from new capacities already scheduled in British Colombia, Quebec, and Newfoundland. The largest increase comes from renewables (mainly wind) that account for 70% of the additional generation activity between 2007 and 2050. However, the share of renewable sources remains rather small in the electricity generation mix, with 25% of the total in 2050. The most significant changes relate to wind power, as important growths occur in several provinces (Quebec, Ontario, Manitoba and Alberta) that have set penetration targets. This important penetration of renewables occurs at the detriment of thermal power that decreases from 25% in 2007 to only 5% of the total generation mix in 2050. As already explained, this trend can be explained on the one hand, by the assumed increases of oil import prices on international markets and on the other hand, by a large variety of options available in Canada for renewable production. The remaining thermal power generation relies progressively more on natural gas, with the coal plant phase-out in Ontario by 2015 as well as other scheduled retirements in Western and Eastern provinces later on when plants reach the end of their useful life. Note also that oil remains the main source used for distributed electricity in isolated areas of many provinces, in the territories of the North region and on the Prince Edward Island. Nuclear power stays constant at 14% with small new capacity in Ontario, while some other nuclear plant units are refurbished. Although Canadian uranium resources are huge, the nuclear capacity is not expected to grow under our socio-economic trend assumptions. However, in relation with the development of oil sand projects in Alberta for exportations, the possibility of using nuclear power has been discussed by the oil industry.

Figure 8 compares finally the breakdown of electricity generation by type for our three main baselines in 2050. In relation with the total demand for electricity in these alternate baselines, the installed capacity adjusts accordingly to reach 203 GW in the Slow scenario and 255 GW in the Fast scenario (compared with 217 GW in the Reference scenario). The Fast scenario involves a 90% increase in electricity generation between 2007 and 2050, while this rate is about 47% in the Slow scenario (compared with 57% in the Reference scenario). In absolute terms, hydro power remains similar across baselines as the techno-economic potential is already more or less exploited at the maximum. However, its share in the 2050 generation mix varies based on the total electricity generated, i.e. namely 56% in the Fast scenario and 44% in the Slow scenario. Similarly, the effects of economic growth projections on thermal power in the long term are limited due to declining reserves and rising prices; its 2050 share remains below 10% in all baselines. The main differences in the electricity generation mix refer to the trade-off between renewable power versus nuclear. As the best renewable potential opportunities are being exploited to its maximum limit in most baselines (a maximum of 25% of intermittent sources is allowed on the grid), investments in new nuclear reactors are made to cover increasing electricity demands. Biomass-fired plants are not considered a cost-effective option based on our current estimations of their techno-economic attributes, although huge potential exists for biomass of various types.

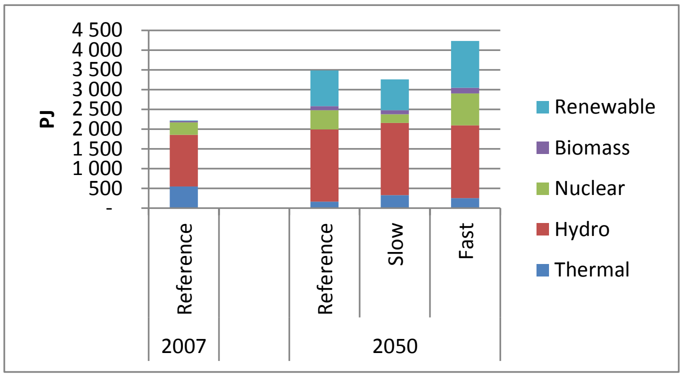


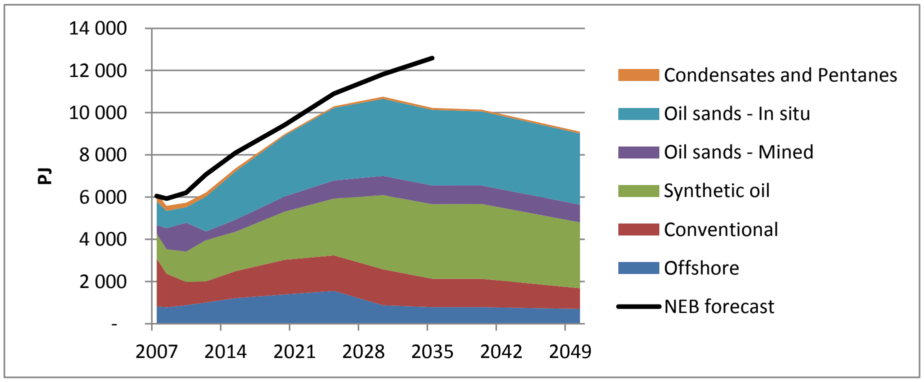
Figure 8: Electricity generation by type in our three main baselines, 2007 & 2050

6 Discussion

Our current paper is based on an optimisation model that defines optimal configuration of the Canadian energy sector in order to satisfy projected demands for energy services. Some outlook publications are using alternative approaches (such as simulation models, econometric models, partial equilibrium models) to provide energy outlook for Canada specifically [3] or for the entire world with Canada as a separate region [6,8]. Other publications are using similar optimization approaches [10,11] at the global level and covering Canada, but in a much less detail manner. It is difficult to directly compare results with the ones we obtain due to the numerous differences between the various outlooks: approaches and models, geographical coverage, time frame, definition of the energy system, end-use sectors and fuel categories, level of details, underlying assumptions, etc. In particular, it is not possible to compare final energy demand directly, as its definition is not the same across sources. In particular, energy demands in TIMES-Canada are specified in physical units, while they are specified in energy units in order Canadian models. Besides, different outlooks do not necessarily report on the same section of the Canadian energy balance.

However, some comparisons in the supply sectors are possible with some outlooks. Regarding oil production, the only comparable source is the [3] and their estimates show comparable trends until about 2025 (see Figure 9). Afterwards, more significant differences occur, due to different assumptions regarding the evolution of the oil industry. Indeed, [3] uses more optimistic assumptions related to increase in the application of multi-stage hydraulic fracturing in tight oil, prospects for enhanced oil recovery by carbon capture and sequestration in wells, and assume that all energy production will find markets and that all necessary infrastructure will be built.

Finally, the comparison of installed capacity for electricity generation with the [3] and the IEO [6] in Figure 10 is relevant to illustrate robust (but slow) trends toward the development of a large variety of renewable projects. The share of hydro, biomass and other renewables power reaches 66% [6], 69% [3] and 72% (TIMES-Canada) respectively in 2035. Our assumptions lead to the most optimistic estimation regarding the development of renewables at the detriment of thermal power. The main assumption being the availability of a significant portion of the potential not yet exploited as of today, as well as the documentation of a large variety of new options available in the model database to develop the remaining potential in a cost-effective manner on the long term. Official projections relies rather on past and current trends ignoring the potential contribution of promising technologies that are still not wide spread or still under development. The result of our model is an important contribution in this sense and even more by looking at the extended trends toward 2050 showing an increasing role for renewables.



* The NEB (2011) data is converted to PJ using an average coefficient that equal their 2007 estimates with the number provided by Statistics Canada (2007) for oil production.

Figure 9: Comparison of the oil production in the Reference scenario, 2007–2050

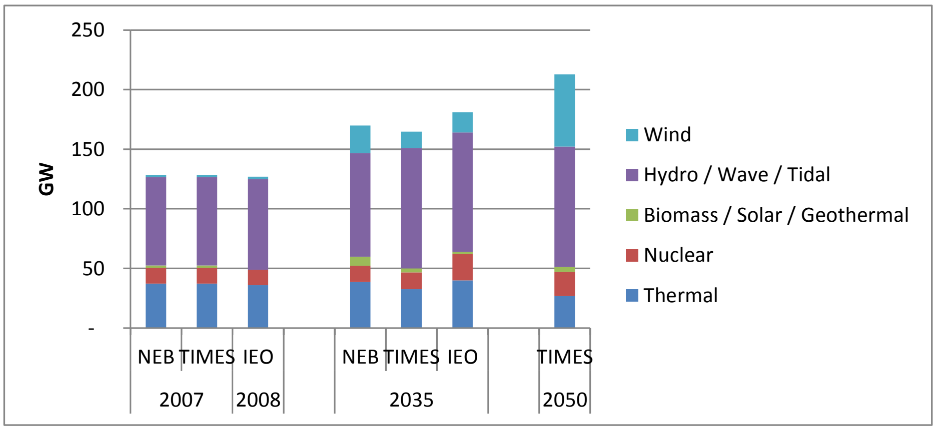


Figure 10: Comparison of the electricity capacity in the reference baseline, 2008, 2035 & 2050

7 Conclusion

In this paper, we use the newly developed TIMES-Canada model to define and analyze possible futures for the Canadian integrated energy system on the 2050 horizon, under different baselines corresponding to different oil prices and socio-economic growth trends.

We have shown that the total Canadian final energy consumption is expected to increase by 43% on the 2050 horizon in the Reference scenario. The fast economic growth baseline (Fast scenario) leads to a 21% increase in total final energy demand for 2050 compared to the Reference scenario, while the slow economic growth baseline (Slow scenario) leads to an 8% decline in the total energy demand for 2050. The effects on the fuel mix are derived from the different factors affecting the different end-use sectors and their different reactions to a change in the demographic and economic growth rates. In all scenarios, oil products will continue to dominate the markets on the long term due mainly to the reliance of the transportation sector on gasoline and diesel consumption, although in a decreasing proportion over time in favour of electricity which accounts for 31% of the additional energy demand up to 2050.

Regarding the optimal energy production path required to meet final energy demand for the Reference scenario, it shows: 1) a gradual replacement of onshore conventional oil & gas sources by unconventional and offshore sources through 2050; and 2) significant penetration of renewables in the electricity mix, namely after 2035 due to increases in oil import prices and decreases in renewable technology costs. Although similar trends are observed in other outlooks [3,6], our assumptions lead to more optimistic estimation regarding the development of renewables for electricity generation at the detriment of thermal power. This is due to the large number of new options available in the model database to develop the remaining potential in a cost-effective manner on the long term.

These results illustrate the relevance of using such a technology-rich optimization model for technology assessment from different baselines. For this purpose, a very detailed database has been built to reflect the current situation on Canadian energy markets and to fit into the TIMES modeling paradigm. In addition, the objective was to integrate emerging technologies that are particularly relevant in the Canadian context in order to provide the model with more flexibility regarding the technology selection and the fuel mix required to satisfy the projected demand through 2050. Special attention has been dedicated to the construction of an accurate technology database in fast-evolving sector such as oil sands extraction and liquefied natural gas imports, but also next generation biomass conversion plants, next generation of nuclear reactors, clean coal technologies, carbon capture and sequestration (CCS) options, hydrogen, electrification of transportation, new power plants with CCS options, etc.

The development of such a comprehensive database and the calibration process behind the final results represent significant contributions to the energy modeling capacity for Canada, especially because of the particularities inherent to the Canadian energy system, its recent evolution and data confidentiality issues. The resulting model, TIMES-Canada, is the only optimization model covering the large diversity of provincial energy systems in Canada on a long term horizon (2050) in such details. Future works will benefit from this powerful tool through sensitivity analyses on techno-economic attributes to assess the potential of emerging technologies in Canadian and provincial energy and climate policies. In particular, we will be working together with our initial supporting organization, Natural Resources Canada, as well as other federal and provincial entities, to set up a series of interesting matters such as: creating the appropriate infrastructure for electricity trade into an integrated electricity market, testing different hypothesis for market potential of renewable energy technologies, exporting versus using unconventional oil & gas sources, fulfilling renewable and specifically climate change mitigation targets.

Finally, further refinements will be brought to the model in parallel, namely with the calibration of the energy demand and production towards the 2100 horizon as well as the review of the techno-economic attributes of technologies and the addition of new technologies as the information becomes available from other research.

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