Key findings from the core North American scenarios in the EMF34 intermodel comparison

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ABSTRACT

Within Canada, Mexico or the United States, policy-making organizations are evaluating energy markets and energy trade within their own borders often by ignoring how these countries' energy systems are integrated with each other. These analytical gaps provided the main motivation for the Energy Modeling Forum (EMF) 34 study on North American energy integration and trade. This paper compares North American results from 17 models and discusses their policy motivation. Oil and natural gas production in the three major countries are modestly sensitive to crude oil and natural gas price changes, although these elasticities are below unity. Carbon taxes displace coal and some natural gas with renewables within all three power markets. Lower natural gas prices replace coal and some renewables with natural gas within electric generation. Higher intermittent renewable penetration in the power sector displaces coal and some natural gas. A key conclusion is that much remains to be done in integrating future analyses and in sharing and improving the quality and consistency of the underlying data.

1. Introduction

The Energy Modeling Forum organized an *ad hoc* working group on North American energy trade and integration to compare model results in 2018–2019 following an initial workshop in June 2017. This group included approximately 50 participants from universities, research organizations, government and companies. This overview article describes the motivation, organization and key findings from the core scenarios developed for this study (EMF34). This discussion serves as a basis for the articles focusing on cross-cutting issues and on individual model results that comprise this special issue.

Within Canada, Mexico or the United States, policy-making organizations are evaluating energy markets and energy trade within their own borders often by ignoring how these countries' energy systems are integrated with each other. This situation leads to a partial understanding of important energy developments that may produce inferior policy and investment choices. The results in section 4 below reveal a wide disparity in crude oil and natural gas trade between countries when produced from individual country models rather than integrated systems. In addition, the study included several subgroups that explored the

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insights gained from conducting integrated assessments, such as the discussion by Bistline et al. (forthcoming) on renewables policies and potential cross-border coordination and their impact on electric sector investments, emissions and cost outcomes.

Thus, the motivation for conducting this effort at this time is to bring together in one forum analyses on the three countries to seek ways where future collaboration and integration may be fruitful. This paper focuses upon two examples from a multitude of results that were discussed by the group: the response of crude oil and natural gas supplies to varying economic incentives and the shifts in generation sources for electric generation for alternative natural gas availability, renewable energy sources and carbon policy.

The next section explains the policy motivation in much greater detail. Section 3 describes the study design including scenarios, variables and models chosen in this effort. Section 4 emphasizes a few key factors that account for the wide variation in reported results, even for a particular scenario. Crude oil production trends for the three different countries are evaluated for two separate oil price trends in Section 5. Similar natural gas production trends are described in Section 6 for two different economic growth trends. Section 7 considers the prominent electric generation source trends for cases when a carbon tax is applied, lower-cost natural gas becomes more available, and intermittent renewable resources become less expensive. The final section summarizes several key concluding points and discusses a few key areas for further evaluation.

2. Motivation for the study

Energy markets are undergoing rapid transitions globally to low-carbon systems while sustaining economic growth. These trends are well developed within the North American countries of Canada, Mexico and the United States. These economies are shifting from direct fossil fuel use towards power and renewables, are in the process of building large transboundary investments for moving energy sources within the continent,[1] and are becoming a dominant source of future oil and gas supplies for world markets. While the trends across the three countries are similar, their pathways to a low-carbon economy have differing temporal and spatial characteristics. Understanding the likely energy developments within this region will be important for both private investment and public policy not only within North America but also within other world regions.

This effort builds upon a previous agreement for the North American Cooperation on Energy Information (NACEI) organized by the national governments of Canada, Mexico and the United States. This process facilitated greater collaboration on North American energy information. The main areas of focus for the NACEI project were energy trade data, geospatial information on energy infrastructure, harmonizing definitions and concepts relating to energy, and comparing outlooks for energy trade across the continent (NACEI, 2015). The outlook project (National Energy Board et al., 2015) provides an overview of national modeling systems in each country, and includes the results of a joint modeling exercise. The modeling involved each country using their own modeling system to create projections for their country to 2029 using a common set of assumptions (consistent with the U.S. EIA's 2015 Annual Energy Outlook). Overall, the outlooks from the individual countries were fairly consistent, and comparing and contrasting the implied trade flows between different countries proved to be an interesting exercise. As a next step, the NACEI initiative identified a desire to better understand the interrelationships between the three countries under different conditions, which provided a key driver for the EMF34 study.

A critical objective of both NACEI and EMF34 has been to facilitate more widespread sharing of important information across national boundaries that can improve policymaking and harmonize rules and regulations. Important ingredients to this collaboration include sharing information on relevant data, best modeling practices, and useful insights about energy markets, cross-border trade and technology advancements. Modeling teams interact with each other and with leading policy analysts and developers in a forum that encourages future interactions and that may lead to the identification of promising areas for further research. Elsewhere in this volume are excellent examples of how groups with common interests in this study worked together on relatively new issues, such as regional coordination of renewable energy resources (Bistline et al., forthcoming) and on the deployment of carbon capture, utilization and sequestration (CCUS) under the U.S. 45Q Tax Credit incentives (Edmonds et al., forthcoming).

The study began by focusing upon how North American energy systems responded to external factors such as higher domestic economic growth and lower world oil prices caused by shifts in foreign oil supplies and demands. These efforts emphasized the range of possible outcomes for energy production, consumption, trade and prices as the economic and world oil systems changed. With new leaders in each of the three national governments, the original focus in these core scenarios did not emphasize introducing new policies like carbon taxes or renewable power coordination. Nevertheless, the wide range of outcomes not only across scenarios but also across modeling teams underscores the importance of developing robust policies that will be effective under a variety of market conditions.

The motivation of this overview paper is to highlight results on two topics that provide useful examples. First, there exists considerable interest in the future development of North American crude oil and natural gas supplies. Hydraulic fracturing of tight oil formations, the marketing of Canadian oil sands, and the restructuring of the Mexican petroleum industry hold significant promise for North America to become a dominant oil supplying region. Similar interests exist in whether the natural gas shale revolution will continue at its rapid pace. The response of these supplies to varying economic incentives can have profound impacts on the need for key pipelines and transportation options that will move these supplies to the most profitable markets.

Second, increased electrification in all three countries will expand the demand for new generation sources in the shift to lower carbon systems. Intermittent renewable sources are likely to penetrate the power sector rapidly, particularly if the trend towards lower costs continues. At the same time, there are significant amounts of inexpensive natural gas that will also compete for market shares. How will these sources fare under alternative scenarios representing lower renewable costs, more inexpensive natural gas, and the emergence of climate policies like carbon taxes?

3. The EMF34 study design

The working group developed a study design that would reveal conceptual insights about the relatively complex interactions between fuels and regions rather than project the most likely future outcome for North American energy markets. The design incorporates 13 core scenarios, 44 variables and 17 different modeling teams.

3.1. Scenarios

Table 1 lists the 13 core scenarios, each one of which might be a reasonable projection of likely future energy market conditions. They are grouped into 7 sets. The Reference case allows each team to offer a scenario based upon their own energy and economic assumptions. The principal advantage of allowing for modeler judgement in defining reference conditions is to emphasize the core uncertainties in North American energy system development. Even without new policies, technology developments and economic incentives, future North American energy markets may cover a range of possible outcomes. These different baseline conditions can alter the responses to climate change and renewable policy changes. Allowing more flexibility in

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[1] For example, see Feijoo et al. (2016) and Cole et al. (2016).

Table 1
Description of EMF34 core scenarios.

Scenario	Description	Motivation/Hypotheses to be tested
1. Reference – Modeler's Choice	• Modeler's own choice of Reference Case	Reference against which side cases to be compared
2. Low Oil Price	Modeled after Low Oil Price case from AEO2018 • Brent lowered via higher oil supply and lower oil demand outside North America	Response of oil consumption, production and trade to lower world oil prices
3. High Gas Supply	High gas supply, modeled as a lower production cost case (20% by 2020 and by 30% by 2050)	Increase in gas intensity in power generation and the economy when natural gas becomes less expensive

4. High Macro Growth	Increased energy demand via macro pull
	• GDP growth rate is increased by 20% vis a vis Modeler's Reference in each case
	• Growth in other countries and outside North America held at Reference case levels unless predicted otherwise by the model
	  4.1 High North America Macro Growth:
	  4.2 High Canada Macro Growth
	  4.3 High Mexico Macro Growth
	  4.4 High U.S. Macro Growth
		Response of fuel imports and exports to stronger North American economic growth
		Response of natural gas supplies to higher natural gas prices caused by greater domestic growth

5. High Intermittent Renewables Penetration	Increased penetration of solar and wind technologies (20% by 2030 and 30% by 2050) through cost reductions	Displacement of fossil fuels, nuclear and hydro-electricity by lower-cost renewables
6. Cross-border Energy Infrastructure (starting 2020)	Case focuses on understanding the impact of energy infrastructure. 6.1 Increases the capacity of electricity transmission by 20% vis-à-vis the Modelers Reference Case; 6.2 Decreases the total capacity of crude transportation (pipeline + rail) by 20% vis-à-vis the Modelers Reference Case; 6.3 Decreases the cost of transporting natural gas by 20% vis-à-vis the Modelers Reference Case.	Effects of investments in cross-border infrastructure for transporting supplies on the use of electricity, crude oil and natural gas
7. Carbon Policy	Case focuses on the impact of carbon policy. • Carbon tax of US $35/tonne starting 2022 and increasing at 5% per year • All other countries outside of North America also impose the same carbon tax Two sub-cases are defined: 7.1 Case 1 models the carbon policy adopted in all three countries (US, Canada, Mexico). 7.2 Second case models the carbon policy adopted in only Canada and Mexico but not in the US	Displacement of fossil fuels when all 3 countries adopt carbon policy and when only Canada and Mexico adopt carbon policy.

baseline conditions makes the policy cases more robust to a wider set of possible outcomes. When teams are uncertain about these conditions, they are encouraged to base their assumptions about economic growth and world oil prices on the Annual Energy Outlook (AEO) 2018 Reference case (US Energy Information Administration, 2018). Consistent with the AEO reference projections, modeling teams did not implement any new policies that the governments had not already adopted. These projections represent baseline conditions for comparing other scenario results but are not necessarily the most likely outcomes.

Alternative cases specify common changes that are applied to the EMF34 Reference case in each model.[2] The Low Oil Price case assumed a lower inflation-adjusted oil price path than in the Reference case in response to events outside of North America such as slower world economic growth or expanded supplies in other regions such as the Middle East. World oil prices decreased gradually from their reference level until they reached 50% below by 2050. The working group selected this percentage reduction based upon the Low Oil Price case evaluated in the 2018 Annual Energy Outlook (U.S. Energy Information Administration, 2018).

The High Gas Supply case was patterned after the AEO 2018 High Oil and Gas Supply case that resulted in low inflation-adjusted North American natural gas prices due to greater low-cost resources and improved drilling technology. Modeling teams implemented these conditions by reducing production costs by 20% in 2020 and by 30% in

2050. The working group selected these percentage reductions based upon the High Oil and Gas Supply case evaluated in the 2018 Annual Energy Outlook (U.S. Energy Information Administration, 2018). Although expanded supply affects both crude oil and natural gas production, these conditions primarily influence domestic natural gas prices with very modest effects on world oil prices. Hence, the group considered this case primarily as a low natural gas price scenario.

Four cases evaluated how the three country energy systems and the cross-border trade between the countries responded to stronger economic activity where individual economies grow 20% faster than in the Reference case. Economic growth outside of North America remains unchanged from the Reference case unless predicted otherwise by the model. The High North America Macro Growth case applies the higher macroeconomic conditions simultaneously to all three countries in the region, whereas the other high growth cases restrict the expanded growth to one but not the other two of the countries. The 20% expansion was chosen to elicit noticeable responses in the models while remaining within the range of reasonable alternative economic conditions.

Solar and wind technologies penetrate the electric power market more rapidly through cost reductions in the High Intermittent Renewables Penetration case. Relative to the Reference case, modeling teams adopted cost reduction to expand these sources by 20% more by 2030 and by 30% more by 2050. These expansions were not based upon any formal estimates of the range in possible future costs but instead were selected by the working group to be sufficiently large to produce meaningful responses in the models.

There existed strong interest within the study group on the role of infrastructure in shaping future supplies, demands and prices. Power transmission lines and crude oil and natural gas pipelines integrate the regional markets within each country as well as the cross-national trade between the countries. How the building of this infrastructure develops will influence the expansion of more abundant natural gas supplies and

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[2] These alternative cases do not exhaust all the possible interesting factors that could be explored. As discussed previously, the core scenarios did not attempt to describe any policy shifts given that it was difficult to evaluate the most likely focus of the new national governments in each country when the study began. Similarly, the scenarios did not address uncertainties in the nuclear or coal industries in these initial rounds, although the option to evaluate them in future rounds remains a distinct possibility.

the growth in renewable power sources like wind and solar. The Cross-Border Energy Infrastructure cases considered situations where the 2020 capacity of electricity transmission was expanded by 20%, the 2020 total capacity of crude transportation (pipeline + rail) was decreased by 20%, and the 2020 cost of transporting natural gas was decreased by 20%. Since only a few models could represent these conditions adequately, these results are not discussed in this analysis of the core scenarios. Another cross-cutting article (Siddiqi et al.) in this special issue considers the natural gas and electricity infrastructure topic.[3]

The final set evaluates the impact of a carbon tax of US $35/tonne-$CO_2$ starting in 2022 and increasing in real, inflation-adjusted terms at 5% per year. At this rate, the inflation-adjusted carbon tax rises to $52 by 2030 and to $137 by 2050 in economies growing by about 2% per year in the Reference case depending upon the country and model. All other countries outside of North America also impose the same carbon tax. The first case assumes that all 3 countries (USA, Canada, and Mexico) impose the tax, while the second case assumes that only Canada and Mexico adopt the carbon policy.

As reported in Fig. 1, ten or more models reported results for the Reference, Carbon Tax (applied to all countries), Low Oil Price, High Renewables, and High Gas Supply cases. The other cases were simulated by six or fewer models. Many models did not report results for the core variables in the infrastructure cases, although other cross-cutting articles of this issue will discuss more extensively regional results from these cases.

3.2. Reported variables

The study assembled 63 variables for these 13 cases.[4] Modeling teams reported results only for the variables that their model covered. These variables were primarily production, consumption, trade and prices for the various main energy sources like electric power, crude oil, refined petroleum products, and natural gas. Additional information was also available for electric generation by fuel or renewable source and for cross-border transmission capacity for electricity and transportation capacity for crude oil and natural gas.

Fig. 2 focuses on only 10 variables but these results highlight the most commonly reported metrics for each country. Each bar represents the number of models reporting a variable by country. Most models represent electricity variables, as represented by electricity use and electric generation[5] by natural gas in this figure. Crude oil, refined petroleum products and natural gas markets in each country are also well represented. Trade variables such as crude oil imports or natural gas exports are often reported but less frequently. The same applies to inflation-adjusted gross domestic product (real GDP) and energy prices.

3.3. Participating modeling teams

The models apply a variety of solution techniques—including energy-system optimization, computable general equilibrium, or simulation—to balance supply and demand conditions and determine market-clearing prices across different fuels and regions. It is not uncommon for a framework to integrate both approaches into a combined,

hybrid model, where the energy system component focuses upon a technology-rich sector like electricity generation. Appendix A contains brief model descriptions.

Table 2 lists the models by name, organization and covered North American countries. The fourth column shows the major solution approach for balancing energy supply and demand, often computable general equilibrium, energy systems optimization, simulation or some combination of approaches. The final column indicates whether the model focuses upon all major fuels (coal, crude oil, natural gas and refined petroleum products) and power (labeled as "energy") as distinct from electric power only (MX-REGEN and ReEDS2.0) or natural gas only (NANGAM). An important observation is that only five models are fully integrated across major energy sources ("Energy") and North American countries (regions = All). These systems are EC-MSMR, ENERGY2020, GCAM, MUSE and MARKAL-NETL. With increasing interest in energy trade and integration within the North American continent, the need for more integrated systems needs further emphasis.

Most models focus solely upon one or more North American country and do not include formal linkages to other regions of the world. Exceptions that do encompass these global linkages include EC-MSMR, GCAM and MUSE. In addition, the NEMS framework can be combined with their international energy model to incorporate many of these international linkages. The main advantage of the global models is that they incorporate the many trading opportunities with other countries when a policy like carbon taxes is imposed. The effects of these policies will depend upon not only domestic substitution responses but also the policies adopted by other countries and the opportunities to trade between all regions.

4. Range of reference outlooks

Energy outlooks, even for the EMF34 Reference case alone, display a wide range of results. Among the numerous influencing conditions, important drivers for energy outlooks are economic growth, population growth, expected alternative fuel and renewable availability and oil price trends. For brevity and as examples, the discussion focuses upon oil price trends and economic growth in the USA, although Canadian and Mexican economic trends and other important drivers also differed across models. In order to highlight the important long-term trends, all charts in this article report only the five-year observations that were reported by all models. Ignoring the intervening years between each five-year period makes it more difficult to trace the full dynamic response in models like NEMS, Energy2020, ReEDs2.0, CER and MX-REGEN that report annual estimates. In some cases, they appear to have more of a stair-step pattern in the charts than a continuous series over all years. By 2050 USA real GDP grows by 80–125% from 2015 levels as shown in Fig. 3. DIEM, Energy2020, and CTUS-NEMS register faster growth than the other models, while MUSE and GCAM indicate a slightly lower trend. Higher economic growth often means more electrification than direct fuel use as well as greater energy imports.

A second important driver is the long-run path for the inflation-adjusted world crude oil price. Higher oil prices in the long-run (by 2035 and later) discourage the use of oil and to a lesser extent other fossil fuels. Fig. 4 shows that the 2050 price reported for the Reference case by the models ranges between $64 and $120 in 2015$ per barrel. After 2035, two distinct patterns for the oil price emerge. The higher price paths indicate an international market where global oil consumption is growing more rapidly relative to global production than with the lower price paths.

Meanwhile, NEB, NATEM and EC-MSMR fall within a group of estimates showing relatively low oil prices after 2035. After a rapid increase, oil prices in NEB and NATEM stabilize at about 75 $US/barrel after 2025 due partly to lower world oil demand. Shared vehicles, electrification and shifting driving patterns particularly among younger drivers reduce oil demand both within North America as well as abroad.

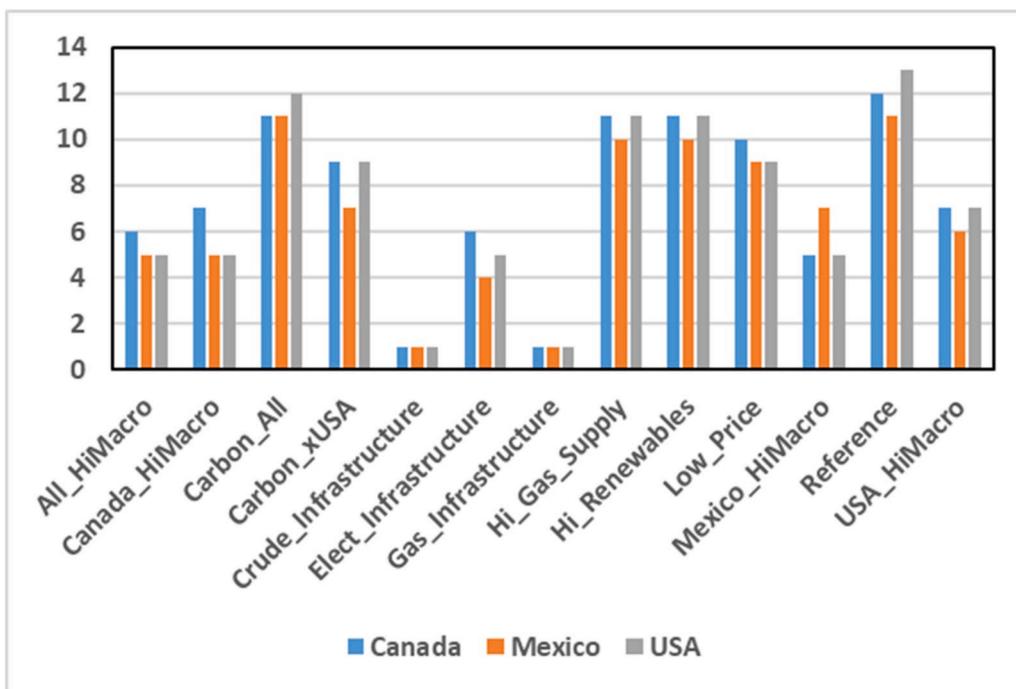It is important to emphasize that many of these models track the

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[3] Although the working group had hoped to have greater participation by more models in the infrastructure case, the full study also evaluated other cross-cutting results based upon a subset of the 17 models that extended beyond the core cases with the full set of models. These articles are introduced and briefly discussed in the editors' introduction to this volume.

[4] These estimates are scenario-based outputs based upon assumptions developed by the working group. They are not forecasts made by each organization about what are the most likely future energy outlooks. The study's database can be accessed at http://www.stanford.edu/group/emf-research/docs/emf34/EMF34-FINAL.xlsx.

[5] Electric generation by other sources are also reported in the full data set.

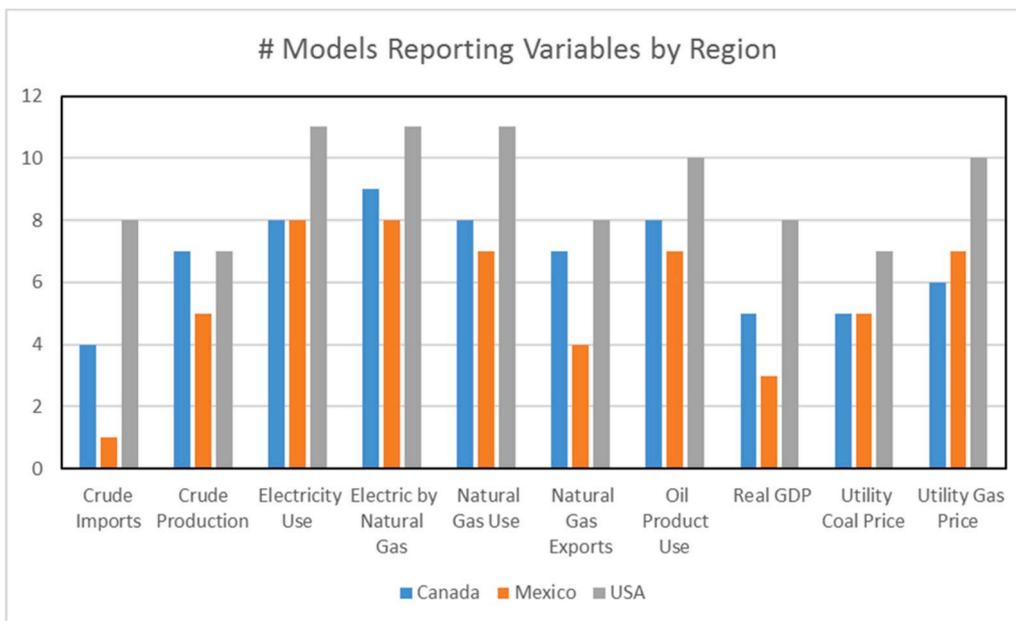**Fig. 1.** Number of models reporting each scenario by country.

Fig. 2. Number of models reporting a selection of variables by country.

long-run energy conditions and ignore short-run perturbations in the oil market and the economy. This observation explains the variation in the oil price reported for 2015 in some models. For example, GCAM calibrates the oil price in 2010 and allows it to change in all subsequent years depending upon the relative balance between long-run world oil demand and supply conditions. Its higher 2015 price of $73 per barrel should be interpreted as what the long-run price would have been if there had not been the Great Recession and subsequent oil price collapse. After 2015, this projection expects the oil price path to readjust to reach the long-run path shown in figure. A similar caveat applies to the MUSE result where the oil price path is also calibrated to a prior

Table 2
Participating EMF34 modeling teams.

Models[a]	Organization	Regions[b]	Model Type[c]	Energy Coverage
ARTIMAS	RTI	USA	CGE	Energy
CER	Canada Energy Regulator[d]	Canada	System Dynamics	Energy
CTUS-NEMS	Onlocation	USA	Energy-Macro	Energy
DIEM	Duke	USA	CGE	Energy
EC-MSMR	Env Canada	All	CGE	Energy
ENERGY2020	Systematic Solutions	All	System Dynamics	Energy
GCAM	JGCRI	All	Integ. Assess.	Energy
IPM	EPA	Canada, USA	Energy Systems	Power
MARKAL-NETL	NETL	All	Energy Systems	Energy
MUSE	Imperial College London	All	Integ. Assess. Simulation	Energy
MX-REGEN	EPRI	Mexico	CGE & Dispatch	Power
NANGAM	American Univ & Johns Hopkins	All	Partial-Equilibrium (Natural Gas)	Natural Gas
NATEM	ESMIA	Canada	Energy Systems	Energy
NEMS	EIA	USA	Energy-Macro	Energy
ReEDS2.0	NREL	All	Dispatch	Power
Temoa	NC State	USA	Energy Systems	Energy
urbs-MX	TU Munich	Mexico	Dispatch	Power

[a] Abbreviation used in comparison charts.
[b] All: Canada, Mexico & USA.
[c] CGE: computable general equilibrium.
[d] Formerly, National Energy Board.

year, when the oil price was higher than about $52 per barrel.[6,7]

As a result, consumption, production and trade for various fuels and power may vary considerably in different Reference outlooks. This wide range of results is expected and often revealed in any study comparing model outputs from a scenario. In addition to variations in economic growth and crude oil price trends, there exists substantial uncertainty

about the cost and penetration of alternative energy-consuming and energy-producing technologies, the geological conditions shaping the oil and natural gas resource bases, and the response rate of energy producers and consumers to different energy-market conditions. An excellent recent example is the revolution surrounding hydraulic fracturing process for recovering natural gas resources (see Energy Modeling
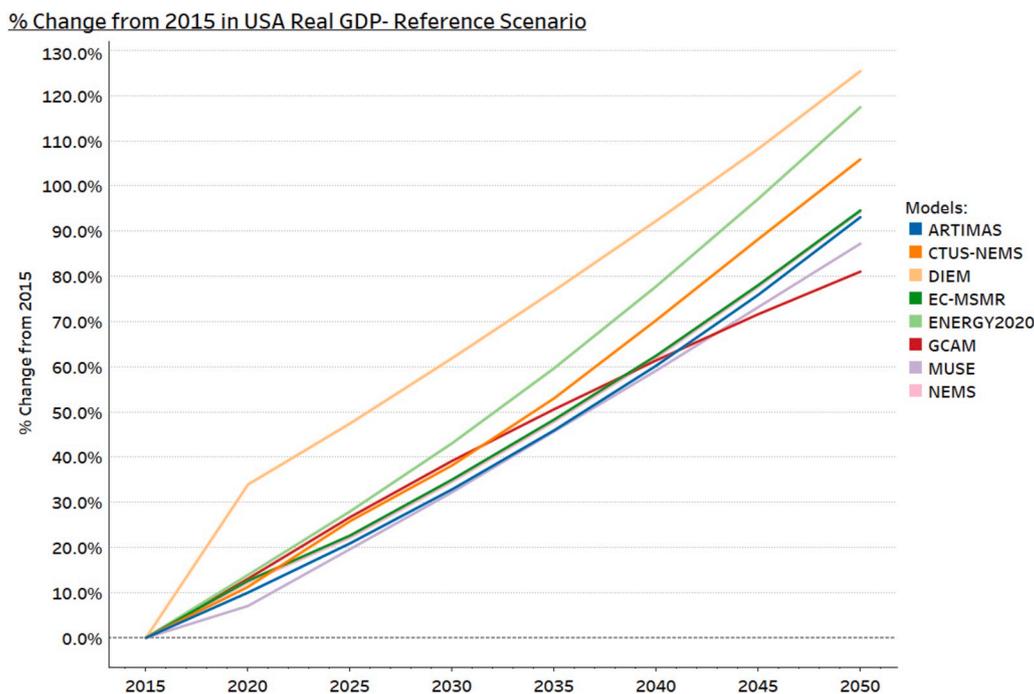

Fig. 3. Real US GDP in the reference case.

Forum, 2013; Huntington, 2016, and Reed et al., 2019) and crude oil resources (see Newell and Prest, 2019).

One important example for Canada would be the trend in net natural gas exports shown in Fig. 5. Net Canadian exports in most models are defined as total pipeline and LNG exports minus total pipeline and LNG imports. One set of models displays rising exports of 20% or more from 2015 levels by 2040, while the other set reveals decreases of at least 36% from 2015 levels. As future cross-border and overseas energy trade expands under Reference conditions, *total* natural gas exports display
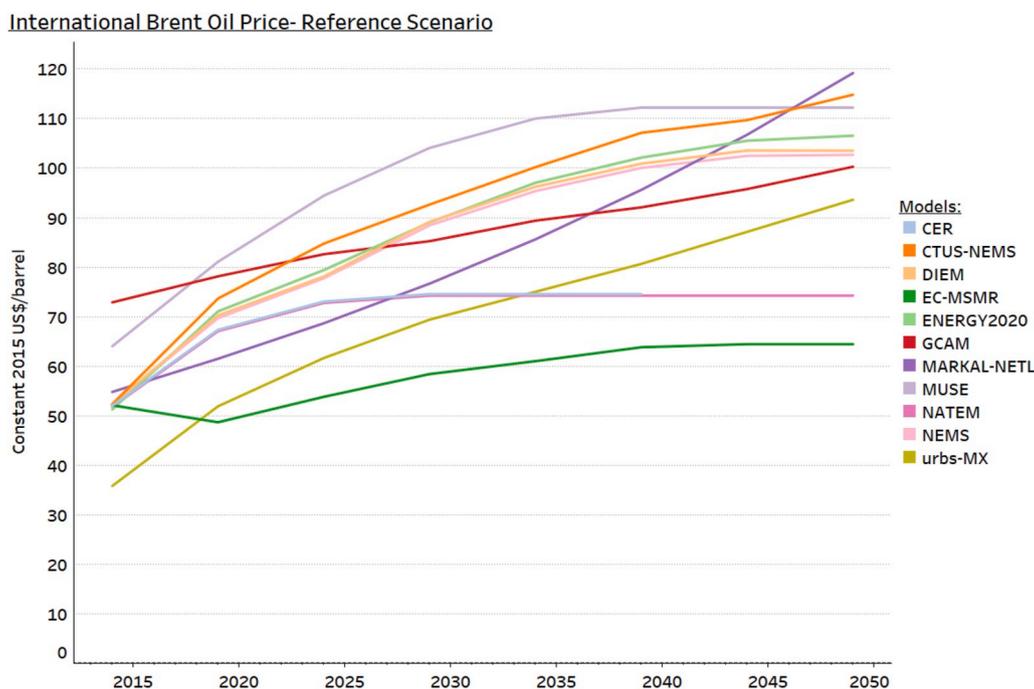
[6] Fig. 4 also shows that the urbs-MX path is calibrated to a lower price than the others. In addition, the EC-MSMR model uses 2011 as a base year and all subsequent prices and production levels are relative to 2011. Rather than keep this higher price, however, their price path is adjusted downward to reflect current conditions. This calibration adjustment results in a lower oil price path than in the other models.

[7] Appendix B shows the oil price paths as a percent of the 2015 level in each model. The interested reader with a focus on the long-run growth rate in prices may find this chart more relevant.

International Brent Oil Price- Reference Scenario

Fig. 4. Real brent crude oil price in reference case.

% Change from 2015 in Canada Natural Gas Net Exports- Reference Scenario
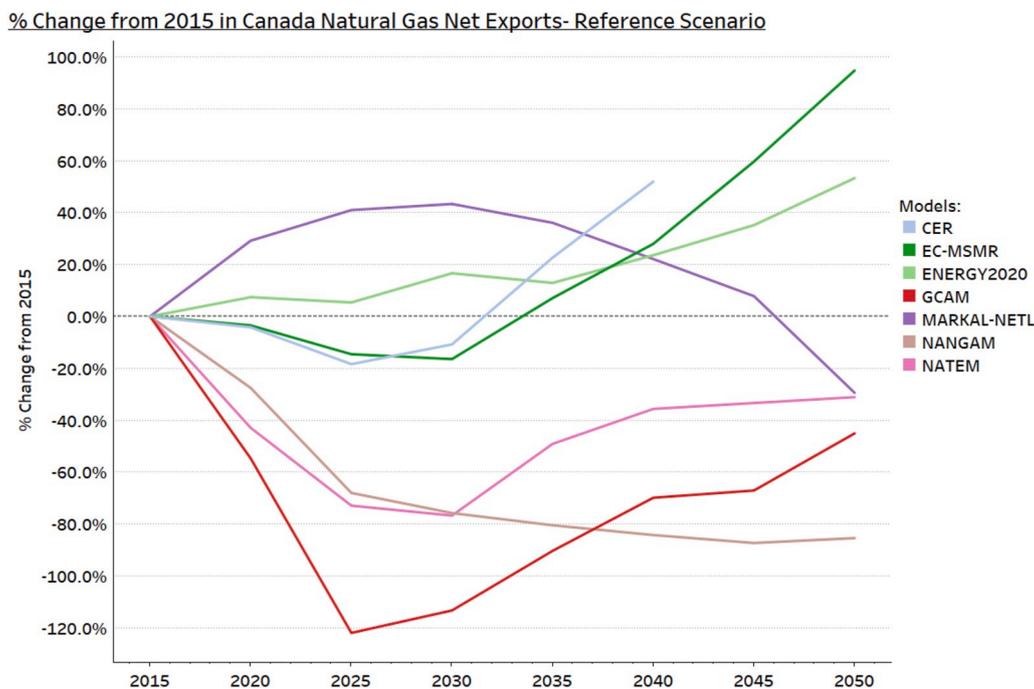

Fig. 5. Net Canadian natural gas exports in the reference case.

larger growth from 2015 values than shown for *net* natural gas exports shown here in Fig. 5.[8]

The MARKAL-NETL (labeled in the figure as NETL) response includes net pipeline exports defined as Canadian production less Canadian demand but excludes LNG exports. In the Reference scenario mid-term Canadian natural gas demand growth leads to a reduction in net exports. As production expands after 2040, production growth starts to outpace demand growth and net exports rise. LNG exports (not

included) can contribute to the growth in net exports after 2025.

The trend in changing exports depends on the assumptions of the time horizon on not only Canadian potential for natural gas production, but also how quickly demand in Mexico is expected to rise and what percentage of the rise in demand is expected to be satisfied by the United States. NANGAM, for example, evaluates natural gas across North America and assumes a robust supply of natural gas for the United States as well as some domestic supply in Mexico. Although Mexican demand is expected to increase, the United States produces enough natural gas to both help satisfy demand in Mexico and satisfy its own demand over time. As a result, natural gas imports from Canada decrease, as revealed

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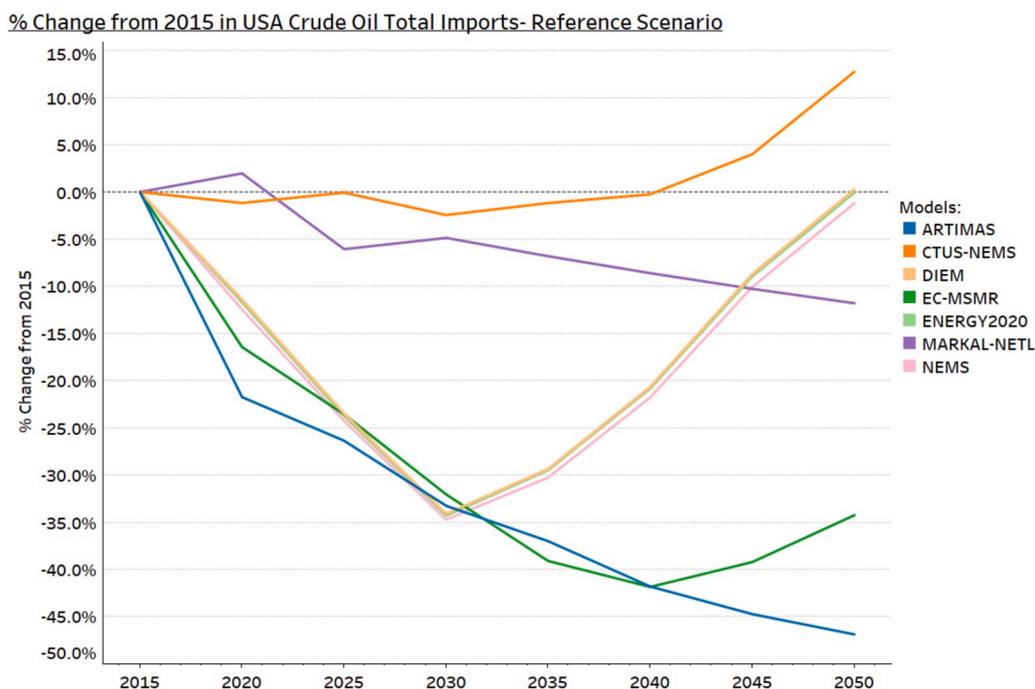[8] See Appendix B for the comparable paths for total natural gas exports.

Fig. 6. Total USA crude oil imports in the reference case.

by the decrease in Canadian exports as shown in Fig. 5.

While natural gas production in NATEM is expected to increase by 49% between 2015 and 2050, exports are declining by 29% in the same period. Most of this decline is due to a lower demand from the USA. Continental exports are partially replaced by an increase in international exports via liquefied natural gas shipping from the West Coast, especially after 2035. The additional production is used for domestic purposes including steam generation in the oil & gas industry and electricity generation.

Another example would be the trend in total US crude oil imports, which equaled 7.35 million barrels per day in 2015. Abundant U.S. reserves of crude oil in conventional and unconventional deposits (such as shale resources) combined with technological advancements and new policies have changed the outlook for oil production in the United States from perceived scarcity to relative abundance. At the same time, the USA is also the world's greatest consumer of crude oil and petroleum products as well as the top producer of crude oil. As a result, the USA remains a net importer of crude oil through 2050. Most trends in Fig. 6 call for either a decline or little adjustment in oil imports from 2015 levels until 2040. By 2030, oil imports decline by a little more than 30% from 2015 levels in many models.[9] After expanding through the year 2020, U.S. crude oil imports in MARKAL-NETL's Reference case decline from 2020 to 2050 by about 13%, from 9.8 million barrels per day to 8.5 million barrels per day.

5. Crude oil production

North America is expected to be an important future source for crude oil production supplied to global markets. This section explores the sensitivity of crude oil production in the three individual countries to a lower inflation-adjusted world crude oil price path.

By 2040 Canadian output reported by the models in the Reference case ranges from 4-7 MMBD, Mexican output from 2.5-3.0 MMBD and

USA output from 8-15 MMBD.[10] These differences are due only partly to the wide range in crude oil prices shown in Fig. 4. Drilling costs, new technologies and geologic conditions represented in the various models also account for these disparities in future production by country.

Oil prices decline in response to higher supply and/or lower demand conditions in areas outside of North America in the alternative Low Oil Price case. By 2050, oil prices under these alternative conditions are assumed to be 50% lower than in the Reference case. A lower world oil price reduces domestic oil production in all three countries in most models. Canadian production shown in Fig. 8 declines more proportionally than does production in the USA (Fig. 7) or Mexico (Fig. 9). The largest Canadian production decline registers about 70% below the Reference level by 2050, compared to about 30% in USA production. Canada's greater sensitivity to lower prices is due to the large role played by oil sands in this country. Sustained lower prices in many models like NATEM discourage development of oil sands, which is a very capital-intensive process that requires considerable time and infrastructure to develop relatively costly resources effectively.

Within any one country, production responses can vary widely by model. Although most models indicate sizable oil production responses to the lower world oil price, MARKAL-NETL and GCAM display much more modest impacts. USA production varies very little from the Reference case in MARKAL-NETL because lower-cost tight oil remains competitive with other world regions due to its lower costs. Moreover, GCAM reveals a very different pattern where lower prices cause USA and Canadian producers to monetize their resources sooner by expanding output earlier. This response reflects the declining value of holding resources longer and selling them in the future in a low oil price world. Selling resources earlier allows producers to earn revenues from other investments that might be more productive than oil production.

Canadian producers are not receiving the global commodity price according to MARKAL-NETL model. Canadian crude oil production in this model is limited by limited pipeline capacity. Major pipeline projects such as Northern Gateway and Energy East have been cancelled;

[9] There are some interesting results on regional oil trade in the global models like EC-MSMR. As this model reaches towards 2050, the primary exporter to the USA shifts to Canada from OPEC. The latter begins exporting more crude oil to developing regions like China, India, other rapidly growing economies.

[10] These Reference results are not plotted in individual charts for reasons of brevity.

% Difference in USA Crude Oil Production- Low Price Scenario wrt Reference Scenario
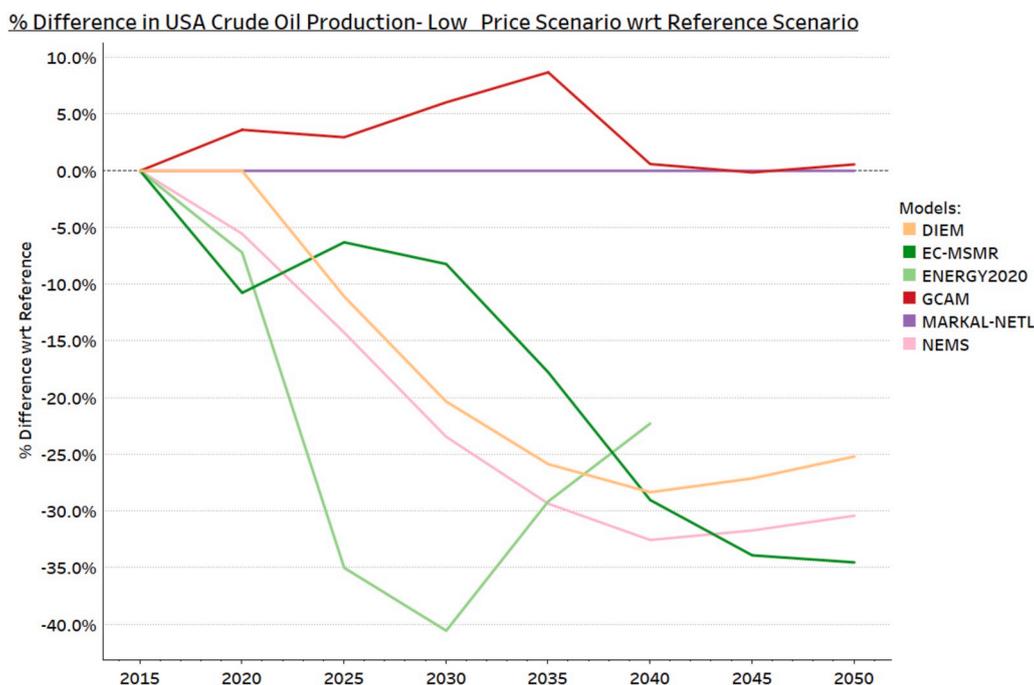
Fig. 7. Response of USA crude oil production to lower price.

% Difference in Canada Crude Oil Production- Low Price Scenario wrt Reference Scenario
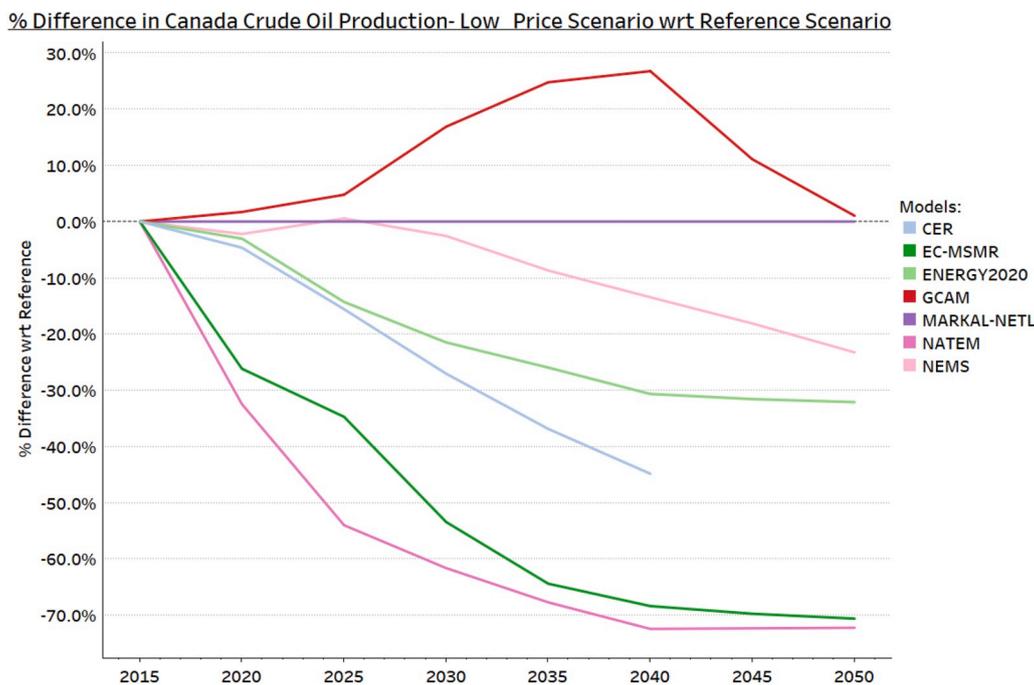

Fig. 8. Response of Canadian crude oil production to lower price.

the Enbridge Line 3 Replacement, the Trans Mountain Expansion and TC Energy Keystone XL projects continue to face challenges. The lack of sufficient pipeline capacity has forced Canadian producers to increasingly rely on rail to get crude to market. According to the MARKAL-NETL model, Canada's limited ability to access existing markets in North America and overseas limits the impact of higher international oil prices on Canadian production.

One can compute a response comparable to the price elasticity of crude oil supply for some models that report both changes in production and oil prices. These price elasticities are calculated as the percentage deviation in a year's production level between the Low Oil Price and Reference scenarios, divided by the comparable percentage deviation in a year's real oil price.[11] Notice that the EMF scenario design assumes that the oil price change results from an external net demand shock for North American oil rather than an internal North American supply

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[11] These percent changes are computed as the difference between logarithms of a variable in order to adjust for the large differences between the variable in each case. This technique can be considered closer to an arc elasticity approach rather than one based upon the point elasticity measured at the Reference case level.
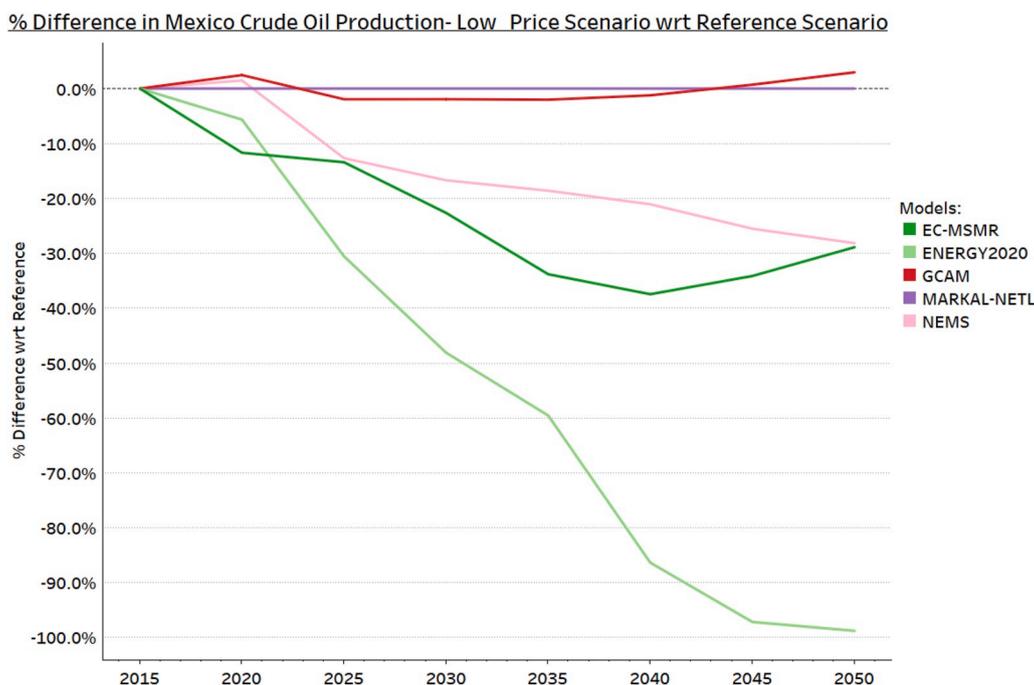
Fig. 9. Response of Mexican crude oil production to lower price.

shock. Separating demand shocks from supply shocks using econometric techniques on historical data is often much more complicated.[12] These inferred responses from the EMF34 study may not be the actual price elasticities used by each model, because other variables like alternative energy prices, economic growth or some other relevant factor may have also changed in the new scenario. However, they provide an overall assessment of the response that may be useful for other analyses. When averaged over all models, these estimates for the United States were 0.30 in 2040, indicating that crude oil production increased by 3% for each 10% escalation in the oil price. Similar estimates were 0.20 for Mexico and considerably higher for Canada (0.69) as lower prices strongly discourage the development of relatively expensive Albertan oil sands resources.

6. Natural gas production

By 2040 Canadian natural gas production in the Reference case ranges from 15-30 Bcf/d, Mexican output from 3-10.5 Bcf/d and USA output from 70-140 Bcf/d.[13] Varying oil and gas prices, drilling costs, new technologies and geologic conditions account for natural gas production disparities by model in the Reference case.

Some natural gas is found in formations that are associated with crude oil. Lower oil prices will therefore also reduce some drilling in these formations, resulting in some declines in natural gas production below Reference levels in the three countries. These impacts are much more modest than the percentage declines in crude oil production discussed above in Figs. 7–9, often declining by 4% or less by 2050 in most models.

Natural gas production is also sensitive to changes in the inflation-adjusted wellhead natural gas price, because producers can shift drilling activities toward finding more natural gas than crude oil depending upon the relative economic incentives. A primary driver of future

natural gas prices will be the strength of North American economic growth. To evaluate these incentives, the working group examined results for natural gas production in the High North American Macro Growth case. Stronger economic growth created more demand for natural gas that raised natural gas prices and natural gas production.

Fig. 10 shows that USA natural gas production increases by about 1–10% above reference levels in the models displaying some response when the economic growth rate is 20% faster than in the Reference case.[14] These responses are a little less for Canadian natural gas production (Fig. 11) and Mexican natural gas production (Fig. 12), but the range of estimates remains quite large.

As was done for crude oil, one can compute a response comparable to the price elasticity of natural gas supply in 2040 for some models that report both changes in production and the Henry Hub wellhead natural gas prices. These inferred responses may not be the actual price elasticities used by each model, because other variables like alternative energy prices, economic growth or some other relevant factor may have also changed in the new scenario. However, they provide an overall assessment of the response that may be useful for other analyses. When averaged over all models, these estimates for the United States were 1.15 in 2040, indicating that natural gas production increased by 11.5% for each 10% escalation in the gas price. Similar estimates were 1.21 for Canada and 1.00 for Mexico. As a result, the models tend to show natural gas production to be more price elastic than crude oil production within the three North American countries.

Further insights can be extracted from exploring these conditions in the NANGAM model, which tracks the production, consumption and

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[12] Globally, oil supply shocks dominated world markets through 1990, after which demand shocks had a more important role (Stock and Watson, 2016, Huntington, 2018).

[13] As with the oil production trends, these Reference levels are not plotted in individual charts for reasons of brevity.

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[14] The increased response for North American natural gas production in EC-MSMR relative to the other models occurs because the framework allows an outward shift in natural gas supply as well as an outward shift in demand. The high macro-economic growth scenarios were implemented in EC-MSMR by an efficiency improvement for capital and labor in all economic sectors including natural gas production. As a result, input costs for natural gas production declined relative to the Reference conditions, making the natural gas fuel more competitive on the global market. This result demonstrates the challenges of devising scenarios in a multi-model comparison that can be implemented uniformly by all groups.
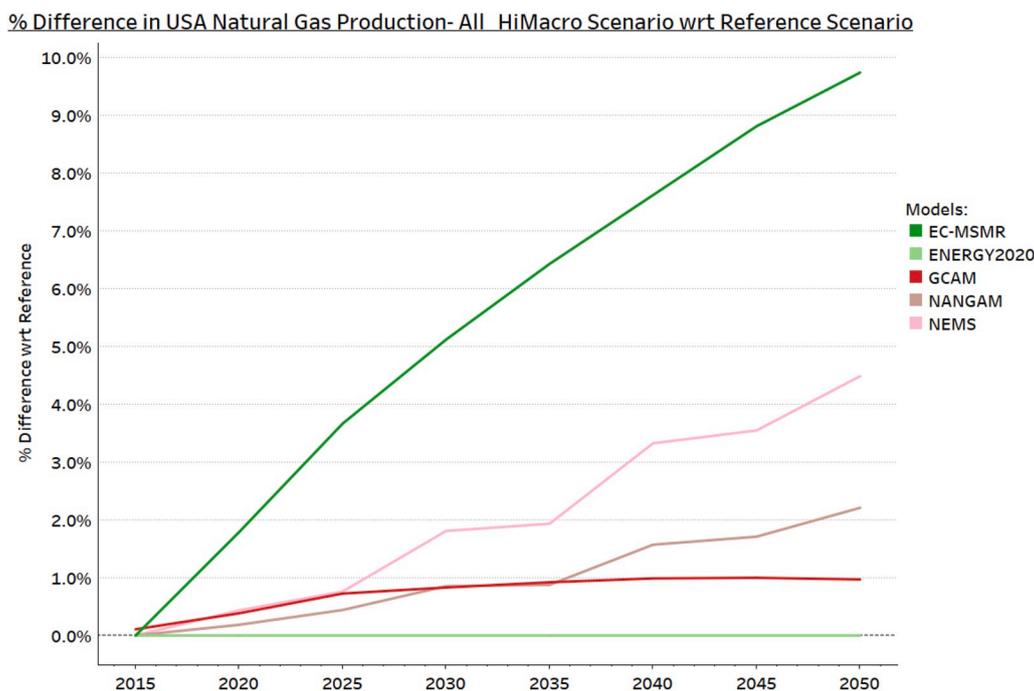
Fig. 10. USA natural gas production in response of higher North American economic growth.
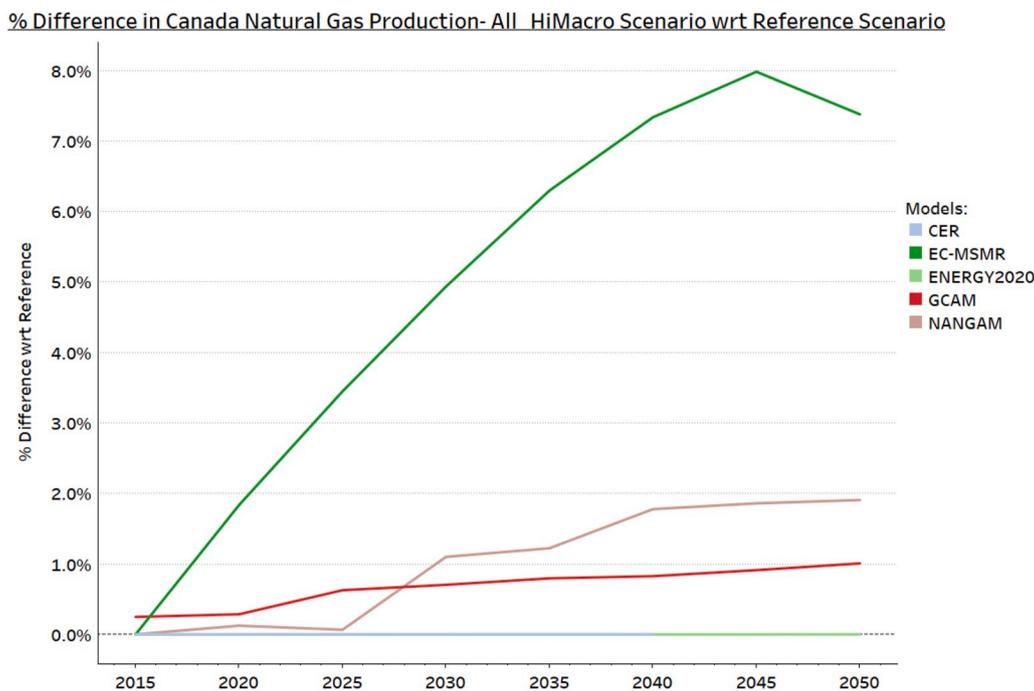

Fig. 11. Canadian natural gas production in response of higher North American economic growth.

trade patterns for natural gas across the three countries. While natural gas production is generally expected to increase across the three countries, this change is primarily driven by an increase in demand for natural gas. In particular, Mexico's energy transition to natural gas for electricity production drives the majority of the future natural gas dynamics in North America. Across the US-Mexico border, there is expected to be an increase in trade of natural gas, evidenced by the current and planned construction of pipelines (see Fig. 13).

Most of this natural gas will be produced and exported from and around the Haynesville region around Texas. What is less certain is

which intra-national pipelines in the United States will be constructed in order to meet these new dynamics. Depending on different future scenarios, regional natural gas demand in the United States could be satisfied by the United States, or by Canada. The uncertainty around where this increase in production will come from is also why in Fig. 5, the models have discrepancies in Canadian exports of gas. The accompanying papers in this special issue provide more details of natural gas dynamics in North America under these future scenarios.

In addition to the changing magnitudes and patterns in demand, natural gas cross-border trade is robust under different scenarios. In the
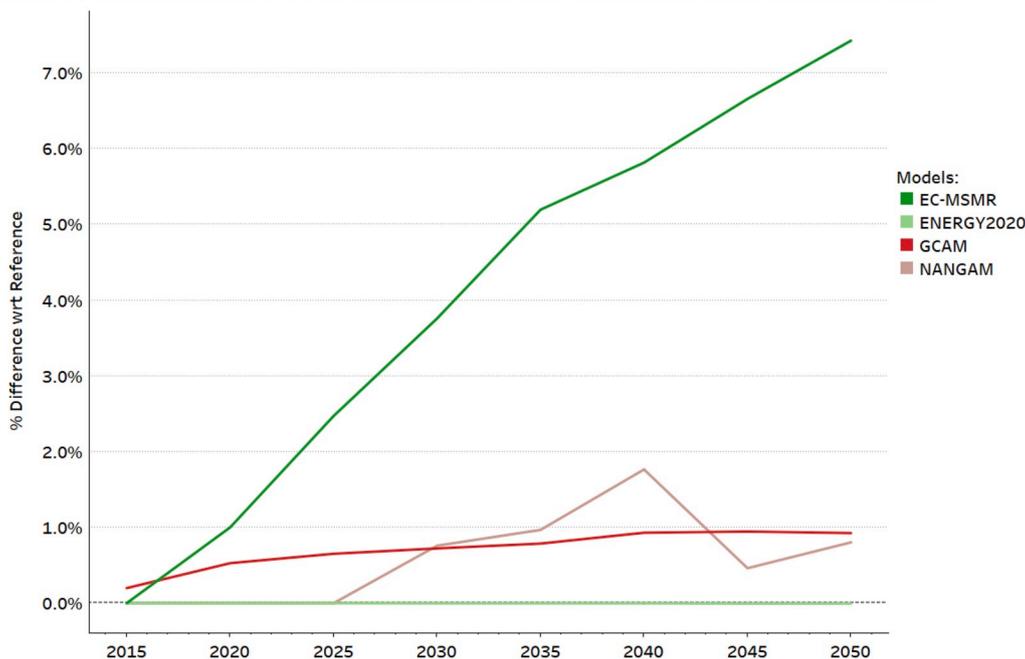
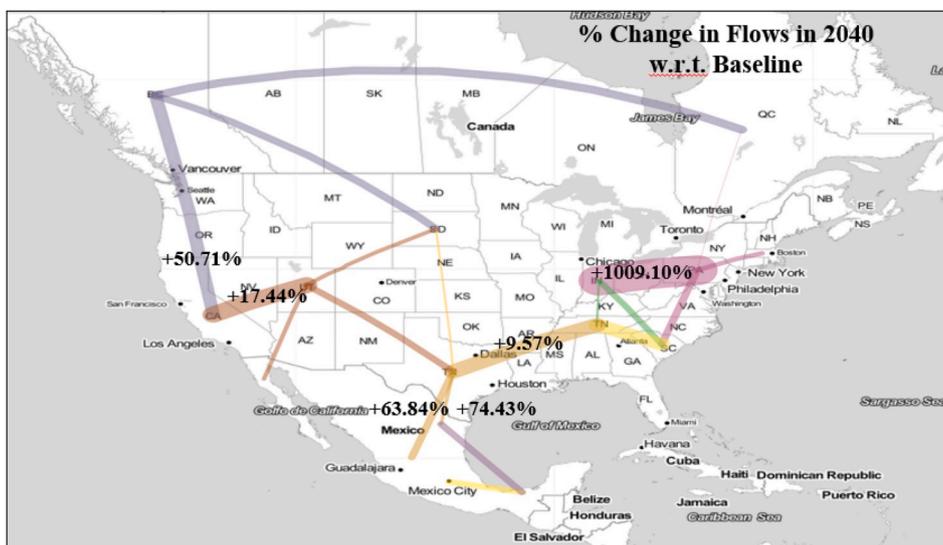**Fig. 12.** Mexican natural gas production in response of higher North American economic growth.

Fig. 13. Map of reference flows in 2015 and % change of flows between 2015 and 2040.

High_Gas_Supply scenario that incorporates higher technological change that consequently reduces the cost of production, Mexican production grows more than that of the U.S. and Canada in the NANGAM results. Still, U.S. exports to Mexico remain unaffected (see Fig. 14 below). The result suggests that Mexico would still import natural gas from the US even if Mexican production grows disproportionately more.

7. Future sources for electric power

The models agree on the future shift towards electric power and renewable sources between 2020 and 2050 even with Reference conditions. The extent and speed of this transformation, however, will vary sharply depending upon assumptions about technology developments and market conditions as well as the underlying model structures (Mai et al., 2018). This section illustrates this point by focusing upon 2040

electric power mixes by generation source in the three countries. It is recognized that one may need to consider impacts in other years for some policies.

For each country, this section begins by reporting the electric sector mix in the Reference conditions. It is important to understand that the reference policy assumptions were not harmonized. Some groups allowed Canadian policies like the province/federal carbon taxes in the Reference case but others did not. Another example is the coal intensity standards "phase out" coal use after 2030 in some models in the Reference case, but other models showing significant 2040 coal use do not incorporate this policy. Similar caveats apply to how models treated several nuclear reactors reaching the end of their lifetime. Some models allowed continued operation of these plants that kept nuclear electricity generation more or less constant through 2050, while a few frameworks did not. These differences among models in how the Reference case was
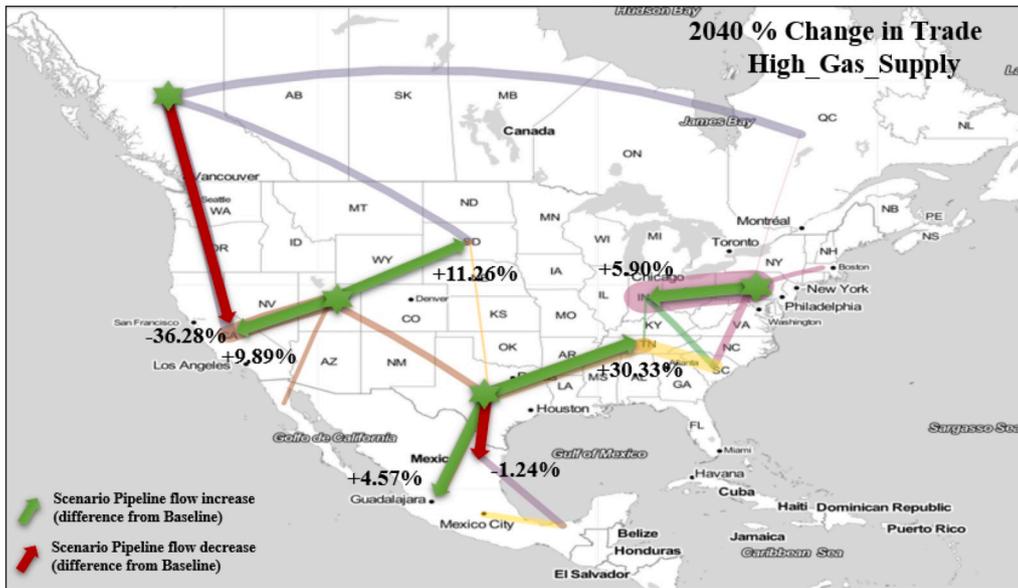
Fig. 14. Map of flows in High_Gas_Supply scenario with respect to baseline flows in 2040.
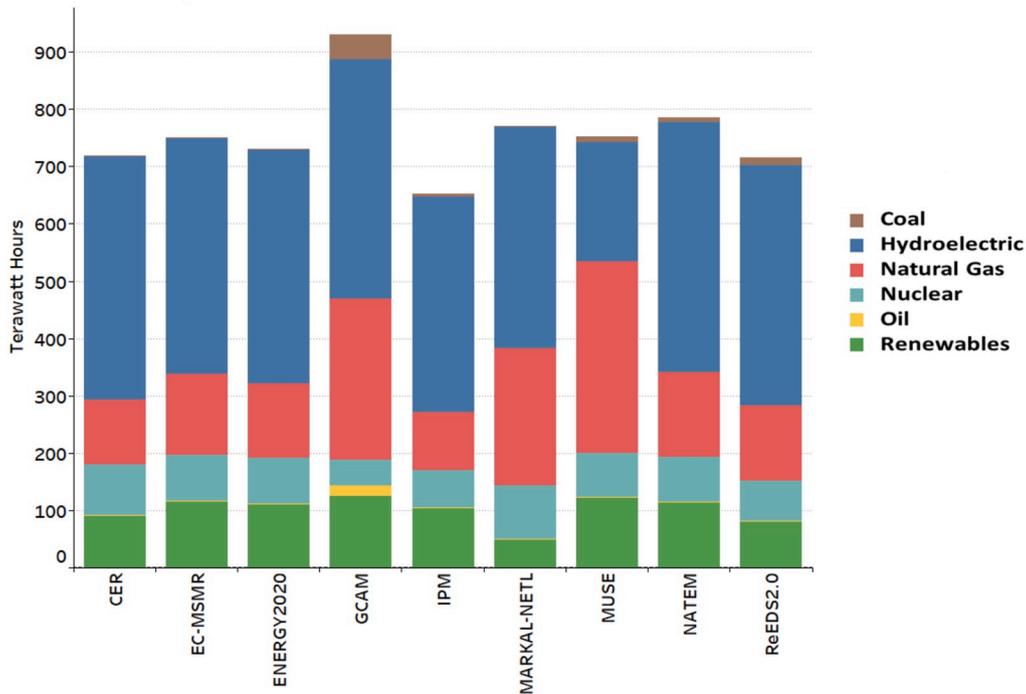

Fig. 15. Canadian 2040 Electric sources in reference case.

specified have important implications in later charts showing how the power sector's fuel mix adjusts when carbon taxes are applied, natural gas is more abundant, and renewables are more competitive.

7.1. Canadian Electric Sources

The Canadian electric system remains dependent upon hydroelectric power throughout the period ending in 2050. Hydropower is somewhat smaller in MUSE than in other models because this source is replaced partially by variable renewables (wind and solar) in the second part of the simulation period. Total generation ranges from 700-1000 TW h in the Reference case, as shown by the total of the stacked bars in Fig. 15.

Table 3
Annual growth rate for intermittent renewables, 2015–2040.

(Average Model Result)			
Case	**Canada**	**Mexico**	**USA**
Reference	3.9%	7.2%	4.9%
Carbon Tax	6.3%	10.3%	7.4%
High Gas Supply	3.3%	6.5%	4.4%
High Renewables	4.6%	8.5%	6.6%

Note: Total renewables excluding hydroelectricity.

The total stacked bars for each model are determined endogenously by the inflation-adjusted electricity price and macroeconomic conditions shaping electricity consumption.

The electricity generation mix indicated by the individual bars for each source depends on model-specific technological choice approaches (which typically weigh the system value and costs of different resource portfolios) and input assumptions. One example is a merit-order approach based on levelized costs of each technology type that is used in the MUSE model. The electricity generation mix for MUSE, GCAM and NETL in the reference scenario shows a growing share of natural gas as indicated by the relatively large red bars. Natural gas is the most efficient technology generation option in these cases, where it replaces coal and some nuclear generation as these plants are decommissioned and retired.

The source labeled as "renewables" in all figures in this section refers to intermittent renewable energy forms like solar, wind and geothermal as distinct from hydroelectric power. Table 3 summarizes the average annual growth rate for this source reported by all models in four key scenarios that will be discussed in this section. The first numerical entry indicates that Canadian renewables grow by 3.9% annually in the reference case.

When the carbon tax is applied in all three countries, renewables displace natural gas by 2040 within Canada's electric power sector (Fig. 16). Averaged across all models, renewables grow at a much faster annual rate (6.3%) than the 3.9% rate in the Reference case. Earlier in the 2015–2040 period, natural gas displaces coal. After 2040 when most of coal has been decommissioned and cannot be rebuilt unless equipped with abatement technologies, the carbon price is sufficiently high to replace natural gas with hydroelectric and eventually renewables. Renewables in the MUSE results undergo a high costs reduction in the second part of the simulated time framework, and, in synergy with the carbon price, they totally displace natural gas after 2040.

Natural gas displaces renewables when natural gas is abundant and less expensive (Fig. 17). Renewables grow at a slower annual rate (3.3%) than in the Reference case. Additionally, nuclear and hydroelectric may also be displaced in some outlooks. Lower natural gas prices in models like MUSE and IPM also reduce electricity consumption modestly by a few percent of Reference levels because the cost of direct natural gas use competes more favorably with electricity than in the other cases. In some models, like NATEM, the impact is relatively minor because the additional natural gas production is exported as liquefied natural gas to international markets rather than used for domestic electricity generation.

Renewables displace natural gas when renewable costs are reduced (Fig. 18). Its annual growth rate (averaged across all models) rises above the reference rate to 4.6%, although it grows less than when the carbon tax is applied.

7.2. Mexican Electric Sources

Under reference conditions, the Mexican electric system uses larger shares of natural gas and variable renewables over time. Total 2040 generation ranges from 400-700 TW h in the Reference case (Fig. 19). Variable renewables grow much more rapidly in Mexico than in the other two countries at a rate of 7.2% annually. Similar to the Canadian results, Mexican generators minimize the levelized costs of competing technologies in their electricity generation investments. Natural gas grows relative to coal as it the most efficient technology early in the horizon. Both MUSE and NETL reveal stronger hydropower growth after 2030 as it becomes more cost effective than other sources.

Renewables displace natural gas in the Mexican power system as they become more competitive when the carbon tax is applied in all three countries (Fig. 20). When coal is still used in the Reference case, it is also displaced by the carbon tax. The average annual growth rate for renewables rises from 7.2% to 10.3%.

Natural gas is favored over renewables when natural gas is abundant and less expensive than under Reference conditions (Fig. 21). Renewables continue to grow strongly at 6.5% annually when averaged across models even though it is less than under reference conditions. This trend reflects the continued favorable cost conditions for renewables included by most models across all cases. Lower natural gas prices also mean lower Mexican electricity prices. As a result, by 2050, electricity consumption lies above Reference levels in 2050 by 4% and 12% in EC-MSMR and GCAM, respectively.

When renewable costs are lower than under Reference conditions, natural gas is displaced by renewables in this sector (Fig. 22). Renewables grow at an average annual rate of 8.5%, which despite its very high rate is below that for the carbon tax.
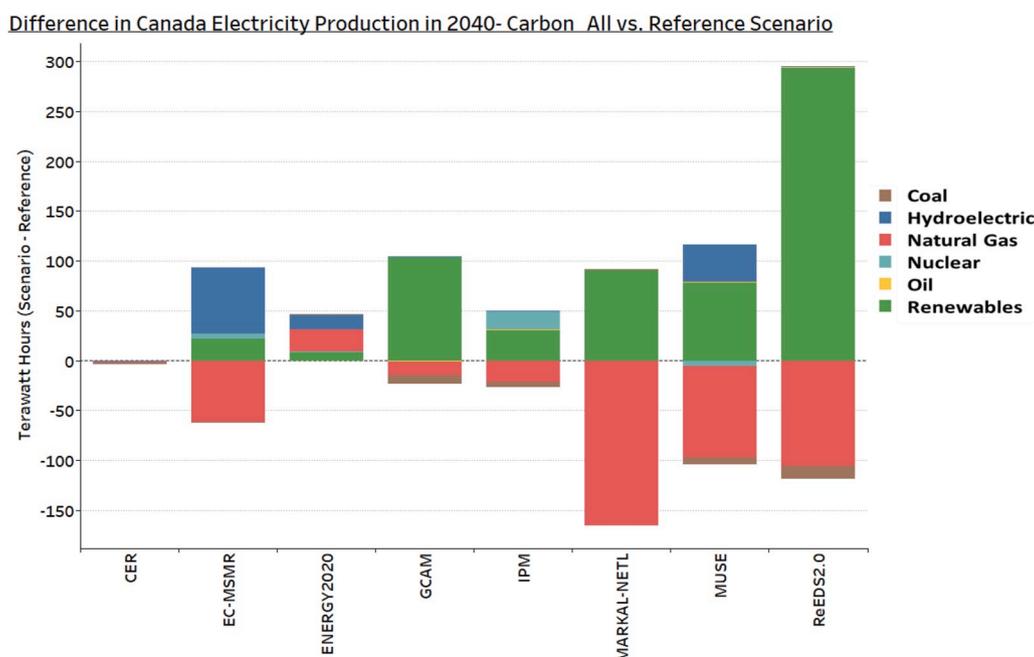

Fig. 16. Changes in Canadian 2040 electric sources in response to carbon tax.
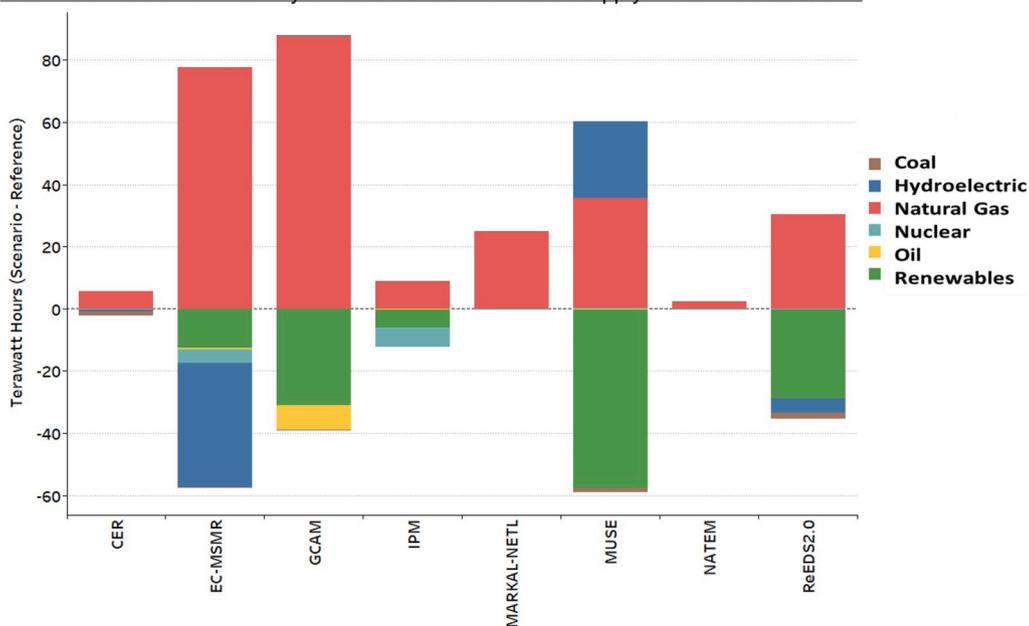
Fig. 17. Changes in Canadian 2040 electric sources in response to high natural gas supply.
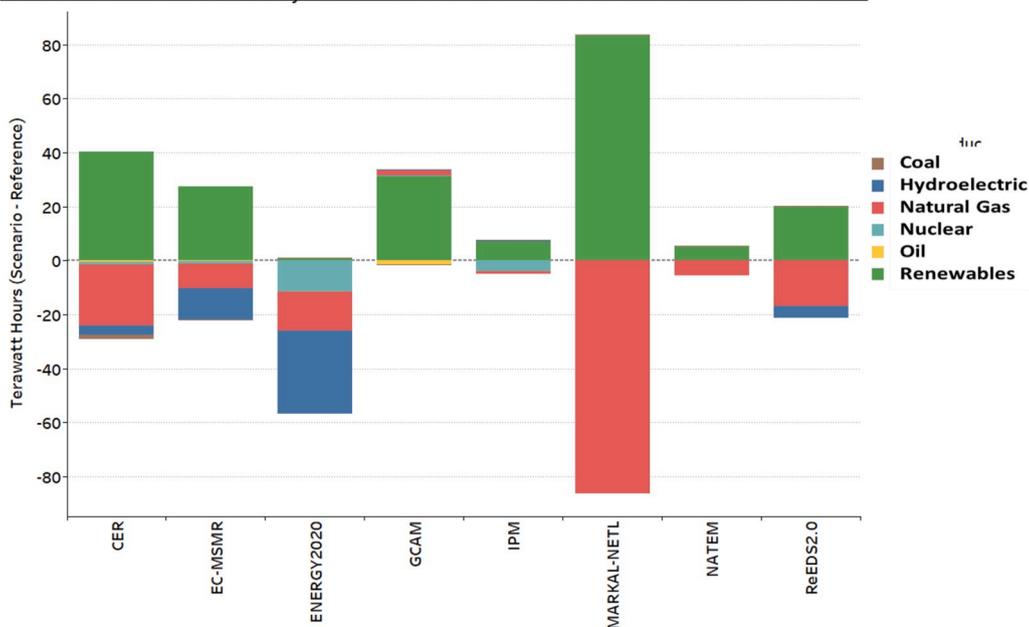

Fig. 18. Changes in Canadian 2040 electric sources in response to greater renewable penetration.

7.3. USA generation sources

Electricity generation in the USA over time includes increasing contributions from natural gas and variable renewables and lower shares of coal and nuclear, according to most participating models. Coal retains a sizable fuel share (47% by 2040) in only one reference outlook (GCAM). Total 2040 generation ranges from 4500-6500 TW h in the Reference case (Fig. 23). In this case variable renewables grow at an annual rate of 4.9% when averaged over all models, as shown above in Table 3.

USA reference trends are similar to those for Mexico and Canada. In the early period, generators expand natural gas use, because this fuel has lower levelized costs than coal and nuclear. Although special constraints

may induce greater coal retirements in some models, the results reflect shifts in the generation mix due primarily to the cost effectiveness of the various technologies.

Within the US power system, a carbon tax applied in all three countries tends primarily to displace coal and natural gas with renewables (Fig. 24), which grows by 7.4% annually and considerably higher than the 4.9% rate in the Reference case. The policy also reduces the growth in US electricity demand relative to the Reference case due to the higher electricity price. Prices in the USA rise more than in Canada when the carbon tax is applied, due to higher Canadian dependence upon fossil-free hydroelectric power. Some models indicate that the tax can increase gas and nuclear generation. The nuclear increases for many models are existing reactors staying online longer rather than generation
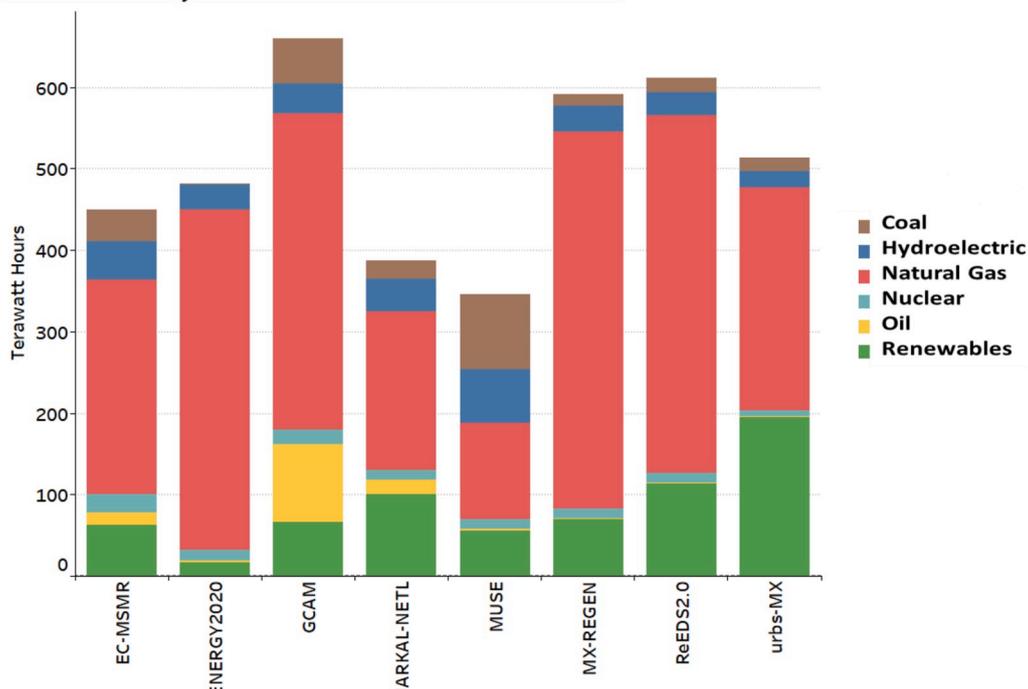
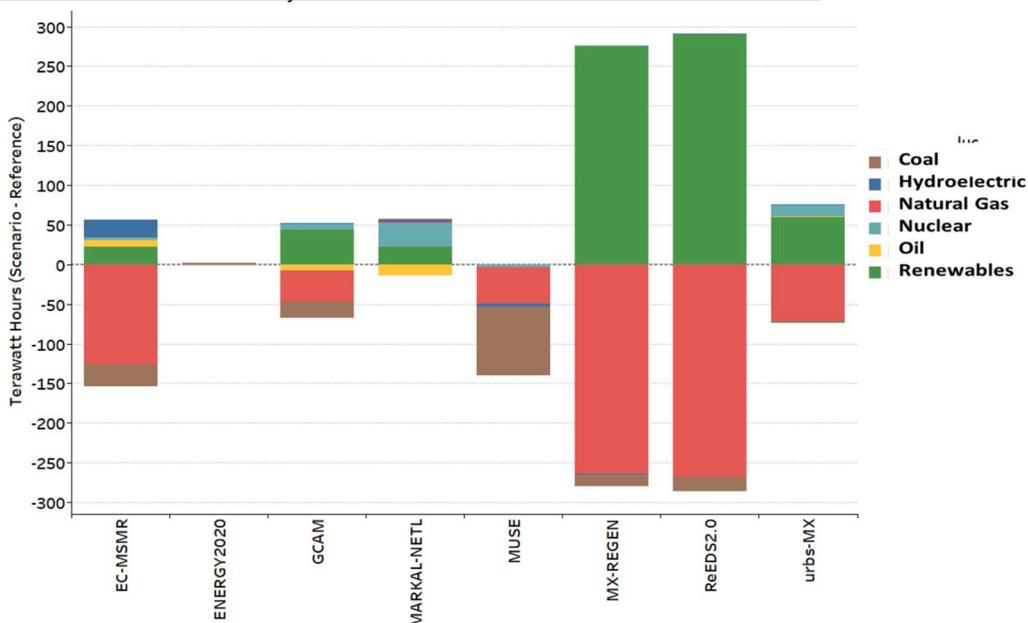**Fig. 19.** Mexican 2040 Electric sources in reference case.

Fig. 20. Changes in Mexican 2040 electric sources in response to carbon tax.

from newly constructed plants. When the power sector selects significant amounts of coal in the Reference case, as with the GCAM results, the carbon tax will also reduce coal well below Reference levels. These general findings are consistent with earlier multi-model exercises on carbon tax impacts in the USA power sector (Bistline et al., 2018).

Natural gas displaces renewables, coal, and nuclear in the generation mix when gas is abundant and less expensive (Fig. 25). Renewables continue to grow briskly at 4.4% annually but at a slower rate than in the other cases. Electricity consumption in many models are modestly higher by no more than 3% in 2040 than Reference levels in most

models. These findings are consistent with earlier multi-model exercises on the impacts of more abundant and less expensive natural gas within the USA (Energy Modeling Forum, 2015; Shearer et al., 2014) as well as globally (McJeon et al., 2014). Generators substitute renewables for natural gas and some coal with lower renewable costs than in the Reference case (Fig. 26). Variable renewables grow by 6.6% annually in this case when averaged across all models.
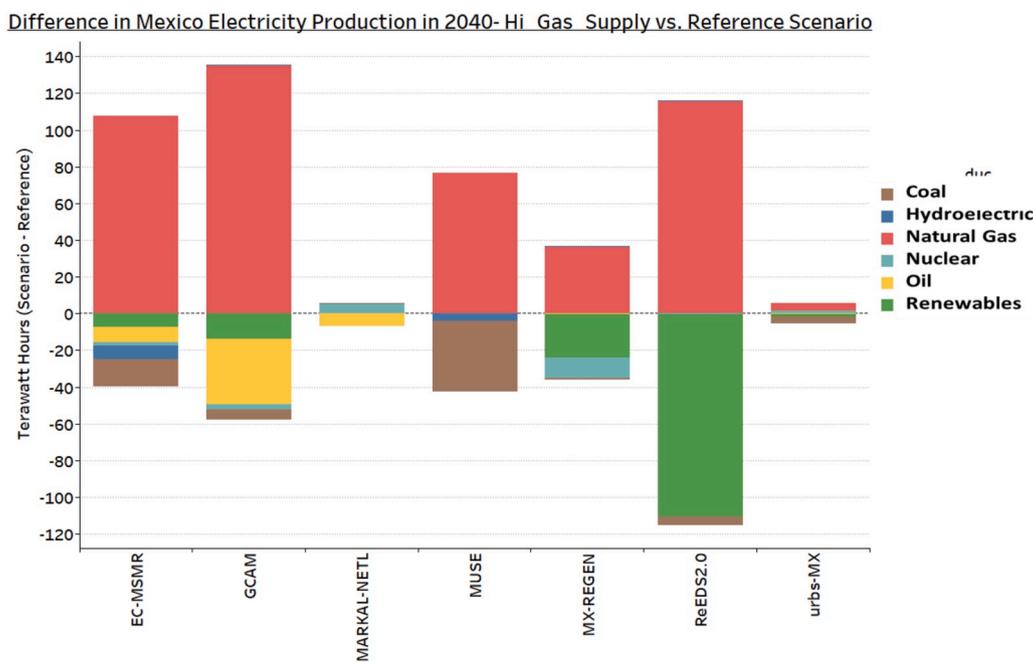
Fig. 21. Changes in Mexican 2040 electric sources in response to high natural gas supply.
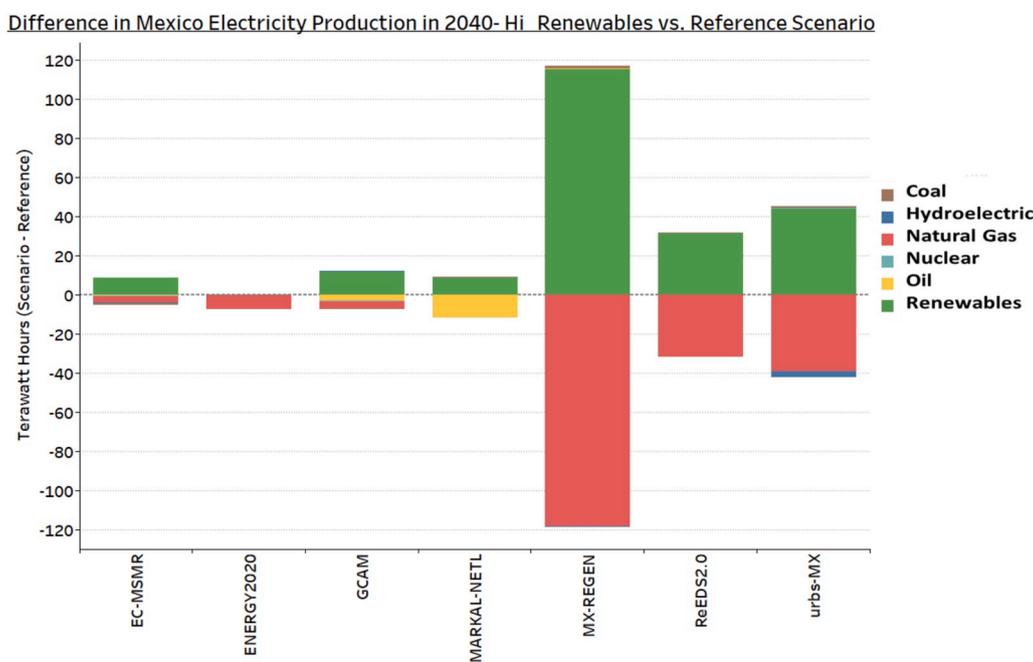

Fig. 22. Changes in Mexican 2040 electric sources in response to high renewable penetration.

8. Conclusions and further work

The EMF34 workshops and model-comparison activities represent an initial effort to analyze the transition towards more integrated North American markets into its major component elements. A major byproduct of this study was the facilitation of expanded communication between analysts from Canada, Mexico and the United States. The sharing of key data, outlooks and insights will likely lead to improved corporate and public policy decisions in the future.

Another important benefit has been the emphasis on the wide range of views that different modeling frameworks bring to decision makers. It underscores for the analyst the importance of sharing and comparing

results and understanding key lessons. It should also remind the policy developers in different government agencies and different countries that policy proposals should incorporate considerable flexibility. If rules and regulations fail to attain this flexibility, they may be less robust if future conditions turn out quite differently from those current outlooks considered most likely at the time of the policy's implementation.

Our introductory work highlighted several important lessons:

1. Important trade information such as trends for oil imports or natural gas exports can be gleaned from comparing projections from different frameworks. Cross-border trade for natural gas, power and crude oil are expected to rise over time, but the various estimates

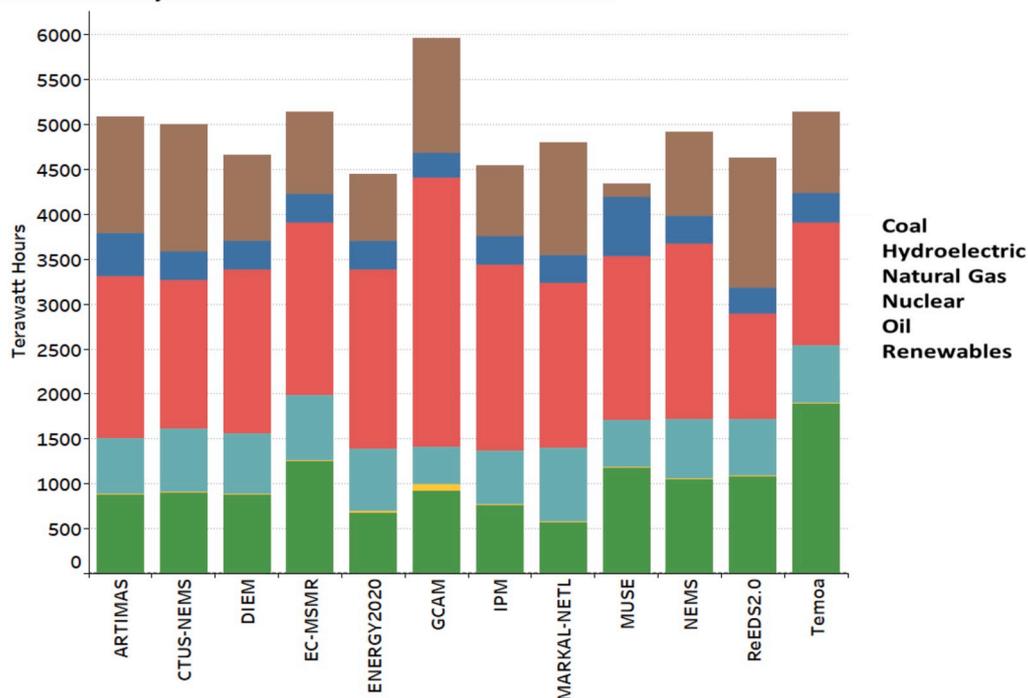USA Electricity Production in 2040- Reference Scenario

Fig. 23. USA 2040 Electric sources in reference case.

Difference in USA Electricity Production in 2040- Carbon All vs. Reference Scenario
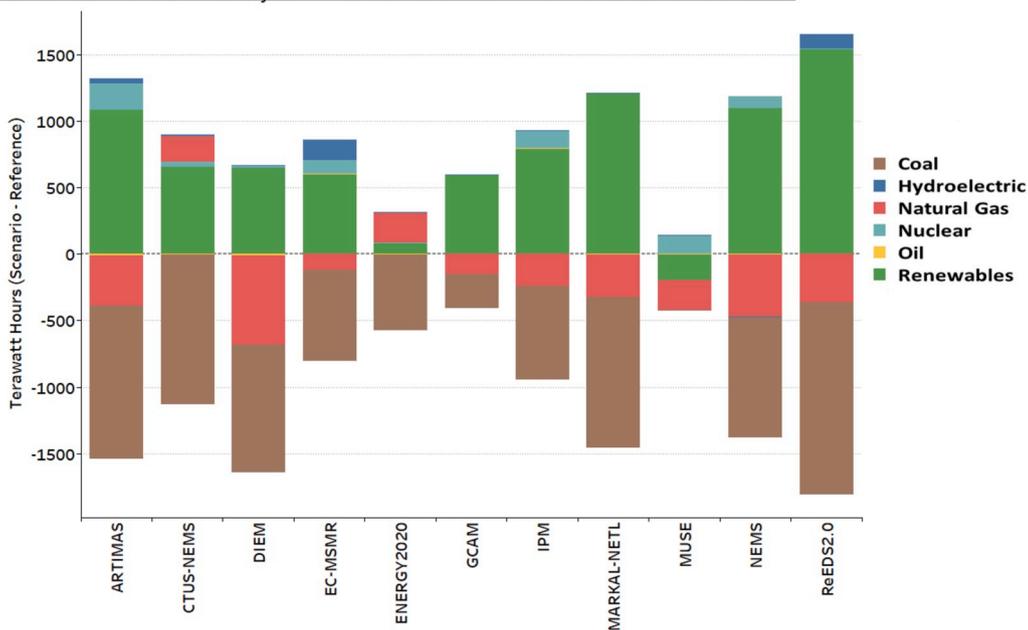
Fig. 24. Changes in USA 2040 electric sources in response to carbon tax.

reflect important differences in supply and demand conditions as well as in transportation opportunities.

2. Crude oil and natural gas production appear to be modestly responsive to energy prices across many if not all models. These results suggest that North America can play a more important role in world oil and gas markets if oil and gas prices increase over time from their current levels.

3. Electric generation by sources may vary widely depending upon the model or scenario. A common theme across frameworks, however, was that carbon taxes often favored renewables at the expense of coal

and some natural gas, that lower natural gas prices often replaced coal and some renewables with natural gas use, and that higher penetration of intermittent renewable sources displaced coal and some natural gas.

The working group identified several important directions for future collaboration and model improvement. Among these issues, the three most important ones include the following:

Difference in USA Electricity Production in 2040- Hi_Gas_Supply vs. Reference Scenario

Fig. 25. Changes in USA 2040 electric sources in response to high natural gas supply.

Difference in USA Electricity Production in 2040- Hi_Renewables vs. Reference Scenario
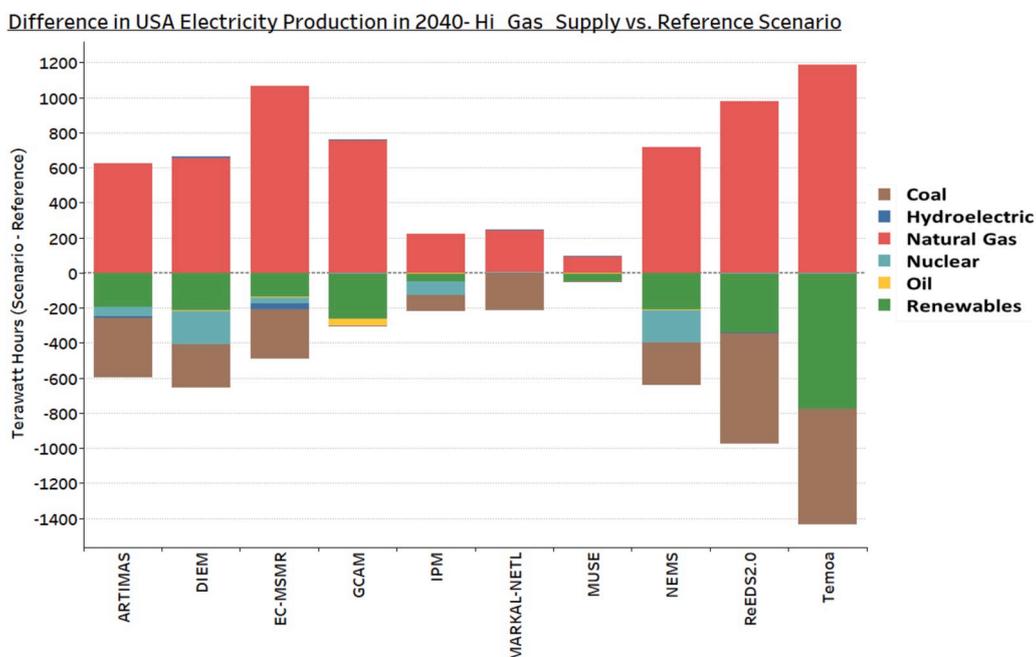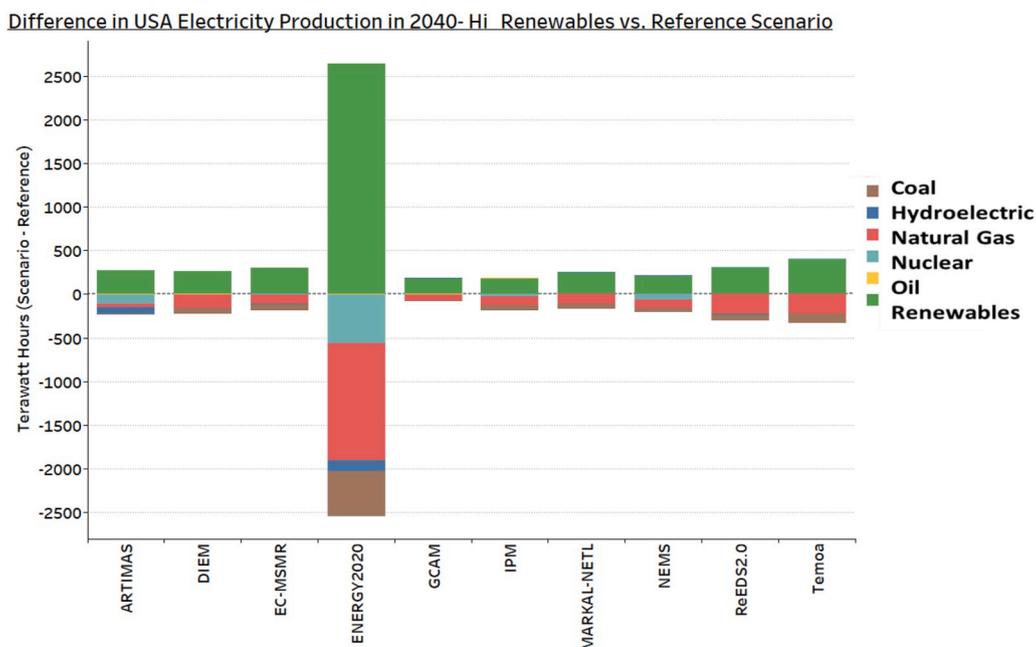

Fig. 26. Changes in USA 2040 electric sources in response to high renewable penetration.

1. Policy developers have a critical need for modeling frameworks that integrate energy analysis not only across major energy sources (oil, natural gas, coal and electric power) but also across the very different North American countries of Canada, Mexico and the United States. Integration will become increasingly important in future modeling efforts

2. Policy developers are increasingly asking important questions about implementing policies that require frameworks that emphasize key cross-border infrastructure and that answer basic regional issues within each country. These efforts must be entertained while improving the models in their treatment of the time of day and location of where energy is produced and consumed.

3. The quality of policy analysis will depend critically upon greater data collection, exchange, and transparency to facilitate cross-border analysis. The data quality and availability varied significantly across the three countries. Having greater access to better data could substantially improve policy decisions and facilitate model development and comparisons across the U.S., Mexico, and Canada.

The initial driver of the EMF34 study was to build upon the work done by the NACEI initiative on energy outlooks (National Energy Board et al., 2015). The NACEI work focused on individual country analysis under a single set of Reference assumptions, and identified better understanding the interrelationships between Canada, U.S., and Mexico under different conditions as a key next step. The EMF34 workshops and

model-comparison efforts achieve that aim by providing insights on many key dynamics within and between countries, under a variety of different scenarios and assumptions, using a variety of different models and methods. The work summarized here, and detailed in the studies collected in this volume, have highlighted that: a) different conditions will impact future energy trends meaningfully, and b) that different perspectives and approaches can produce a wide range of results, but some important insights and commonalities can be found within them.

Credit

All authors contributed equally to this article.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enpol.2020.111599.

Appendix A. Model Descriptions

ARTIMAS. An RTI Macroeconomic Analysis System (ARTIMAS) is a foresighted dynamic computable general equilibrium (CGE) model of the United States with nine different households by income and can be run at national or regional geographies (national for this study). The model represents 30 production sectors with detail focused on energy and pollution-intensive industries and it includes a technology-rich representation of the electricity sector based on RTI's Micro-level Environmental and Economic Detail of Electricity (MEEDE) database (Woollacott and Depro, 2016). The MEEDE database provides a unit-level characterization of environmental, engineering, and economic attributes of electricity generators and abatement equipment on the US grid. The electricity sector in ARTIMAS represents approximately 60 electricity generation and abatement model technology configurations based on the MEEDE data with dedicated capital stocks with putty-clay dynamics. ARTIMAS tracks emissions for oxides of nitrogen and sulfur, particulate matter, mercury and four types of greenhouse gases in the electricity sector and GHGs from fossil-fuel combustion in the rest of the economy.

CER. The Canada Energy Regulator's (CER) Energy Futures Modeling System is a multi-model framework used to develop the energy supply and demand projections found in the National Energy Board's (NEB) Canada's Energy Future series of outlooks. Natural gas production projections are primarily based on an NEB-developed deliverability model for the Western Canadian Sedimentary Basin that estimates future production based on various inputs including detailed historical well data, assumed prices and revenue reinvestment, drill day cost, well productivity, and LNG exports. Electricity generation and energy use projections are made using the ENERGY2020 model, developed by Systematic Solutions Inc. ENERGY2020 is a system dynamics model where detailed energy use by type, economic sector, and region in Canada interacts with an electric supply simulation for each region. Key inputs include energy prices, energy supply projections, technology costs, policy parameters, and macroeconomic projections which are provided by Stokes Economics.

CTUS-NEMS. For the EMF34 analysis, OnLocation created the "CTUS-NEMS" model,[15] which is based on the AEO 2017 version of the

National Energy Modeling System (NEMS) that is described below. This enhanced version of the model includes a representation of 45Q sequestration tax credits which were amended and expanded in 2018. These credits provide additional revenue for electric generators and industrial sources using carbon capture utilization and storage (CCUS) technologies that capture and permanently sequester CO_2 in geologic storage or use the captured CO_2 for enhanced oil recovery (EOR). The modeling framework in CTUS-NEMS allows the model to perform an integrated assessment of the economic attractiveness of CCUS and the 45Q tax credits for power and industrial facilities in conjunction with opportunities for CO_2 use for EOR and the costs of pipeline transport and storage.

DIEM. The Dynamic Integrated Economy/Energy/Emissions Model (DIEM) model includes a computable general equilibrium (CGE) component and an electricity component that gives a detailed representation of U.S. regional electricity markets. The electricity model (DIEM-Electricity) can be run as a stand-alone model or can be linked to the DIEM-CGE macroeconomic model to incorporate feedbacks among economy-wide energy policies and electricity generation decisions and interactions between electricity-sector policies and the rest of the U.S and global economies. Broadly, DIEM-Electricity is a dynamic linear-programming model of U.S. wholesale electricity markets that represents intermediate-to long-run decisions about generation, capacity planning, and dispatch of units. It provides results for generation, capacity, investment, and retirement by type of plant. It also determines wholesale electricity prices, production costs, fuel use, and CO2 emissions.

EC-MSMR. Environment and Climate Change Canada's multi-sector, multi-region (EC-MSMR) model is an international recursive-dynamic CGE model with 16 regions, 20 basic commodity-producing sectors, three final demand sectors and features bilateral trade of goods and services. The electricity sector is split into different generation types including renewables, transmission and distribution. Canada's crude oil sector features seven different crude oil supply technologies (conventional and bitumen) and bitumen upgrading/refining. EC-MSMR is calibrated to the 2011 input-output data from the Global Trade Analysis Project database Ver. 9 and then forward projected to align with country-specific energy, emissions and economic baselines coming from AEO 2019, EIA 2017 and ECCC 2018 E3MC projections. The formulation of EC-MSMR uniquely positions the model to highlight the interaction effects of a worldwide-integrated energy market and the implication of different energy policies in North America on bilateral trade flows of goods and services with the rest of the world. Ghosh et al. (2012) provide an algebraic documentation for a previous version of the EC-MSMR model. A more recent and thorough model description is contained in Zhu et al. (2018).

ENERGY 2020. ENERGY 2020 is an integrated energy-emissions model that simulates the energy markets of Canada, the U.S., and Mexico on an annual basis through 2050 and beyond (Systematic Solutions, Inc., 2017). The model is designed with a bottom-up, causal approach simulating the feedback effects between supply and demand for all types of fuels and the resulting effects on emissions. Multiple methodologies are incorporated to simulate the energy system, including principles of consumer choice theory to provide realistic simulation of consumer decisions, principles from system dynamics to track capital stock turnover, and optimization methodologies for dispatching electricity. With this approach, detailed policies are able to be simulated showing impacts of feedback effects across sectors and fuels and interaction effects of running multiples policies simultaneously. Projections include energy consumption, efficiency, investments, production, imports, exports, and fuel prices given a variety of assumptions regarding factors such as economic indicators, consumer preferences, characteristics of energy technologies, resource availability and costs, transmission constraints, and the regulatory environment. Projections also include energy and non-energy related emissions across eighteen greenhouse gas pollutants and criteria air contaminants. ENERGY 2020

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[15] OnLocation modified the NEMS model to support this study. All subsequent references to the model and its outputs will be referred to as CTUS-NEMS.

is able to be dynamically linked to a macroeconomic model to create a fully integrated energy-emissions-economy modeling system.

GCAM. The Global Change Assessment Model (GCAM) is a global model that represents the behavior of, and interactions between five systems: the energy system, water, agriculture and land use, the economy, and the climate (Joint Global Change Research Institute, n.d.). It is used in a wide range of different applications from the exploration of fundamental questions about the complex dynamics between human and Earth systems to the those associated with response strategies to address important environmental questions. GCAM is a community model stewarded by The Joint Global Change Research Institute (JGCRI). The overall structure of the energy system can be thought of as consisting of three main elements: energy resources, energy transformation, and final energy demands. It also tracks international trade in energy commodities. Consistent with the overall structure of GCAM, all the different elements of GCAM interact through market prices and physical flows of, for example, electricity. Technology choices are made based on prices using discrete choice methods.

IPM. Integrated Planning Model (IPM) integrates wholesale power, system reliability, environmental constraints, fuel choice, transmission, capacity expansion, and all key operational elements of generators on the electric power grid in a linear optimization framework. It provides a detailed representation of every electric boiler and generator in the power market being modeled. The fundamental logic behind the model determines the least-cost means of meeting electric generation energy and capacity requirements while complying with specified constraints, including air pollution regulations, transmission constraints, and plant-specific operational constraints. The version included in this study been used to support the U.S. Environmental Protection Agency's (EPA) analyses of utility air emissions.

MARKAL-NETL. The MARKet ALlocation (MARKAL) model is used with assumptions used by the National Energy Technology Laboratory (NETL). It is a bottom-up, dynamic, linear programming optimization model to find the cost-optimal pathway within the context of the entire energy system. MARKAL does not contain an in-built database, so in this study, the publicly available EPAUS9r2017 database (Lenox et al., 2013; Loughlin et al., 2011; Babaee and Loughlin, 2017) for the U.S. energy system had been adopted and modified. MARKAL-NETL represents the U.S. Census regions, Canada and Mexico to represent changes in North America energy sector in 2005–2055 with 5-year time periods. Each of the 11 regions was modeled as an independent energy system with different regional costs, resource availability, existing capacity, and end-use demands. Regions are connected through a trade network that allows transmission of electricity and transport of gas and fuels. Electricity transmission is constrained to reflect existing regional connections between North American Electric Reliability Corporation regions as closely as possible. Several caveats should be noted regarding the modeling assumptions and results. First, Mexico and Canada are reproduced as single regions without further disaggregation. Including multiple regions into Mexico and Canada sub-modules could affect modeling results. Second, crude oil and LNG demand and supply from Rest of the World (ROW) were represented through trade with a "dummy" region R0 and the resources in R0 are apportioned to the regions based on historical data via export and import technologies. Exploring the Mexico and Canada regional disaggregation and including supply and demand curves for ROW could be an avenue for future work.

MUSE. MUSE (ModUlar energy system Simulation Environment) represents a technology-rich, agent-based, recursive dynamic simulation of long-term energy system change. MUSE is hybrid and modular in the sense that each energy producing, transforming or consuming sector in the energy-economy is represented via an agent-based module that is designed to characterise the investment decision making process in that specific sector. As such, MUSE strives to represent investment decision making in a more realistic fashion than more normative models such as those based on intertemporal optimization. Within each agent-based sector module, detailed technology cost and performance data is utilised, and investor "agents" choose between these options to meet demands for energy commodities or energy services. MUSE represents a partial equilibrium on an entire national, regional or global energy system via iterative convergence on price and quantity of each energy commodity in each region in the model, achieved via a central market clearing algorithm (MCA). End-use sectors receive commodity prices from the MCA and use this to inform investment decisions, and then return resulting commodity demand levels to the MCA. These demands are passed through the MCA to the transformation and/or primary energy supply sectors, which then calculate new prices for meeting these demands. Iteration between sector modules continues until convergence is achieved. Representative applications include Kerdan et al. (2019) and Sachs et al. (2019).

MX-REGEN. MX-REGEN uses the Regional Economy, Greenhouse Gas, and Energy (REGEN) modeling framework to examine electric sector decisions in Mexico. The electric sector module of REGEN is an economic capacity planning and dispatch model that uses an innovative algorithm to capture the joint variation in load, wind, and solar output in a multidecadal model (Blanford et al., 2018). The model performs an intertemporal optimization of new generation investments, retrofits, and retirement decisions while simultaneously making linked decisions about system dispatch and co-optimized transmission investment and trade. Through scenario analysis, the model facilitates assessment of key technological, market, and policy uncertainties (Bistline and Young, 2019). Full REGEN documentation is provided in EPRI (2019).

NANGAM. The North American Natural Gas Model (NANGAM) was developed by Feijoo et al. (2016) and is a perfect foresight, game-theoretic model of the interconnected North American natural gas market that includes the US, Canada, and Mexico. The US is disaggregated into its nine Census regions, Mexico into five regions (Northwest, Northeast, Interior, Interior-West, South-Southwest), and Canada into two (East and West). There are 13 nodes with natural gas (shale and non-shale) production capacity and all nodes in the US and Canada have representative storage facilities across three seasons (low, high, and peak). The 17 regions are interconnected via 69 arcs that represent inter-regional pipeline infrastructure. Investment and marginal cost of pipeline expansion and operation are based on data of 778 existing and 187 new projects. Finally, demand in each region is represented by a linear inverse demand function. NANGAM distinguishes itself from other bottom-up natural gas models by allowing for endogenous expansion of both natural gas extraction and pipeline capacity. Moreover, it incorporates Nash-Cournot competition between profit maximizing producers, allowing for an imperfect market. The equilibrium finding problem is posed as a Mixed Complementarity Problem. NANGAM is based on Multimod (Huppmann and Egging, 2014), is developed in GAMS, and runs in 5-year time steps up to 2050. In other studies, NANGAM has a stochastic version of the model (Sankaranarayanan et al., 2018), and has been coupled with the integrated assessment model GCAM by Feijoo et al. (2018).

NATEM. The North American TIMES Energy Model (NATEM) is an optimization model that belongs to the TIMES family of models supported by the Energy Technology Systems Analysis Program (ETSAP) of the International Energy Agency (Loulou et al., 2016). TIMES is a modelling platform for local, national or global energy systems, which provides a technology-rich basis for estimating how energy system operations will evolve over a long-term horizon. It follows a techno-economic (bottom-up) approach to describe the energy sectors in many details through a variety of specific technologies characterized with their technical and economic parameters. As such, NATEM describes the integrated energy system of the 13 Canadian provinces and territories through 4500 technologies and 400 commodities while capturing all energy flows between jurisdictions. The model is driven by 70 end-use demands for energy services which are projected to the 2050 horizon. NATEM computes a partial equilibrium on energy markets and determines an optimal configuration of the energy systems to satisfy service demands at a minimum cost over a long-term horizon, while

respecting policy constraints such as renewable penetration targets or greenhouse gas (GHG) emission limits. The main outputs of the model include future technology investments with their annual activity levels, optimal energy trade movements, as well as marginal prices for each energy, material and demand commodity. An important assumption about the decision process of economic actors is the perfect foresight approach, where actors can anticipate future events while making optimal decisions today. The model has already been mainly applied to support climate mitigation policy making in Canada (Vaillancourt et al., 2017, 2018).

NEMS. The National Energy Modeling System (NEMS) is a detailed computer-based, energy-economic modeling system of U.S. energy markets (US Energy Information Administration, 2019). NEMS projects energy supply, demand, imports, conversion, and prices annually to the year 2050. Key input assumptions include macroeconomic and financial factors, world energy markets, resource availability and costs, behavioral and technological choice criteria, cost and performance characteristics of energy technologies, and demographics. The model was developed and is maintained by the U.S. Energy Information Administration for use in developing annual projections for the Annual Energy Outlook (AEO). NEMS explicitly represents domestic energy markets by the economic decision-making involved in the production, conversion, and consumption of energy products. Where possible, NEMS includes explicit representation of energy technologies and their characteristics. Because energy costs, availability, and energy-consuming characteristics vary widely across regions, considerable regional detail is included.

ReEDS 2.0. The Regional Energy Deployment System (ReEDS) model is a capacity expansion and dispatch model that simulates the electric power sector in the contiguous United States, Canada, and Mexico. It uses linear programming to solve the system-wide least cost optimization for 205 regions and 17 timeslices to estimate the type and location of future generation and transmission capacity. In this study, the model is recursive-dynamic in that it solves a linear program for each two-year period as it moves successively through the model horizon, reaching the final potential year of 2100. Capacity credit and curtailment valuations are computed between solve years using the expected contributions of variable resources during top load hours and statistical convolutions, respectively. The '2.0' designation is used to indicate that the model was redeveloped in 2017–2019 and is now available as an open-access GitHub repository, interested parties can request access at https://www.nrel.gov/analysis/reeds/.

Temoa. Tools for Energy Model Optimization and Analysis (Temoa) is an open source energy system optimization model. Energy systems modeled in Temoa are described algebraically as a network of linked technologies that convert a raw energy commodity (e.g., coal, oil, biomass, uranium) into an end-use demand (e.g., lighting, transport, water heating, conditioned air), often through a series of one or more intermediate commodities (e.g., electricity, gasoline, ethanol). Each technology is defined by a set of engineering, economic, and environmental characteristics (e.g., capital cost, conversion efficiency, emissions rate) associated with converting an energy commodity from one form to another. The model utilizes linear programming techniques to minimize the present cost of energy supply by deploying and utilizing energy technologies over time to meet a set of end-use demands. The initial model formulation is provided in a peer-reviewed publication (Hunter et al., 2013), with updated documentation publicly available on the web (DeCarolis et al., 2013). The model source code and data are open source, enabling third party verification of published model results (TemoaProject, 2020). In addition, Temoa includes the capability to perform various forms of uncertainty analysis in order to better characterise the future energy system decision space.

urbs-MX. urbs-MX is a nine-region model of the Mexican power system based on urbs, an open-source linear optimization modeling framework for capacity expansion and unit commitment analyses [Dorfner et al., 2019]. It minimizes the annual system costs that comprise all investment costs by their annualized depreciation as well as the operational and environmental costs. As a result, the least-cost portfolio of generators, storage and transmission that meets the exogenous electricity demand at every time step under capacity and environmental constraints is deterministically calculated. Furthermore, it allows the integration of multiple input/output commodities resulting in detailed representations of the energy conversion processes. urbs-MX considers 17 power generation technologies and two storage options. A high temporal resolution (8760 h per year) is used to ensure the chronological tracking of storage. Further details on the model are found in Molar-Cruz et al. (2018).

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