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Integrated North American energy markets under different futures of cross-border energy infrastructure

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ABSTRACT

We study how changes in cross-border energy infrastructure in North America will impact local and national markets. Electricity and natural gas are all transported across the borders of Canada, US, and Mexico. However, future changes in the energy production mix will lead to the further development of these infrastructures, as energy supply and demand cause stress across borders. We use a multimodel approach to investigate what happens to standard output metrics of local energy markets when these infrastructures are changed under different scenarios. These scenarios include increasing the capacity of electricity transmission by 20% and decreasing the cost of transporting natural gas by 20% vis-à-vis the modelers' reference case starting 2020. We find that electricity transmission across the Canadian-US border increases, with most of the increase in electricity production by natural gas. We also find that natural gas trade increases across the US-Mexico border, with a change in flows of natural gas within the US moving away from the northeast and northwest. While electricity production from renewable energy is expected to increase in the reference scenario, the changes in cross-border energy infrastructure do not significantly impact the generation from renewable energy. The scenarios help identify bottlenecks in the cross-border energy infrastructure, and propose future investment opportunities to decrease overall system costs for producing and consuming energy.

1. Introduction

Affordable, clean, and secure energy is essential for improving economic productivity, enhancing the quality of life, and protecting our environment. Furthermore, the energy landscape is changing. With the US the world's leading producer of oil and natural gas combined, policy discussions have shifted away from worries about rising oil imports and high gasoline prices to concerns about the reliability of energy infrastructure, the flexibility of the ideal energy production mix, and understanding what changes in future energy supply and demand will help meet the global climate change challenge (Department of Energy., 2015). In these discussions, energy infrastructure – including infrastructure for energy production, transmission, storage, and distribution – is challenged by transformations in energy supply, markets, and patterns of end use; issues of aging and capacity; and cross-border trade. In particular, the future development of cross-border energy infrastructure will play a large role in determining not only the development of regional infrastructure, but also how national supply and demand will be driven by cross-border trade.

Infrastructure-integrated fuel and power markets are expected to increase the flexibility and efficiency of North American energy systems. They will allow private industry to tap into new and more affordable resources to meet rapidly transforming energy requirements, while also reducing emissions. Economically, this process will create more

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competition and will change relative prices between and within each country and region. Given the political implications of cross-border infrastructure, success of these integrated markets will require considerable cooperation between Canada, Mexico and the US, including common market rules and cross-border pipelines and transmission lines to achieve these gains.

In most existing studies, long-term decisions about large energy infrastructures are often exogenous (externally fixed) to the scenarios for future energy supply and demand. The methodological goal of this paper is to make the development of such infrastructure endogenous to the scenario-development, and then test the system under different policies of cross-border restrictions. Optimally directing the evolution of cross-border infrastructure – such as pipelines, transmission lines, and railways – is key to understanding the future of an integrated North American energy market. However, infrastructure investment decisions are very different than infrastructure operation decisions; the former require longer-term information that accounts for future revenues and uncertainty. Many operational studies of energy infrastructure hold infrastructure investment decisions constant. We aim to flip this traditional analysis around in this study, and put the focus on cross-border energy infrastructure and its role in the resilience of the North American Energy System.

Cross-border trade of electricity in North America has unique characteristics of being constrained to an integrated wide-area transmission grid which is often two-way. A state may import and export electricity over the course of a year, a single day, or even at the same time if there are multiple transmission lines across a border. The US and Mexico are net importers of electricity and Canada is a net exporter. To date, there is very little academic focus on the role of Canada and Mexico on the North American electricity market. Unlike other commodities, electricity cannot be stored, so supply must meet demand immediately. Technologically, the main barrier to an increase in international trade in electricity has been the problem of long-distance power transmission. The increasing importance of electricity in North America and the emerging boom in transmission capacity investments raise several important questions such as:

- Is the existing energy infrastructure sufficient to satisfy the increasing demand for electric power?
- What are the plausible ranges of the magnitude of future investments into electricity infrastructure capacities, particularly for renewable energy?
- How are these investments regionally distributed?

In addition, international trade opens opportunities to reduce excessive reserve capacity. Is it possible that environmental improvements through emissions reduction can be achieved through electricity trade in North America, notably via better resource allocation and capacity sharing?

In contrast to electricity, the North American natural gas markets have gone through significant changes in the last decade. These changes were mainly driven by technological development and identification of new natural gas resources, which have resulted in evolved patterns for production, altering traditional energy independence of countries. Technological development helped to overcome obstacles related to infrastructure, particularly, in technologies and processes necessary to extract, process, store, transport and distribution to consumers. A clear example of the evolving gas market is the shale gas “boom”, which allowed economically feasible production of unconventional shale gas. In the US, natural gas surpassed coal to become the leading source of electricity generation in 2016, the most important sector consuming natural gas. In addition, US pipeline and liquefied natural gas (LNG) exports have increased significantly over the last five years and are expected to continue to increase through the mid-century. Furthermore, LNG is projected to dominate US natural gas exports, increasing total US liquefaction capacity by roughly ten times (Energy Information Adm, 2019) between 2016 and 2019. It is worth mentioning that in recent years, the US has become a top oil producer, Canada has increased substantially its oil output, and Mexico has implemented energy reforms. Extensive cross-border infrastructure is used to transport oil, refined petroleum products, and natural gas between the US, Canada and Mexico.

2. Literature review of cross-border energy infrastructure

Several studies on cross-border infrastructure have focused on the US and North American natural gas sector. The US Department of Energy (DOE) analyzed the US gas infrastructure under different demand scenarios from the power sector (US Department of Energy, 2015). Increased demand for natural gas in the power sector will lead to pipeline capacity additions. Feijoo et al. (2016a) and Sankaranarayanan et al. (2018) studied the effect of increased Mexican natural gas demand from the power sector. Results show higher US pipeline exports to Mexico, which are possible under a shift of flows within the US and pipeline capacity expansions in both the US and Mexico. It has also been shown that lack of US pipeline capacity has resulted in network congestion and increased transportation costs. The increased prices could be managed by increased storage or additional pipeline capacity (Oliver et al., 2014; Brown and Yücel, 2008; Oliver, 2015).

While these studies have studied changes in cross-border infrastructure under different levels of supply and demand, the contribution of our study is a multi-model approach to study national changes in supply and demand given restrictions on cross-border energy infrastructure.

Cross-border electricity infrastructure is substantial between the US and Canada, but it is limited between the US and Mexico: there are 30 major US–Canadian transmission connections, while the US–Mexican connections exist only between Mexico and California. The US and Mexico have traded electricity since 1905, but the trade is limited by few transmission lines cross the US-Mexico border and most of the cross-border interconnections are not used for regular trade but emergency purposes (Antweiler, 2016). The US and Canadian systems operate at synchronous frequencies, conversely, there are only a handful of cross-border interconnections with Mexico—and only the connections with California—are fully synchronized with the US grid (Ibanez and ZinMn, 2016). In 2016, the US signed an agreement with Canada and Mexico pledging to increase carbon-free sources of electricity, with a North American total goal of at least 50% of electric energy from wind, solar, and other carbon-free sources of electricity (Beiter et al., 2017).

Few studies have focused on the US and North American electricity infrastructure and trade, particularly between Canada and US. There exist theoretical models of two-way trade in electricity between the US and Canada, where electricity is in a homogenous good in the presence of convex costs and stochastic demand, and where exports and imports follow the load difference between the two jurisdictions (Energy Information Admini, 2013).

One NREL study developed a representation of the US and Canadian electricity sectors in a single planning module, through the NREL ReEDS model and analyzed the potential for Canada and the US to benefit through collaborative actions, such as shared GHG mitigation goals and transmission planning (Department of Energy, 2015f). Another NREL study focused on a set of ReEDS's model metrics to analyze the impact from restricted cross-border transmission capacity expansion under a carbon cap scenario and concluded that if new cross-border transmission is allowed between the US and Canada, electricity trade between the two countries increases over time under the reference and carbon cap scenarios (White House, 2016).

Steinberg et al. (2018) performed analysis for the Eastern Interconnection, which is one of three major AC electricity grids that extends from the western great plains to the eastern coast of the US and from south-central and eastern Canada to the Gulf Coast, and is comprised of an interconnected network of generators, transmission lines, buses, transformers, distribution systems, and electricity loads. The study applied a production cost model to estimate the maximum potential and cost of reducing power sector CO2 emissions through coal to NGCC re-dispatch in the Eastern Interconnection and used a set of scenarios to quantify the potential for re-dispatch and the associated cost under a range of natural gas price conditions (Steinberg et al., 2018).

Thus, the degree of grid integration has been a key determinant of historical electricity trade and prospects for future trade between the US and its neighbors. The changing of the generation mixes among the US, Canada, and Mexico has also been a factor affecting trade and may be an opportunity for trade growth.

However, the natural gas and electricity sectors are intertwined. In the case of the US, almost 35% of demand for natural gas comes from the electricity sector (EIA, 2017a). At the same time, power system stability issues (Ulbig et al., 2014) require the existence of fuel-fired plants at least for the short-term (Bruninx et al., 2016). In this case, natural gas is the most appealing option due to its low emissions rate with respect to coal and oil and the cheap resources available in North America (McDonald et al., 2016). By assuming that the two infrastructures will be operated jointly, Martinez-Mares and Fuerte-Esquivel (2012) studied what are the implications of co-optimizing the two systems, instead of studying the two systems separately (Martinez-Mares and Fuerte-Esquivel, 2012). Moreover, Correa-Posada and Sanchez-Martin (2014) expand the previous analysis by introducing security constraints in a co-optimization scheme. In addition, several studies have focused either on the impact of natural gas prices to the electricity sector (Munoz et al., 2003), the propagation of shocks via the network interconnections (Qiao et al., 2016), or revisiting the optimal power flow problem when the two systems are coupled (Unsihuay-Vila et al., 2007).

Co-optimization presupposes a hard link between regional markets that would lift political or other barriers that in turn would render economic incentives as the primary driver of infrastructure operation and expansion. It has been shown that regional integration of energy infrastructures results in more efficient allocation of regional resources (Ericson, 2009). In the case of North America, the integration of natural gas and electricity infrastructures of the US, Canada, and Mexico allows for Canada and the US to allocate their regional surplus of natural gas and electricity to neighboring regions (EIA, 2017b).

This paper studies the implications of trade policies for the natural gas and electricity infrastructures under integrated regional energy markets in North America. Moreover, this study combines and compares results from six different large-scale energy models. Finally, it provides insight regarding the benefits and losses that certain agents could incur, in a first attempt to inform policy-makers. Note that this study compares model results across different scenarios and does not involve model integration. We hope the results of this study inspire integration of models across different sectors.

3. Objectives and scenarios

Our objective is to understand the development of cross-border energy infrastructure under different future scenarios. We have a suite of models with different capabilities which will be running a number of scenarios to understand the development of cross-border energy infrastructure:

1) **Reference:** A Reference Scenario to provide a counterfactual basis for comparing the infrastructure scenarios to one without changes to the status quo of cross-border trade.
2) **Elect_Infrastructure:** This case increases the capacity of electricity transmission by 20% vis-à-vis the Modelers Reference Case starting 2020. We test the hypothesis that greater cross-border power capacity expands power trade and increases renewable and hydro generation.
3) **Gas_Infrastructure:** This case decreases the cost of transporting natural gas by 20% vis-à-vis the Modelers Reference Case starting 2020. We test the hypothesis that lower-cost cross-border natural gas capacity expands gas trade within North America.

As this work is part of the broader EMF 34 study, the scenario percentages were chosen by the working group in order to elicit noticeable responses in the models while remaining within the range of reasonable changes in infrastructure. The percentages were chosen to be consistent with the other scenarios in the EMF 34 working group, which were based on the Annual Energy Outlook. These levels are not intended to emulate specific economic outcomes but are selected to quantify the importance of cross-border infrastructure in a stylized but realistic setting. The results are sensitive to the 20% threshold but the direction of the results and core of the outcomes remains consistent.

For all three cases, models with exogenous builds increase their total available cross-border capacity by 20%. For models with endogenous builds, it was the modeler's choice on how to implement the 20%. For models with exogenous infrastructure expansion and a single country, such as DIEM and NATEM, this was accomplished by increasing cross-border capacity by 20%. For models with endogenous infrastructure expansion, such as ReEDS 2.0, MARKAL, and IPM, this scenario was implemented by increasing available capacity in 2020 by 20% compared to the Reference case, and letting the models expand more if needed endogenously.

4. Methods

Since our study is a multi-model comparison, our methods section will begin with a quick description of the models that ran the scenarios above. Table 1 shows the characteristics of the models, as well as if they had endogenous or exogenous builds.

The DIEM model (Ross, 2014) includes a macroeconomic, or computable general equilibrium (CGE), component and an electricity component that gives a detailed representation of US regional electricity markets. The electricity model (DIEM-Electricity) discussed in this paper 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 US 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.

The Integrated Planning Model (IPM) (EPA, 2019 https://www.ep, 2019) is a multi-regional, dynamic, deterministic linear programming model of the US electric power sector. It provides forecasts of least-cost capacity expansion, electricity dispatch, and emission control strategies for meeting energy demand and environmental, transmission, dispatch, and reliability constraints. IPM can be used to evaluate the cost and emissions impacts of proposed policies to limit emissions of sulfur dioxide (SO2), nitrogen oxides (NOx), carbon dioxide (CO2), hydrogen chloride (HCl), and mercury (Hg) from the electric power sector.

The North American Natural Gas Model (NANGAM) (Feijoo et al., 2016b) is a long-term partial-equilibrium model of the US, Mexican, and Canadian gas markets. NANGAM considers a total of 17 nodes, of which nine correspond to US census regions 1–9, one node to Alaska, two nodes to Canada (East and West), and five to Mexico (Northwest, Northeast, Interior-West, Interior, and South-Southeast). Of the above-mentioned nodes, there are 13 nodes with natural gas production capacity (census regions 2–9 for the lower-48 states, one for Alaska, two for Canada, and two for Mexico). The 17 production-demand nodes are currently connected through 69 pipelines. NANGAM also considers storage operator in the US and Canada. The model allows for endogenous infrastructure development and expansion, and is built in five-year time-steps up to 2050, considering three seasons (low, high, and peak)

Table 1
Overview of characteristics for participating models. Refer to model documentation of individual models for more detailed information.

Model Name	Abbr.	Scenarios	Endogenous Infrastructure Expansion?	Countries	Supporting Organization(s)
Dynamic Integrated Economy/Energy/ Emissions Model	DIEM	Elect_Infrastructure,	No	US	Duke University
Integrated Planning Model	IPM	Elect_Infrastructure	Yes	US, Canada	EPA
North American Natural Gas Model	NANGAM	Gas_Infrastructure	Yes	US, Canada, Mexico	Johns Hopkins University
MARKet ALlocation Framework	MARKAL	Elect_Infrastructure	Yes	US, Canada, Mexico	National Energy Technology Laboratory
North American TIMES Energy Model	NATEM	Elect_Infrastructure	No	Canada	ESMIA Consultants Inc.
Regional Energy Deployment System	ReEDS 2.0	Elect_Infrastructure	Yes	US, Canada, Mexico	National Renewable Energy Laboratory

for each time-step.

The North American TIMES Energy Model (NATEM) is an optimization model that belongs to the MARKAL/TIMES family of models. TIMES is a modeling platform for local, national or multi-regional energy systems, which provides a technology-rich basis for estimating how energy system operations will evolve over the long term, multiple period time horizon (Loulou et al., 2016). TIMES offers thus a detailed representation of energy sectors, which includes extraction, transformation, distribution, end uses, and trade of various energy forms and materials. It follows a techno-economic approach to describe the energy sectors in many details through a variety of specific technologies characterized with their technical and economic parameters. TIMES determines an optimal configuration of the energy systems to satisfy service demands at a minimum cost over a long-term horizon, while respecting greenhouse gas (GHG) emission limits. As such, NATEM-Canada describes the entire integrated energy system of the 13 Canadian provinces and territories while capturing all inter-jurisdictional flows of energy commodities and materials. The model is driven by 70 end-use demands for energy services in five end-use sectors (agriculture, commercial, residential, industrial, transport) which are specified exogenously over the 2050 horizon. The optimization is done once over the whole time horizon through 10 variable length time periods and 16 annual time slice (four seasons and four intraday periods).

The version of the NATEM model used in this paper includes Canada only; it was used to model the reference and the electricity infrastructure scenario. Inter-jurisdictional interconnections are modeled though specific technologies characterized with their technical and economic attributes. All energy trade movements including electricity between Canadian jurisdictions are modeled endogenously, i.e., the model computes the energy prices and determines the optimal flows up to the current infrastructure capacities. It can also invest in new capacities. Although international interconnections are also modeled through specific technologies, the electricity trade movements are modeled exogenously with fixed infrastructure capacities (a combination of existing interconnections plus some projects). The electricity infrastructure scenario was implemented by exogenously increasing each provincial interconnection capacity by 20% from 2020 compared with the reference scenario. The most important trading capacity is between Quebec and New England.

The MARKet ALlocation (MARKAL) is an integrated energy system modeling platform that can be used to analyze energy, economic, and environmental issues at the global, national, and municipal level over a timeframe of up to several decades. MARKAL is a bottom-up, dynamic, linear programming optimization model to find the cost-optimal decarbonization pathway within the context of the entire energy system. MARKAL represents energy imports and exports, domestic production of fuels, fuel processing, infrastructures, secondary energy carriers, end-use technologies and energy service demands of the entire economy. MARKAL does not contain an in-built database, so the user is obliged to enter input parameters. In this study, the publicly available EPAUS9r2017 database for the US energy system had been adopted and modified. EPAUS9r2017 with the US Census regions representation was created by EPA in 2017 to model changes in US energy sector through 2055. We extended EPAUS9r2017 and included Canadian and Mexican energy systems as two new regions. Each of eleven regions (Canada, Mexico and nine the US Census 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 (NERC) regions as closely as possible.

The NETL MARKAL's database divides the US into nine regions based on the US Census Divisions, Canada and Mexico. Each region is 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. Electricity transmission is constrained to reflect existing regional connections between North American Electric Reliability Corporation (NERC) regions as closely as possible. Electricity trade in MARKAL represent the transfer capability of the transmission network to transfer electricity from one area to another for a single demand and generation pattern. Trade in electricity is broken into domestic inter-regional trade, and international trade between Canada, Mexico, and the US. As MARKAL simulates the growth in the energy market on a regional basis, the model assumes the placement of the new generating capacities within each region with the interconnection of these capacities to the existing transmission grid. New transmission grid could be built for electricity trade between all regions, including Mexico and the US Existing transmission lines are represented through residual installed capacity. Elect_Infrastructure scenario was implemented through increasing residual installed capacity by 20% in 2020–2050.

ReEDS 2.0 (Brown et al., 2020) is a best-in-class electricity capacity expansion model maintained by the National Renewable Energy Laboratory (NREL). NREL designed the Regional Energy Deployment System (ReEDS) to simulate electricity sector investment decisions based on system constraints and demands for energy and ancillary services. It has detailed representation of Canada, Mexico, and the US with 205 Balancing Areas and 454 Resource Supply Regions. It was re-developed in 2018 to include a myopic, sliding window, or intertemporal outlook; residential device adoption; and flexibility in regionalization, plant detail, and temporal dimensions. Although it covers a broad geographic and technological scope, ReEDS 2.0 is designed to reflect the regional attributes of energy production and consumption. The model considers a large suite of generating technologies, including fossil, nuclear, and renewable technologies, as well as transmission and storage expansion options. The ReEDS 2.0 model is built using GAMS (General Algebraic Modeling System) version 24.7, Python version 3.7, and R version 3.4.4.

5. Results

5.1. Baseline scenarios

Electricity production is generally a function of several factors, including end-use demand, energy and environmental regulations, the efficiencies of the generation, transmission and distribution systems, international trade and the technologies used to generate electricity. The electricity generation profiles of Mexico, the US, and Canada are different from one another not only in terms of overall size, but also their generation portfolios. Mexico has the smallest electricity sector, with 75 GW of available generating capacity in 2017, 70.5% corresponds to power plants conventional electricity and 29.5% to power plants electrical with clean technologies (https://www.gob.mx/cms/up, 1770a). Canada has an installed base of approximately 145 GW (https://www150.statcan.gc, 2510). The US electricity sector is massive by comparison, with total generation capacity around 1100 GW—over five times the capacity of the other two countries combined (Figs. 1–3).

For many years, the growth in electricity consumption in the US could be directly related to growth in the US economy. However, with the energy efficiency improvement, a decoupling of growth in electricity demand from GDP has occurred. The recent trend of flat to no growth in electricity demand could be changing, as new technologies could couple with new regulations to increase electricity demand. Electricity consumption in Canada is projected to grow steadily through 2050 in the Reference scenario, though the production mix is also expected to increase in diversity according to modeling results. Since 2010, annual electricity demand in Mexico has grown at about 3% per year, driven primarily by increased demand from residential and industrial sector (https://www.gob.mx/cms/up, 1770b).

In Mexico electricity prices are heavily subsidized, so electricity demand in the future and capacity additions are uncertain. The evolution over time of Mexican electricity production is quite different according to MARKAL and ReEDS2.0, see Fig. 2. In the former model, production increases by only 28%, to reach by 2050 a level of 411.40 TWh. Whereas in the latter model, production increases by 163% (to 746.83 TWh). The same discrepancies are reported in Fig. 2 for electricity consumption in Mexico: MARKAL projects a 30% increase overtime (to 381 TWh), and ReEDS2.0 a 161% increase (to 709.94 TWh).

Electricity demand in MARKAL increases at 1% annually as electricity prices in Mexico might be less subsidized. However, future electricity demand growth in Mexico is about 3% annually according to ReEDS 2.0 modeling results. Furthermore, the Mexican electricity pricing environment is changing as a result of regulatory restructuring. Thus, Mexico's pricing structure, coupled with the ongoing regulatory transition in the generation market, creates uncertainty regarding electricity sector projections for Mexico.

Fig. 3 displays Canada electricity production in the reference case. All models envision a growth for electricity production between 2015 and 2050, albeit at a different rate. At the two extremes, the IPM model computes a 5% growth, reaching a level of 682.85 TWh by 2050, and the MARKAL model a 33% growth, reaching a level of 871.14 TWh. The other two models follow a trend closer to the highest growth with ReEDS2.0 suggesting a 20% growth and NATEM a 30% growth. Similarly, all models suggest similar trends but with different growth rates for electricity consumption between 2015 and 2050 (Fig. 3): 5% (IPM), 32% (ReEDS2.0), 34% (NATEM) and up to 41% in MARKAL. One can however notice that at mid-horizon (2030–2035), results diverge by at most 7% between the different models.

Fig. 4 shows the production mix in the reference scenario for the US and Canada. In general, the production mix sees a decrease in production from coal, and an increase in production from renewables over the time horizon. The degree of this change is different by country depending on the model assumptions.

NANGAM's calibration follows closely the "2017 Annual Energy Outlook" of the Energy Information Administration (EIA, 2017c) for the US, "Canada's Energy Future 2017" of the National Energy Board of Canada for Canada (NEB, 2017), and the "Natural Gas Outlook 2016–2030" of SENER for Mexico (SENER, 2017) up to 2050 (Figs. 5–7). MARKAL on the other hand proposes quite a different reference projection for natural gas in Mexico than the other model considered for this study (NANGAM), see Figs. 5 and 6. Between 2015 and 2050, gas production is computed to decrease by 20% according to MARKAL, with a drop of 49% by 2035 followed by a partial recovery (to 3.96 bcf). By contrast, NAGAM projects a 15% in gas production between 2015 and 2050, to a level of 4.99 bcf. For gas consumption, MARKAL projects a 30% decrease over time (to 5.60 bcf by 2050), whereas NAGAM projects a 20% increase (to 8.77 bcf).

Results for Canada diverge more significantly between models regarding natural gas production, (Fig. 7). Not accounting for the discrepancy in 2015, both NANGAM and MARKAL do not show a growth in gas production between 2020 and 2050. Conversely, in NATEM, gas production increases by 46% between 2015 and 2050, to reach a level of 22.92 bcf by 2050. These projections follow the assumptions developed by the Canadian National Energy Board in their reference scenario (NEB National Energy Boa, 2017). As such, NATEM includes optimistic assumptions regarding demand markets for natural gas; the model assumes that the excess of natural gas production over domestic demand and continental exports to the US will be sold on international markets (in the form of liquefied natural gas). Fig. 7 shows the evolution of natural gas consumption in the reference case in Canada with 2015–2050 growths of 54% (NANGAM), 59% (MARKAL), and 85%

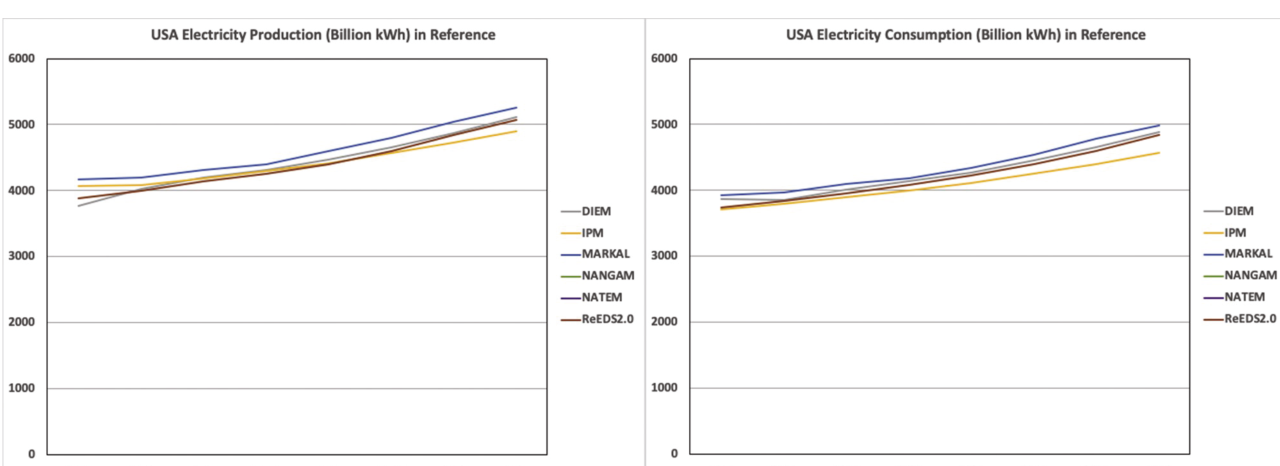

Fig. 1. Electricity production and consumption in the US.

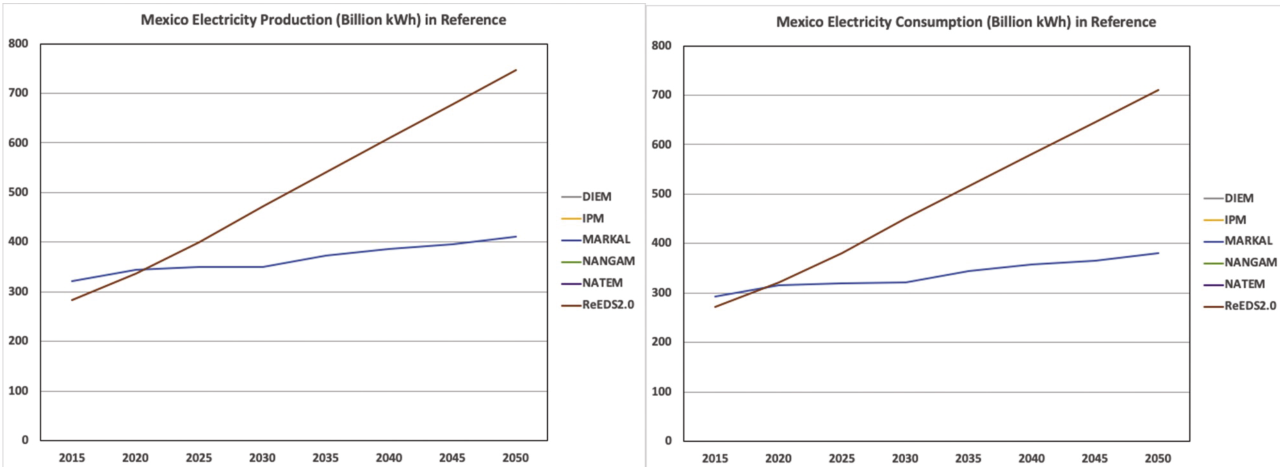

Fig. 2. Electricity production and consumption in Mexico.

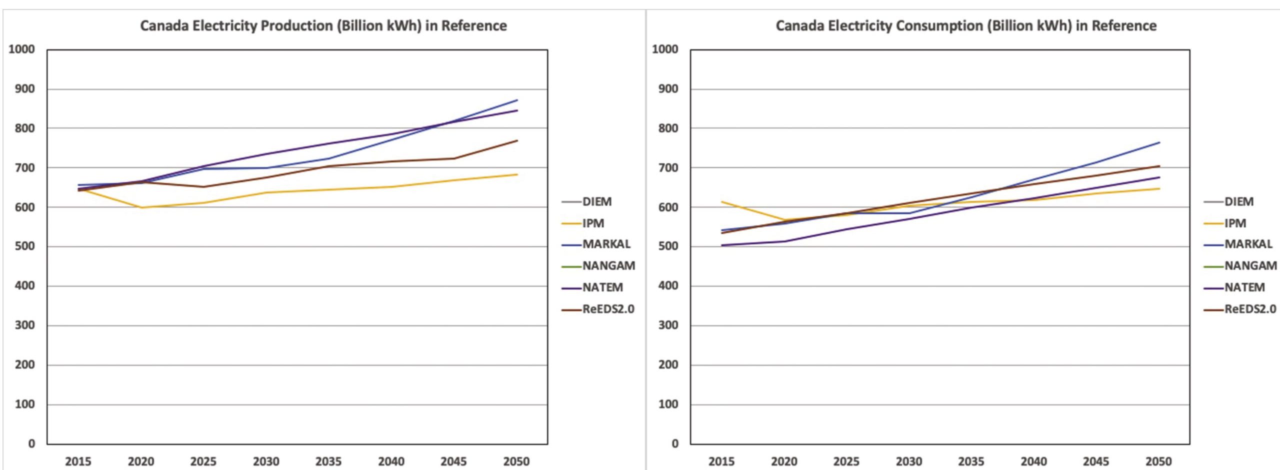

Fig. 3. Electricity production and consumption in Canada.

(NATEM). Values reported by NAMGAM and NATEM differs by less than 10% from 2030 on.

5.2. Policy scenarios

In this section, we focus on the key findings of the study in the two scenarios. In particular, we focus on the electricity production mix as well as transmission across the US-Canada border and natural gas infrastructure across the US-Mexico border.

Fig. 8 compares, for different models, the 2050 electricity production mix between the reference scenario and the electricity infrastructure scenario. In the latter case, the increase by 20% of electric transmission capacity between Canada and the US has almost no effect (relative to the reference) according to IPM and ReEDS2.0. In MARKAL, production increases by about 1%, covered by gas-fired power plants. The production increase is more significant in NATEM (about 8%), again covered by natural gas with a 2050 market share that goes from 25% in the baseline to 31% in the electricity infrastructure scenario.

The model structures and the sets of assumptions used by each modeling team in all their scenarios including the reference case have more impact on the evolution of the electricity generation mix, *i.e.*, the proportion of natural gas versus intermittent renewable in particular. Among the most sensitive assumptions that may differ between models include the existing policies included in the reference case (*e.g.*, the federal carbon tax and the clean fuel standard that are under discussion), the cost evolution of intermittent renewables and storage options, intermittent resource distribution, hourly load curves of electricity demands, and discount rates. The impact on domestic electricity consumption is very minor with less than 1% difference between the two scenarios for all the models and on the whole horizon. The additional electricity production, although minor in most cases, is exported to the US.

Compared to the other models, the increase of transmission capacities between the US and Canada is evaluated by NATEM to be quite large, up to 80% more exports and up to 100% more net exports (Fig. 9), by 2050, compared to the baseline. By contrast, the other models show an impact of at most 20% more (net) exports. These discrepancies arise from the fact that NATEM does not optimize the US energy (or electricity) system. NATEM rather assumes that the US acts as a price taker, importing (up to the exogenous limits) Canadian electricity based on its selling price. Note that in the Elect_Infrastructure scenario, models that allow an endogenous change in infrastructure do not change much from the base case, since they were expanding infrastructure anyways when profitable. NATEM, on the other hand, has a large change in electricity trade given the expansion. This shows the potential for electricity transmission infrastructure across the US-Canada border.

For Mexico under the MARKAL and ReEDS2.0 models, the increase by 20% of electric transmission capacity between Mexico and the US has virtually no effect (less than 0.1%). The same is true for domestic electricity consumption, with differences less than 0.05% between the two

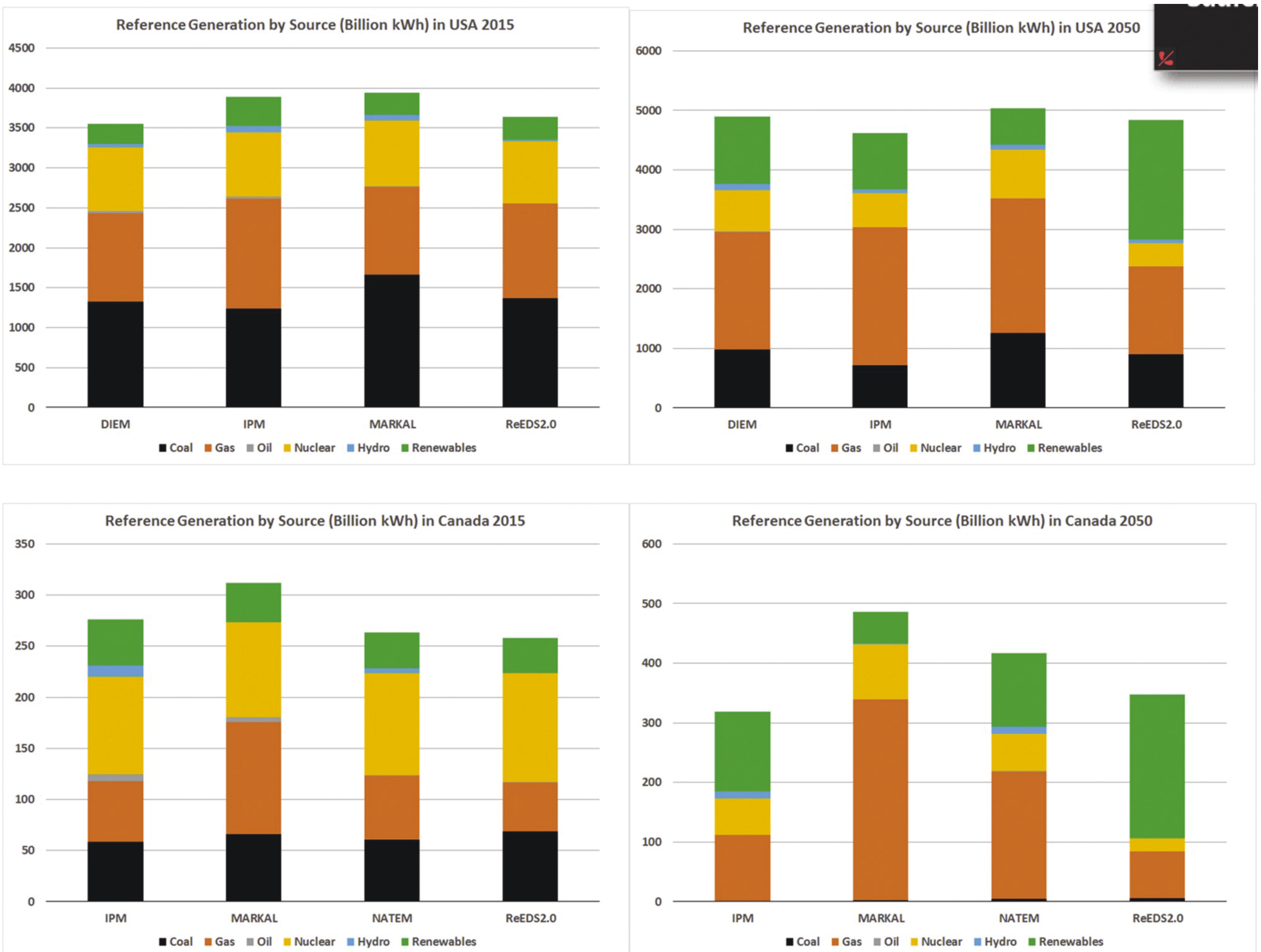

Fig. 4. Electricity Production Mix (in Billions of kWh) in the US and Canada.

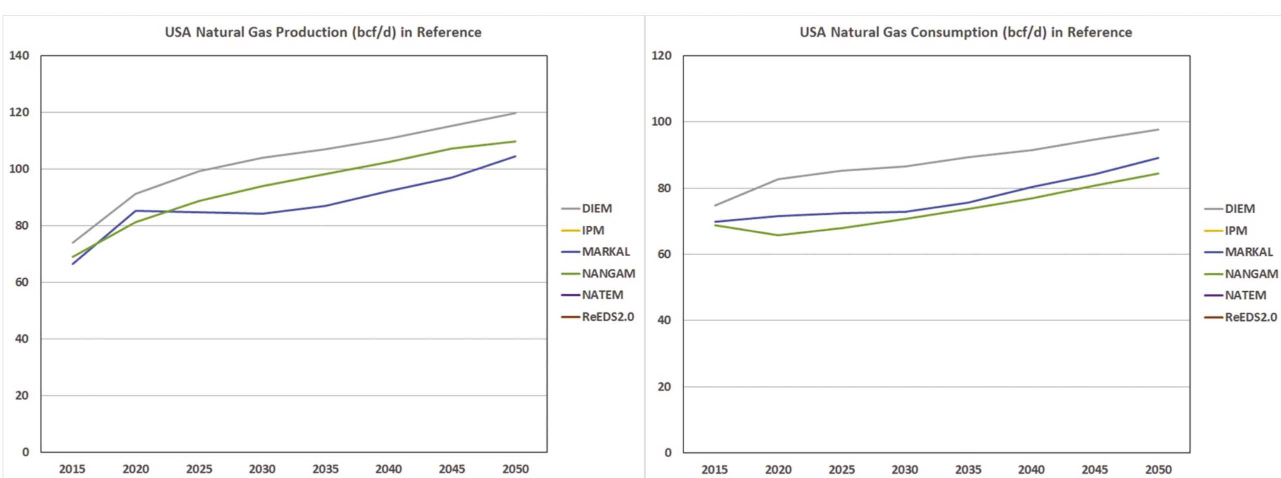

Fig. 5. Natural gas production and consumption in the US.

scenarios for both models. For the US, there is little change as well, as shown by Fig. 10.

Under the Natural Gas Infrastructure Scenario, US natural gas production is only marginally affected. The same is also true for US consumption. However, trade between the US and Mexico progressively increases up to 16.5% by 2050. The changes in natural gas pipeline infrastructure and intra-country trade explain the three results shown in Fig. 11.

In 2030, trade between Texas and North-West Mexico increases by 5.59% whereas trade between Texas and North-East Mexico increases by 1.92%. For this to happen, the supply to the South Atlantic via East-South Central from Texas decreases accordingly. A similar substitution is viewed also in the case of the Pacific region. The reduction of the US-Canada cross-border cost results in a 27.17% increase in US imports

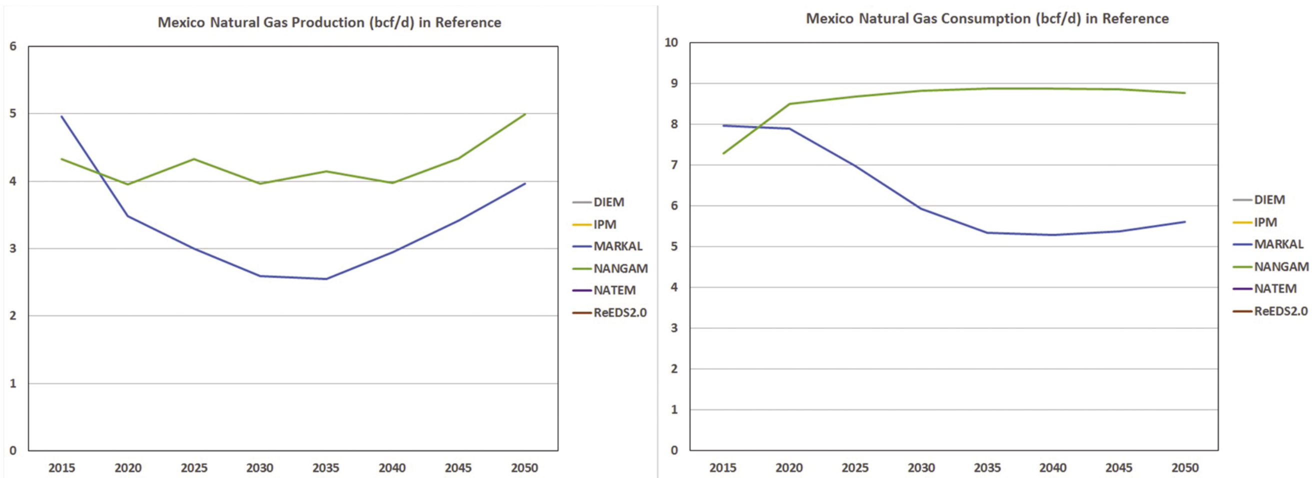

Fig. 6. Natural gas production and consumption in Mexico.

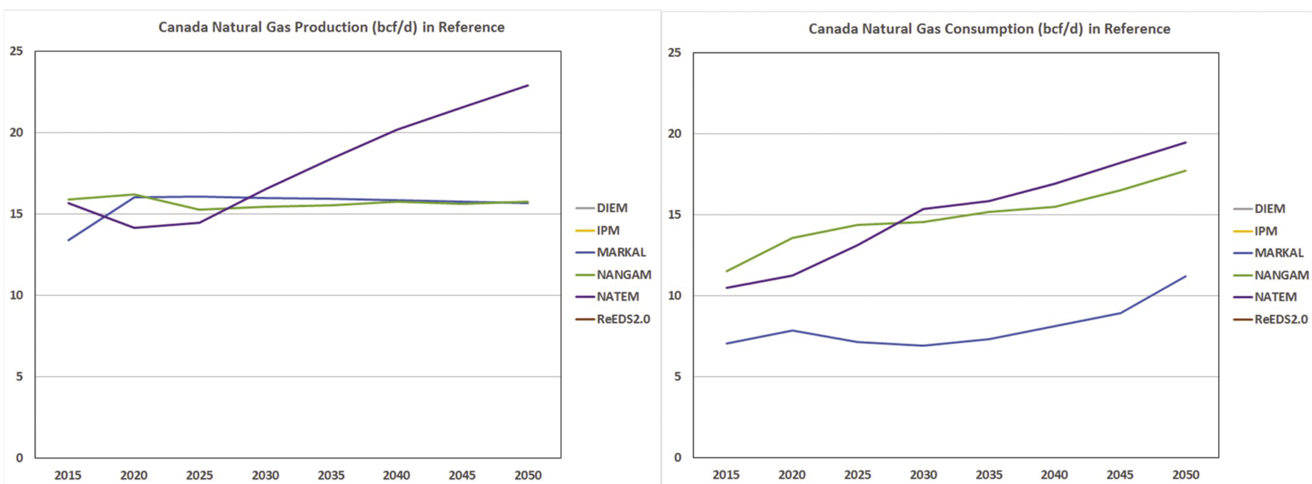

Fig. 7. Natural gas production and consumption in Canada.

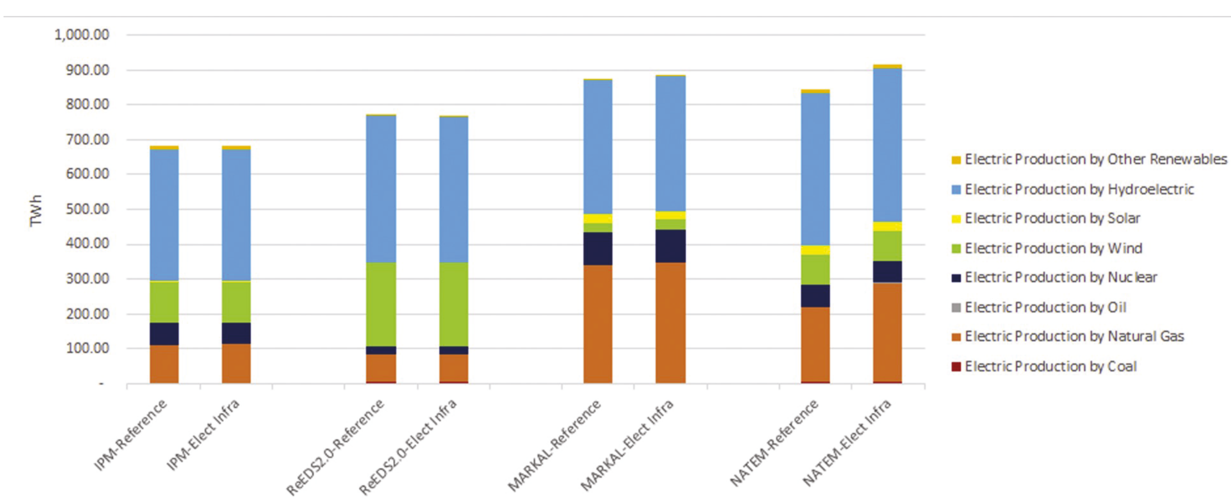

Fig. 8. Electricity production mix for Canada in 2050.

from Canada and a subsequent reduction of inflow of natural gas from the major supplier to the Pacific, the Mountains region. The latter flow is reduced by 4.31%. Given that net exports of Canada to the US are projected to decrease (See Annual Energy Outlook, 2019), the policy provides a boost to the sustainability of Canada-US projects.

The aforementioned trade patterns are even more prevalent in 2030

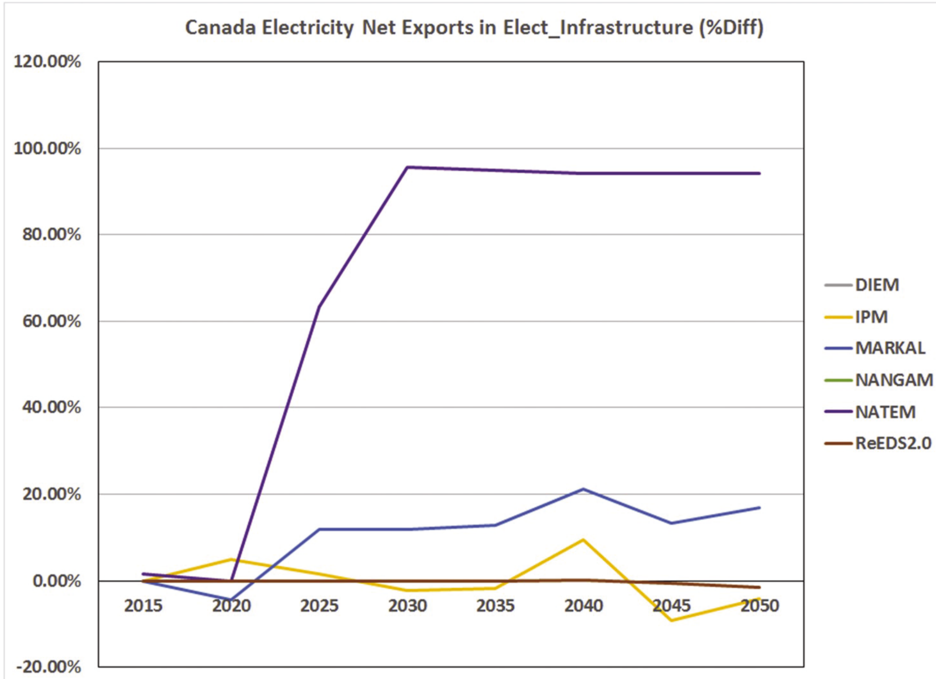

Fig. 9. Percentage difference in net exports for Canada in the electricity infrastructure case compared to the reference case.

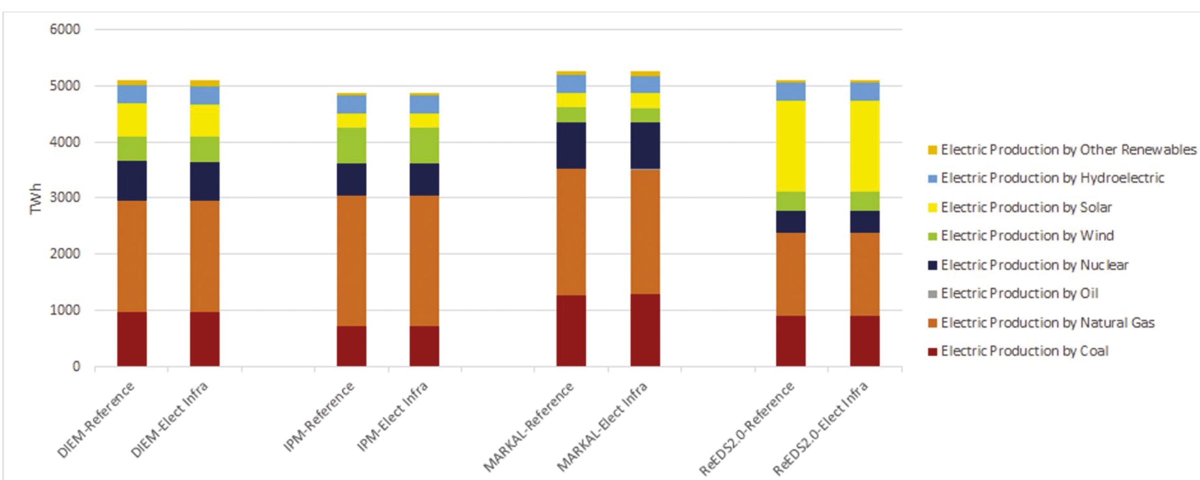

Fig. 10. Electricity production mix for the US in 2050.

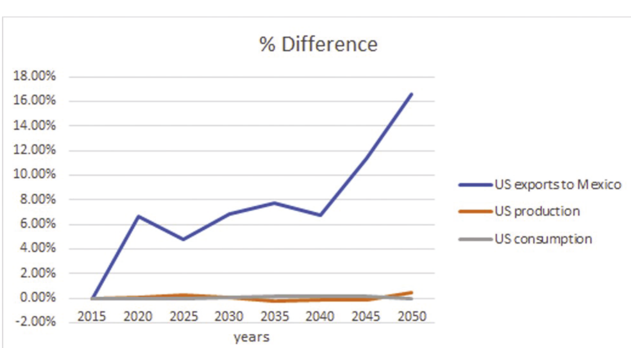

Fig. 11. Percentage difference in the natural gas infrastructure case compared to the reference case.

and are depicted in Fig. 12. Exports from Texas to North-West Mexico increase by 10.95% whereas exports to North-East Mexico increase by 36.01%. At the same time, flows from Texas to South Atlantic via East-South Central are eliminated. Finally, we observe a similar type of substitution in this year as well between production from the Mountains region and Canada. The mountain region's supply to West-North Central decreases by 11.64% due to a 30.48% increase in flows from Canada.

6. Conclusion and policy implications

In this study, we tested what would happen to North American energy markets under different cross-border infrastructure scenarios. Using a multi-model study, which included diverse models with differing structures and projections, we ran scenarios that changed the endogenous structure of capacity of electricity transmission across borders, and the cost of transporting natural gas across borders. This is in line with the idea of liberalizing trade across the countries, and the large

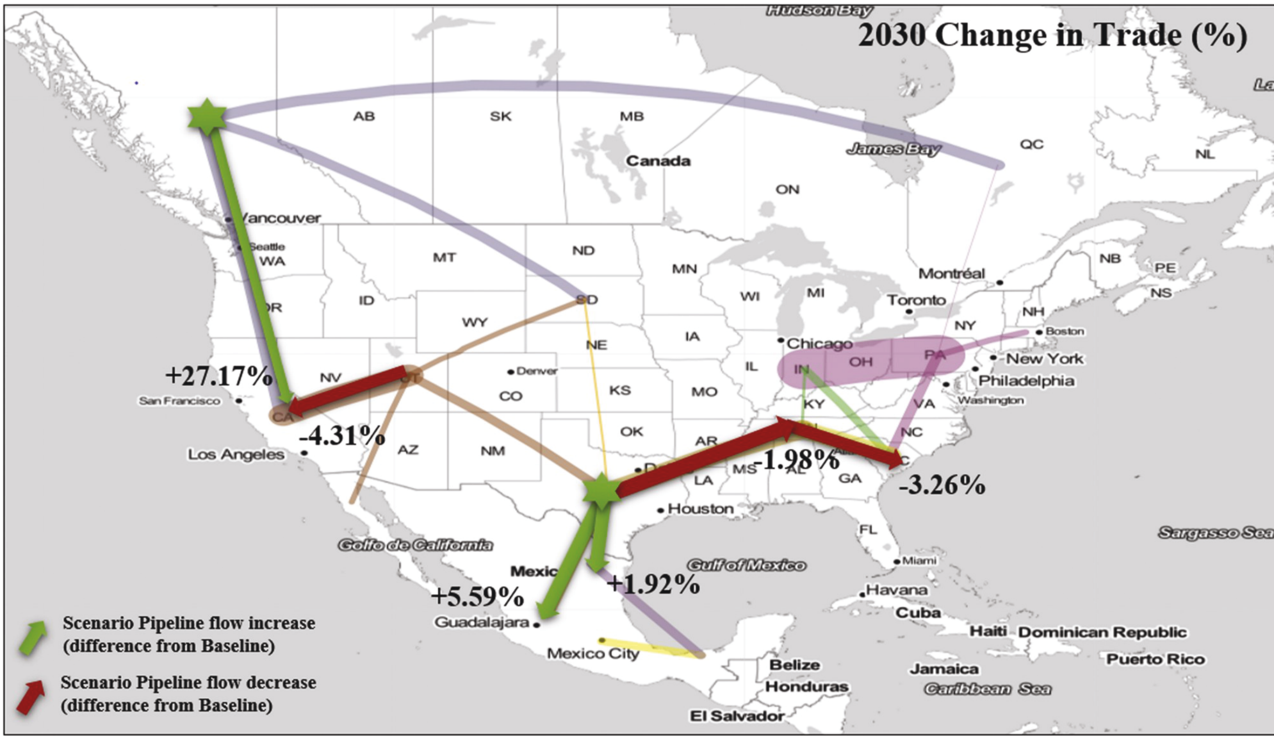

Fig. 12. Percentage change in natural gas pipeline transport the natural gas infrastructure case compared to the reference case.

amount of natural gas infrastructure being built across the US-Mexico border.

We show that for the scenario where we expanded cross-border electricity infrastructure, trade across borders increased, but Canadian net exports to the US showed the most consistent increase. This is in line with our hypothesis for this scenario, where expanding capacity leads to more trade, particularly across the Canadian and US borders where there is potential to satisfy increasing demand. All models showed a slight increase in the production of electricity, but models that were more robust and detailed on Canadian electricity supply (*e.g.*, NATEM) showed the highest increase in the production of electricity by natural gas. On the other hand, there wasn't that much expansion in the production of renewables and hydroelectricity, indicating that its potential might not be as valuable when looking at increased cross-border trade. These results drive home the fact that any policy on renewable energy needs to be coupled with trade across the borders in North America, particularly the Canadian-US border, where there is potential for natural gas to take over if there aren't enough renewable sources.

In the scenario for expanding natural gas infrastructure, we see an increase of trade from the US to Mexico, increasing the already rising trade between the two countries. The key finding is how regional US trade changes between the states, but doesn't impact production by much. Certain parts of North America thus have sufficient infrastructure to make up for the increased imports by Mexico, and regional production is not stressed by much. Adding to the consistency of the results, Canadian natural gas exports into northwest US also increase, as the US finds it profitable to export additional gas to Mexico. We conclude that decreasing the cost of cross-border trade promotes bilateral trade within North America without significantly disrupting regional production. Moreover, at the new equilibrium, inter-country pipelines connections are favored at the expense of intra-US pipelines which are underutilized. We are able to isolate the connections that are negatively affected due to the network effect. The last observation implies that tension can potentially arise between policy-makers and certain stakeholders that would be negatively affected. Finally, the identification of the stakeholders that benefit the most can inform legislation that would allocate the burden, if needed.

While our study has individual models that could handle regional energy markets and policies, the multi-model comparison does not lend itself to account for local policies, such as California's Energy Imbalance Market. While such regional issues are not expected to impact cross-border trade, future work could include a multi-scale analysis of the interplay of regional and federal policies. Further, since our study does not involve any model integration, the results across the different models are independent of their individual results. While this lack of integration would not change results within the same energy sector, it could lead to perturbations across energy sectors. For example, the results of NANGAM only involve the natural gas sector and aren't coupled with the electricity sector models. Coupled models across different sectors could result in different magnitudes of infrastructure investment across the border. But since our study includes some models with multiple sectors such as MARKAL and NATEM, we are confident that the qualitative nature of the results will not change.

This study shows the benefit of using a multi-model comparison when looking at the impact of cross-border infrastructure on trade and markets in North America. Since different models have different assumptions about how future markets will behave, the study allows us to isolate key findings that are consistent across models and also pick out which characteristics can be beneficial for future findings. In this paper, it is particularly important to focus on what happens to trade under different policies that could be developed to increase the production of electricity from renewables, and/or reduce carbon emissions across North America. In particular, the paper shows that policy interventions in Electricity cross-border infrastructure between the US and Canada as well as Natural Gas cross-border infrastructure between the US and Mexico will be beneficial for future integration of markets. Thus, policy design can start with focusing on these aspects of infrastructure. Our study showed consistent results for the benefits of such policy. This study provides a first step to answering pertinent questions on the implications of cross-border infrastructure and can be coupled with other papers in the EMF 34 study in order to help develop energy and economic policy for the future.

CRediT authorship contribution statement

Sauleh Siddiqui: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing - original draft, Writing - review & editing. **Kathleen Vaillancourt:** Conceptualization, Formal analysis, Investigation, Methodology, Resources, Software, Validation, Visualization, Writing - original draft. **Olivier Bahn:** Conceptualization, Formal analysis, Investigation, Methodology, Resources, Software, Validation, Visualization, Writing - original draft. **Nadejda Victor:** Conceptualization, Formal analysis, Investigation, Methodology, Resources, Software, Validation, Visualization, Writing - original draft. **Christopher Nichols:** Conceptualization, Formal analysis, Investigation, Methodology, Resources, Software, Validation, Visualization, Writing - original draft. **Charalampos Avraam:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Software, Validation, Visualization, Writing - original draft. **Maxwell Brown:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Resources, Software, Validation, Visualization, Writing - original draft.

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