Energy Policy 147 (2020) 111757

Contents lists available at ScienceDirect

Energy Policy

journal homepage: http://www.elsevier.com/locate/enpol

Natural gas infrastructure development in North America under integrated markets

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ARTICLE INFO

Keywords:
Natural gas
North America
Integrated markets
Infrastructure
Pipelines

ABSTRACT

The exploitation of low-cost shale gas in the Marcellus Formation, the deregulation initiatives in the U.S. and Mexico, and the emergence of natural gas as a bridging fuel to a low-carbon economy has fueled the growth of North American natural gas production, which is projected to keep growing in the mid-term to support the increasing LNG exports. Greater introduction of renewables and deeper electrification suppress both supply and demand for natural gas in the long-term. The long lead times of pipeline operation and field exploitation render the timing of natural gas abatement critical to natural gas infrastructure stakeholders. Full integration of the U.S., Canadian, and Mexican natural gas markets implies that the abatement trajectories of the three countries are tightly linked. This paper studies the development of the integrated North American natural gas markets and infrastructure under different assumptions on resource availability, technological progress, and global crude oil prices. We quantify the impact of each scenario by using the North American Natural Gas Model. Our analysis shows that cross-border U.S.-Mexico trade is more resilient under all three shocks compared to U.S.-Canada trade. Increasing Mexican production could drive the growth of the domestic Mexican market instead of reducing U.S.-Mexico trade.

1. Introduction

The North American natural gas sector has been thriving the last decade and its outlook remains optimistic. Natural gas in the U.S. surpassed coal for the first time in 2016 as the primary fuel used for electricity generation[1]. Moreover, U.S. exports of liquified natural gas continue to grow and are projected to constitute more than 55% of total U.S. exports by 2030 per the "Annual Energy Outlook 2019" (EIA, 2017a). Mexico's domestic natural gas demand grew by 47.5% between 2005 and 2015 (EIAa). Finally, Canada's production is projected to grow by 11.23% by 2040 compared to 2016 (NEB, 2017).

Growth of North American natural gas production comes as a result of the rapid expansion of U.S. natural gas production. The latter is mainly attributed to the discovery of low-cost, technologically recoverable shale gas in the Marcellus Formation in 2008, rendering the U.S. the largest producer of natural gas since 2012 (EIA, 1000). Consequently, new pipeline projects were planned and completed (EIAc) in order to facilitate the distribution of the newfound resources in mainland U.S. In addition, the decreasing cost of transforming and shipping (Maxwell and Zhu, 2011) Liquified Natural Gas (LNG) provides U.S. producers with the opportunity to expand their reach beyond Canada and Mexico, who have been the major natural gas trade partners of the U.S. Therefore, even though U.S. demand is projected to grow modestly (EIA, 2017b), growth of U.S. natural gas production is projected to trend upwards as a result of low-cost natural gas resources and expansion of trade capabilities.

The boost of North American natural gas production has come not only as a result of unforeseen events, but also as a result of (de)regulatory initiatives. On the supply-side, other than the aforementioned discovery of low-cost shale gas in the Appalachian Basin, the ongoing deregulation of the natural gas market, starting from the Natural Gas Policy Act (NGPA) of 1978 (Energy Information Administration, 1978), is a policy-induced attempt to increase the penetration of natural gas into the U.S. energy mix. Starting in 1978, the U.S. has gradually removed stringent wellhead price ceilings set by the Natural Gas Act in 1938. The new price ceilings enforced by the NGPA were designed to

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[1] See "Electricity explained. Electricity in the United States." Available at: https://www.eia.gov/energyexplained/index.cfm?page=electricity_in_the_united_states.

https://doi.org/10.1016/j.enpol.2020.111757
Received 11 January 2020; Received in revised form 28 March 2020; Accepted 10 July 2020
Available online 16 September 2020

account also for the geology, location, and other characteristics of each well. The new wellhead prices incentivized producers to increase their production and expand their search for new sites. All wellhead price ceilings were removed under the Natural Gas Wellhead Decontrol Act of 1989 (Federal Energy Regulatory Commission, 1989). Canada started dismantling protections for domestic crude oil and natural gas producers with the introduction of the "Western Accord on Energy" in 1985 (Fertel et al., 2013). The legislation aimed to address the increasing surplus of supply in Canada during the 1980s.

In addition, Mexican policy-makers introduced in 2013 the Energy Reform (Aleman-Nava et al., 2014) in order to promote Mexican production and exploit domestic resources. In an attempt to curb the decline of Mexican natural gas production and increase investment on existing sites, in 2019 the Mexican government called for restrictions on invitations for oil block bids that were previously allowed under the 2013 Energy Reform (Graham, 2018). Moreover, the government has also proposed stricter regulations on pipeline contracts between the Mexican government and pipeline operators as a way to decrease the cost for the public sector. This has led to the renegotiation of contracts for new pipelines that subsequently delayed their connection to the system (Stilman, 2019). However, restrictions on natural gas infrastructure need to be the same for both domestic investors, i.e., state owned companies, and U.S. investors under the United States-Mexico-Canada (USMCA) Agreement (Gantz, 2019).

On the demand-side, excise tax and infrastructure tax credits have contributed to the adoption of natural gas in the commercial and residential sectors. Finally, state-level policies aiming to mitigate climate change, such as cap-and-trade (Tsao et al., 2011), lead to the substitution of coal-fired plants with natural-gas fired plants.

More specifically, fossil-fuel power plants are indispensable to electricity generation in the short-term for stability and resiliency reasons. First, fuel-fired power plants contribute to the stability of the power grid's frequency (Ulbig et al., 2013). Second, the operation of renewables requires a certain amount of active fuel-fired power plants at all times (Bruninx et al., 2014). However, the transition to a low-carbon economy (European Commission, 2018), as a result of climate change, necessitates the decrease of emissions in the power sector and the increase of energy efficiency of all sectors of the economy. The policies to reduce emissions include the creation of a market for emissions allowances (Goulder et al., 2009), carbon taxes (Larry and John, 1994), as well as updated buildings insulation standards (Li and Colombier, 2009). The first two policies favor natural gas-fired plants over other conventional fuel-fired plants due to the low emissions rate of natural gas consumption. For that, natural gas has emerged as a bridging fuel during the transition to a low-carbon economy. Hence, in North America natural gas is both an economically competitive and a "cleaner" option for power production compared to coal and oil due to the low emissions rate of natural gas consumption, the availability of natural gas resources, and the power system's reserves and grid frequency stability requirements.

Still, natural gas-fired power plants remain CO2 emitters, albeit the least intensive ones. Consequently, the deeper the penetration of renewables, the greater the displacement of natural gas-fired plants in the long-term. A complete treatment of the change in natural gas consumption would need to rely on an integrated framework that would grasp the interactions between the natural gas sector and the rest of the economy. However, some trends are prevalent. Natural gas is being displaced in fuel-intensive sectors, such as the transportation sector (Williams et al., 2011), due to increasing electrification.

Therefore, the timing of natural gas abatement, which is critical for the maintenance and development of natural gas production and pipeline infrastructure, depends on multiple factors. On the one hand, the availability of resources and stability requirements of the power sector render natural gas an economical short-term alternative to conventional fossil fuels. On the other hand, moving to a low-carbon economy implies the abatement of natural gas in the long-term. Hence, the challenge of studying the development of the natural gas sector in North America lies in the complexity of the interactions of the natural gas sector with all other sectors of the economy, the political nature of fossil fuels exploitation, and the uncertainty of resource availability. In this study we isolate potential sources of disruption for the natural gas sector and look to understand their impact. More specifically, we ask:

- How resilient is North American natural gas production and pipeline infrastructure, given uncertainty in future resource availability and technological change?
- Which North American producers and pipeline operators are the most vulnerable and should be accounted for in policy design?
- How does the growing exposure of the U.S. to international markets affect Canada and Mexico?

2. Literature review

We can divide the studies of the natural gas market into two categories: global and regional. While global studies aim at analyzing the drivers of increasing LNG trade, regional analyses focus on arbitraging between regions and pipeline infrastructure development. Egging et al. (2010) study international LNG trade using the World Gas Model (WGM), which includes 80 countries and assumes Nash-Cournot competition between representative producers. In WGM, Mexico is represented by one node, Canada is divided into two, and the U.S. into six. Avetisyan et al. (2011) use WGM to study the impact of CO2 emissions policies and availability of resources in the U.S. to the international natural gas market. To do so, they updated WGM to include environmental regulations. (Siddiqui and Gabriel (2012)), enhanced WGM by assuming that the census region that contains the two largest shale plays, the Barnett and Haynesville shale plays, is a leader in the market in a "Leader-Follower" setting. Egging (2013) enhanced WGM by introducing a Benders Decomposition scheme for stochastic mixed complementarity problems. Apart from the US, neither Canada nor Mexico are included in the latter version. Finally, Aune et al. (2009) highlight the role of decreasing LNG costs on integrating global markets. The authors develop FRISBEE, a recursive-dynamic, partial-equilibrium model of the global natural gas market with 13 regions where the U.S. is represented as its own region, whereas Canada and Mexico are part of other regions.

Focusing on Europe, the Price-Induced Market Equilibrium System (PRIMES) includes a detailed natural gas submodule with regional detail of Europe, Russia, Middle Africa, North Sea, China, and India, and has been used to produce the "EU Reference Scenario 2016" (European Commission, 2016). Golombek et al. (1995) focus on the liberalization of Western European natural gas markets. Modeling-wise, they are the first to introduce a nonlinear marginal cost of production. (Holz et al. (2008)) highlight the importance of liberalizing the downstream market using GASMOD. In their analysis they only represent the European natural gas market with added detail on the regions that import and export natural gas from and to the European Union. Abada et al. (2013) study the impact of long-term contracts using GaMMES. GaMMES is formulated as a Generalized Nash Equilibrium problem.

Beltramo et al. (1986) were among the first to study the outlook of the natural gas sector of North American countries. For this, they developed the North American Gas Trade Model (GTM) which was one of the first models of North America with regional detail regarding the U. S. and Canada that explicitly took into account pipeline interconnections between the two countries. (Gabriel et al. (2005)) introduced a model with 12 regions for the U.S. and two regions for Canada to study market power in North America. Finally, the Natural Gas Market Module (NGMM) (U.S. Energy Information Administration, 2018), a submodule of the National Energy Modeling System (NEMS) developed by the U.S. Energy Information Administration (EIA) has been used to produce Annual Energy Outlooks for the U.S. NGMM incorporates the nine census regions, one region for Canada and another for Mexico. In

NGMM, capacity expansion is not endogenous, but extra capacity is allocated exogenously based on the increase in national demand. On the other hand, the North American Natural Gas Model (NANGAM), developed by Feijoo et al. (2016), accounts for endogenous capacity expansion both in production and in pipeline infrastructure. Moreover, it includes all nine census regions for the U.S. but breaks down Canada into two regions and Mexico into five. NANGAM has been used to study the impact of the Mexican Energy Reform to cross-border Mexico-U.S. infrastructure.

Although the models in all the above studies implicitly assume some level of market interaction between regions, only few of them explicitly deal with market integration. Evidence on the lack of market integration in the 1990's can be found in De Vany and Walls (1995). On the other hand, (Serletis (1997)) argues that there is no split between Eastern and Western U.S. prices. Serletis and Herbert (1999) suggest that greater integration between North American regions, as a result of the liberalization of the natural gas market, leads to more effective arbitraging mechanisms. Siliverstovs et al. (2005) also try to empirically assess market integration, but focus on the global market. Feijoo et al. (2016) and Sankaranarayanan et al. (2017) treat a fully integrated North American natural gas market and aim to study the development of cross-border infrastructure. They find that higher Mexican demand leads to higher pipeline exports from the West South-Central region to Mexico. Feijoo et al. (2018) focus on the impact of socioeconomic factors that influence natural gas infrastructure. The study concludes that the resulting heterogeneity in demand can lead to investment in certain pipeline interconnections while other pipeline interconnections are underutilized.

The low international natural gas prices, the recent discovery of low-cost shale gas in the Middle-Atlantic region, the Energy Reform in Mexico, and the recent discovery of the largest hydrocarbon reserves deposit in the last 30 years in Mexico (Ore et al., 2019) constitute major changes that can affect the North American natural gas market in the long-term. In lieu of these developments, this paper provides the most up to date assessment of the impact of resource availability, international trade, and low oil prices on natural gas infrastructure development in North America.

3. Objectives and scenarios

Our objective is to analyze the implications for the natural gas production and pipeline infrastructure of a range of scenarios under integrated North American natural gas markets. For that, we formulate a comprehensive list of scenarios that are designed to explore the uncertainty of future resource availability, technological change, and potential policy changes:

a) **Reference:** A scenario that serves as benchmark against which all other scenarios will be compared to. Reference production and consumption projections are consistent with AEO2017 for the U.S. (EIA, 2017b), "Canada's Energy Future 2017" for Canada (NEB, 2017), and the "Natural Gas Outlook 2016–2030" of the Mexican Secretary of Energy (Secretaría de Energía) SENER (SENER, 2017) for Mexico. The process of attaining the Reference scenario is detailed in Section 4.1.

b) **Low_Oil_Price:** Following the low natural gas prices after 2014 (Linn and Muehlenbachs, 2018), we assume a shock in the international market that consequently affects regional demand. This scenario aims to quantify the resiliency of the North American natural gas system to decreased oil prices which consequently lead to decreased demand for natural gas. We implement this scenario by computing the change in regional natural gas demand with respect to reference demand in the "Low Oil Price" scenario of the "Annual Energy Outlook 2017" (EIA, 2017b). We then impose the same percentage change to NANGAM's reference regional demand (variable Q^{D}_{yhnde} in (Feijoo et al., 2016)), starting from 2020.

c) **High_Gas_Supply:** We assume that due to technological improvements, the cost of production of natural gas decreases by 20% in 2020, 30% by 2030, and by 30% for the remainder of the time horizon. More specifically, we decrease all terms of the marginal cost function, namely the linear, quadratic, and Golombek terms (parameters lin^{P}_{ysne}, qud^{P}_{ysne}, gol^{P}_{ysne} in (Feijoo et al., 2016)), by the respective percentages of each time period.

d) **Natural Gas Resources:** We assume that our medium-term projections regarding the availability of natural gas are correct and introduce a shock to the availability of resources in 2030 through 2050. By simulating two different variations, these scenarios aim to explore the ability of natural gas infrastructure to adjust to the (un) availability of resources.

i) **High Natural Gas Resources (High_NG_Res):** We constrain natural gas infrastructure (variables z^{P}_{ysne}, z^{A}_{ya} in (Feijoo et al., 2016)) to be the same as in Reference up until 2030, and allow endogenous change in infrastructure for the remainder of the time horizon. Beyond 2030, the greater availability of resources translates into our model to a lower operational cost of natural gas production in the US. The linear, quadratic, and Golombek terms of the marginal cost function (parameters lin^{P}_{ysne}, qud^{P}_{ysne}, gol^{P}_{ysne} in (Feijoo et al., 2016)) are changed according to the percentage change in the operational cost of each region in the U.S. The percentage change in the operational cost is calculated using the "High Oil and Gas Resources" scenario of AEO2017.

ii) **Low Natural Gas Resources (Low_NG_Res):** The implementation is identical to the "High Natural Gas Resources" scenario, with the exception that the applied percentage changes are calculated using data from the "Low Oil and Gas Resources" of AEO2017.

In both High_Gas_Supply and High_NG_Res we change the parameters of the marginal cost function. Nonetheless, the High_NG_Res aims to study the response of the system in a scenario of abundant U.S. resources, whereas the High_Gas_Supply studies the effect of higher productivity in all of North America. Therefore, the implementation differs. In the High_Gas_Supply, the parameters of the marginal cost function of all producers are decreased by 20% in 2020, whereas in the High_NG_Res scenario the decrease in 2020 is 15%. The change in marginal cost parameters is different between the two scenarios for all subsequent years as well.

4. Methods

The North American Natural Gas Model (NANGAM) is an intertemporal, bottom-up, partial-equilibrium model of the interconnected natural gas sectors of the U.S., Canada, and Mexico (U.S. Energy Information Administration, 2018). NANGAM is built with a focus on North America. It comprises nine census regions of the U.S. (Fig. 1), a region for Alaska and Hawaii, five regions for Mexico (Northwest, Northeast, Interior, Interior-West, South-Southwest), two regions for Canada (East, West), amounting to seventeen regions in total. There exist 13 producing regions, based on regional historical capacity data, namely census regions 2–9, both regions in Canada, Northeast Mexico, and South-Southwest Mexico. In addition, the seventeen regions are connected via 69 representative links that emulate the inter-regional pipeline interconnections. In addition, storage facilities exist in each node in the U.S. and Canada. We use a database of 778 existing projects and 187 new ones provided by the U.S. Energy Information Administration (EIAc) to produce estimates of pipeline investment cost, as well as fixed and marginal cost of transporting natural gas. For the documented pipelines, the database provides the technical characteristics, their cost structure, and whether they are interstate, intrastate or cross-border projects. NANGAM is thus able to account for endogenous flows and

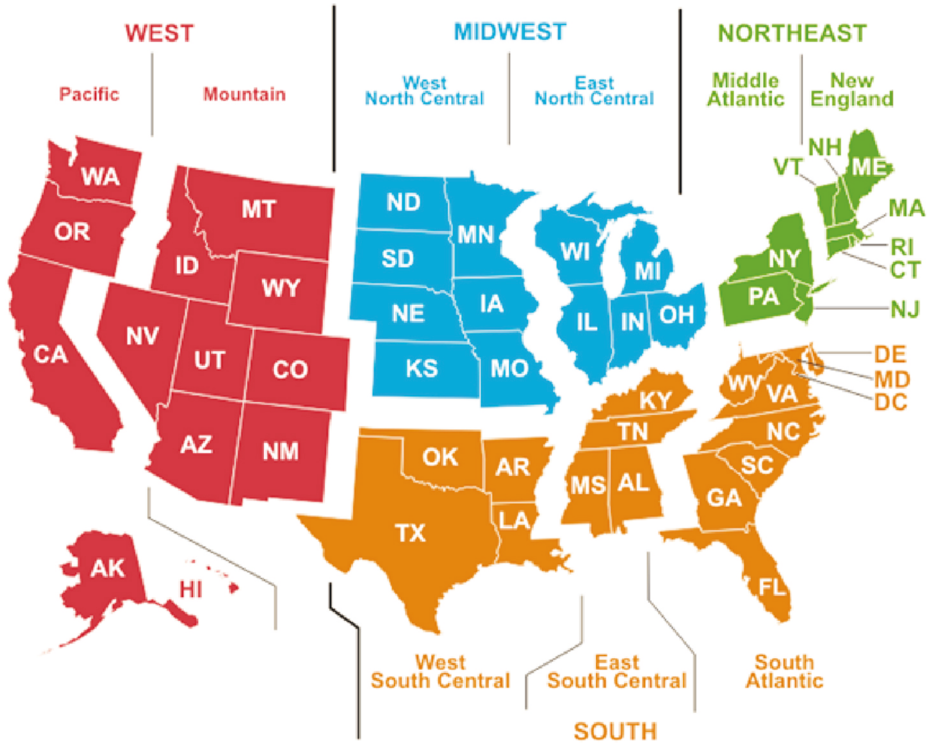

Fig. 1. Census regions. Source: Energy Information Administration.

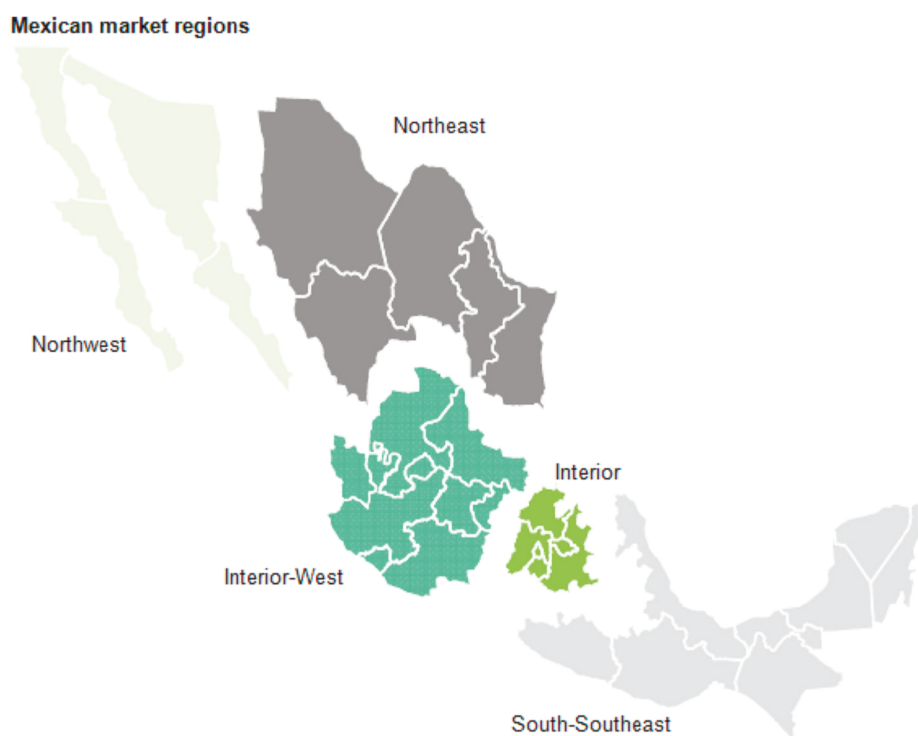

Fig. 2. Regional disaggregation of Mexico in NANGAM. Source: Energy Information Administration.

investment on pipeline capacity. NANGAM runs in 5-year time steps up to 2050, is formulated as a Mixed Complementarity Problem (MCP), and is run using the General Algebraic Modeling System (GAMS) (see Fig. 2).

The agents incorporated in NANGAM include regional suppliers (upstream players) that extract and deliver natural gas to pipeline operators that in turn deliver natural gas to final consumers or storage facilities (midstream). Each agent is assumed to be a profit maximizer and decisions on infrastructure development are endogenously generated based on future profitability. Demand is incorporated via a linear inverse demand function for each region. NANGAM is based on Multi-Mod (Huppmann and Egging, 2014) from where it inherits all the assumptions regarding the interactions of the market participants. For that, agents compete ala Nash-Cournot and NANGAM computes regional prices and quantities that clear every regional natural gas market. Finally, NANGAM can be used for the analysis of supply or demand-side shocks, policy interventions, and infrastructure investment. The above scenarios can be implemented at a regional, national or international level. NANGAM further inherits all the types of potential regulation that can be applied in MultiMod, such as greenhouse gas emissions constraints and taxes or fuel mandates. Finally, NANGAM, similarly to MultiMod, can be coupled with other energy, climate or economic models.

4.1. Reference scenario

As discussed in Section 3, production and consumption in the version of NANGAM used in this study is consistent with AEO2017 for the U.S. (EIA, 2017b), "Canada's Energy Future 2017" for Canada (NEB, 2017), and the "Natural Gas Outlook 2016–2030" of the Mexican Secretary of Energy (Secretaría de Energía) SENER (SENER, 2017) for Mexico. For production and consumption of each region to be consistent with the different databases, we calibrate the linear and quadratic terms of the marginal cost function and the capacity expansion cost of each producer, as well as the pipeline tariffs charged by pipeline operators. Benchmark data on the cost of production (EIAb) as well as pipeline projects (EIAc) are extracted from the Energy Information Administration. End-use prices are consequently affected by the calibration of costs across the supply chain, but we do not further calibrate these costs to match end-use prices perfectly (see Fig. 3).

The calibration of the model is an iterative process, with each iteration comprising of two steps. In the first step demand parameters are automatically computed for given demand elasticity. For consistency, costs are manually updated to better match the production in the second step, altering equilibrium demand. The two steps are repeated until equilibrium production and consumption for all regions does not differ from reference data by more than 5% until 2040. For the remaining years we ensure that the deviation of consumption is within 3%, while the deviation of production is within 10% for the major producing regions. Reference production and consumption data for the three regions are shown in Fig. 4.

5. Results

5.1. Low_Oil_Price

We implement this scenario by constraining regional natural gas consumption in each country (variable Q^{D}_{yhnde} in (Feijoo et al., 2016)). We fix regional natural gas consumption in each region of each country at a new level that differs from the reference value by the percentages shown in Table 1 below.

The uniform decrease in North American demand implies that production in all three countries readjusts, as shown in Fig. 5. U.S. production is the one that decreases the most in the mid-term as a result of the projected increasing U.S. exports through 2030. Canadian production decreases by 0.55 BCM (3.7%) in 2050, whereas Mexican production remains largely unaffected in absolute value throughout the time horizon. The decrease in Canadian consumption in 2040 by 6.53 BCM along with a slight adjustment of exports results in Canada decreasing its production by 7.86 BCM or 4.82% compared to reference 2040 natural gas production. Therefore, the percentage change in Canadian natural gas production in 2040, the largest among all countries for all time periods, is attributed to the decrease of domestic natural gas consumption. Moreover, since the U.S. faces the largest absolute change in natural gas consumption, it is the country that drives the change in consumption in North America. North American production decreases from 2015 to its nadir in 2045 and increases in 2050, which is consistent with the change in consumption in Table 1.

Trade between the three countries is also affected, with exports of the U.S. to Mexico decreasing by 4.80%, while imports of the U.S. from Canada also decrease by 12.91%. In Fig. 7 we can observe how the flows from Middle-Atlantic to East-North-Central decrease by 4.98% and the flows from Mountains to the Pacific region decrease by 5.44% in 2040.

Fig. 3. Representation of endogenous natural gas flows in NANGAM.

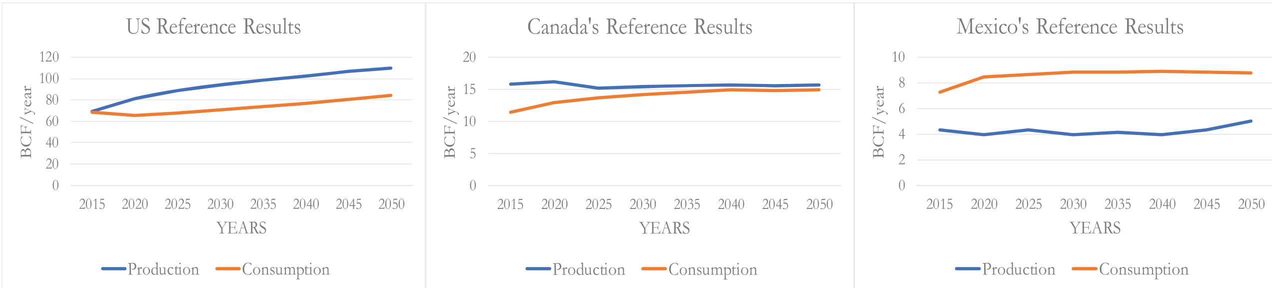

Fig. 4. U.S. (left), Canadian (center), and Mexican (right) reference production and consumption.

Table 1
Percentage change in natural gas consumption per country under the Low_Oil_Price scenario.

	Imposed % Change of Consumption							
	2015	2020	2025	2030	2035	2040	2045	2050
USA	0.00	−2.21	−2.88	−3.16	−3.86	−4.24	−4.90	−4.16
Canada	0.00	−2.21	−2.88	−3.16	−3.86	−4.24	−4.90	−4.16
Mexico	0.00	−2.21	−2.88	−3.16	−3.86	−4.24	−4.90	−4.16

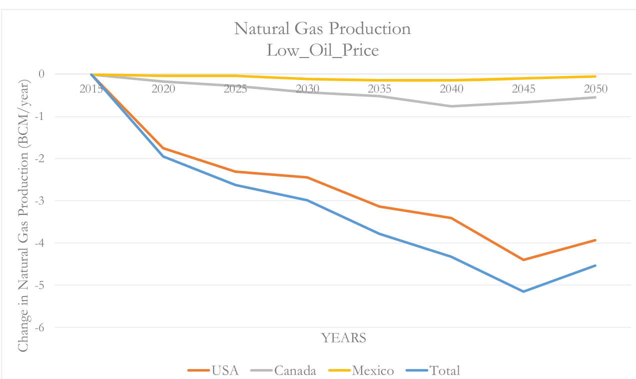

Fig. 5. Change in natural gas production per country under the Low_Oil_Price scenario. Production in all three countries adjusts according to the applied change in consumption.

Moreover, all flows from West-South-Central decrease, with exports to Mexico decreasing by an aggregate of 4.80% and flows to East-South-Central decreasing by 14.95%. Fig. 8 illustrates how the adjustment of the flows within the U.S. are either comparable or greater than the adjustment of exports to Mexico. Among major inter-regional interconnections, the interconnection between West-South-Central and East-South-Central is the most sensitive.

Lower demand in the Low_Oil_Price scenario results in smaller production capacity infrastructure expansion compared to Reference. Fig. 6 reveals that the change in production infrastructure is heterogeneous among regions. The two biggest producing regions in the U.S., Middle Atlantic and West-South Central, decrease their investment in production capacity by 8.51 BCM/year and 16.64 BCM/year respectively. On the other hand, smaller producing regions decrease their investment in new infrastructure only marginally. Fig. 6 also reveals that the observed decrease in Mexican production is attained by decreasing the utilization rate of available capacity in 2050.

In conclusion, the projected increasing exposure of the U.S. to international markets renders the U.S. more vulnerable to shocks in international prices in the mid-term. Investment in new production capacity infrastructure in the North-American system is also smaller. The results highlight the resiliency of cross-border trade between the U. S. and Mexico and, consequently, the high sensitivity of neighboring pipelines. On average, regional decrease in demand leads to further under-utilization of the pipelines connecting major U.S. producers to smaller producing regions with high demand.

5.2. *High_Gas_Supply*

Enhanced overall productivity in North America results in an increase of production for all three countries. Moreover, the greater availability of low-cost gas results in increased overall consumption. In this scenario, we adjust the linear, quadratic, and Golombek terms of the marginal cost function (parameters lin^P_{ysne}, qud^P_{ysne}, gol^P_{ysne} in (Feijoo et al., 2016)) according to the definition of the scenario. That is, by 20% in 2020, by 30% by 2030, with linear ramps between 2020 and 2030 and a 30% change for the remainder of the time horizon after 2030. Fig. 9 highlights how increased productivity allows Mexico to tap into its unexplored potential and thus grow even more than the U.S. and Canada. In Fig. 10 we can see that consumption of Mexico grows by 4% in 2050, whereas U.S. and Canadian consumption grow by 5% in 2050.

Although Mexican production grows disproportionately more compared to Reference than that of the U.S., U.S. exports to Mexico decrease only marginally. At the same time, Mexican consumption expands as a response to cheaper available natural gas in Mexico. Fig. 11 shows the intertemporal change of Mexican natural gas production and consumption. The expansion of Mexican consumption at a rate similar to the expansion of natural gas production leads to only marginal changes in cross-border trade between the U.S. and Mexico. Fig. 12 shows the regional disaggregation of net flows between the U.S. and Mexico. Net exports to Mexico-Northeast decrease and net exports to Mexico-Interior-West increase, leading to a 1.97% overall decrease in 2040. The decrease in consumption of both Mexico and the U.S. suggests that the increase of Canadian production stems from the expansion of the domestic Canadian market.

Cheaper production capabilities in High_Gas_Supply result in lower overall production capacity infrastructure expansion in the North-American natural gas system. In Reference, producers often do not deplete their capacity due to the nonlinear marginal cost. From an infrastructure point of view, the lower marginal cost of production allows producers to utilize existing infrastructure more efficiently and subsequently invest in less capacity inter-temporally. Overall investment in North-American natural gas production infrastructure decreases by less than 1% inter-temporally or 3.21 BCM/year. Fig. 13 reveals that our intuition is true for large producers, the Middle Atlantic and North-West Central regions, but not for small ones, such as North-East Central

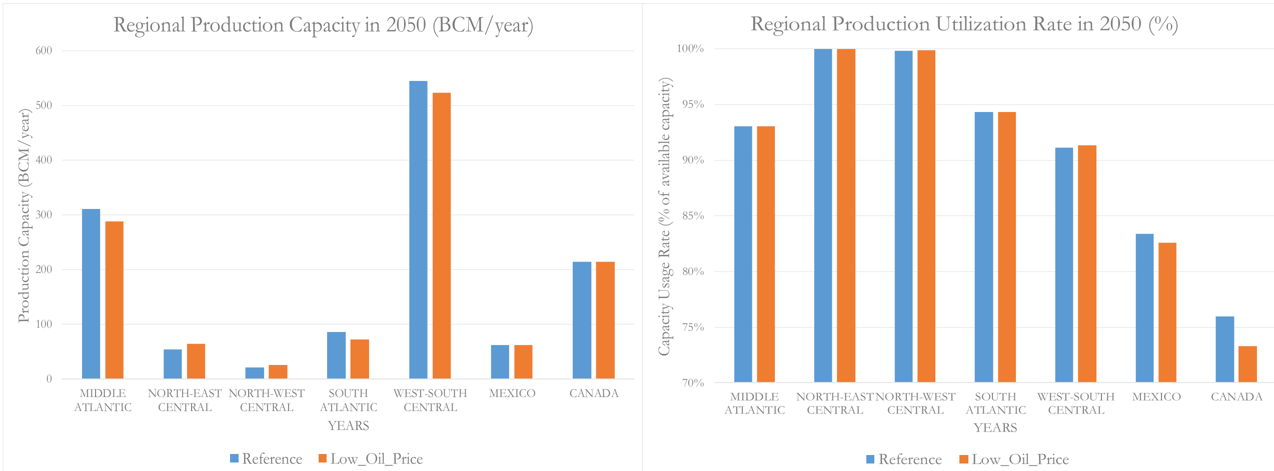

Fig. 6. Production capacity for selected regions (left) and regional production utilization rate (right) in 2050 in Reference and Low_Oil_Price scenarios. Producers that do not decrease their investment in new production infrastructure adjust their utilization rate.

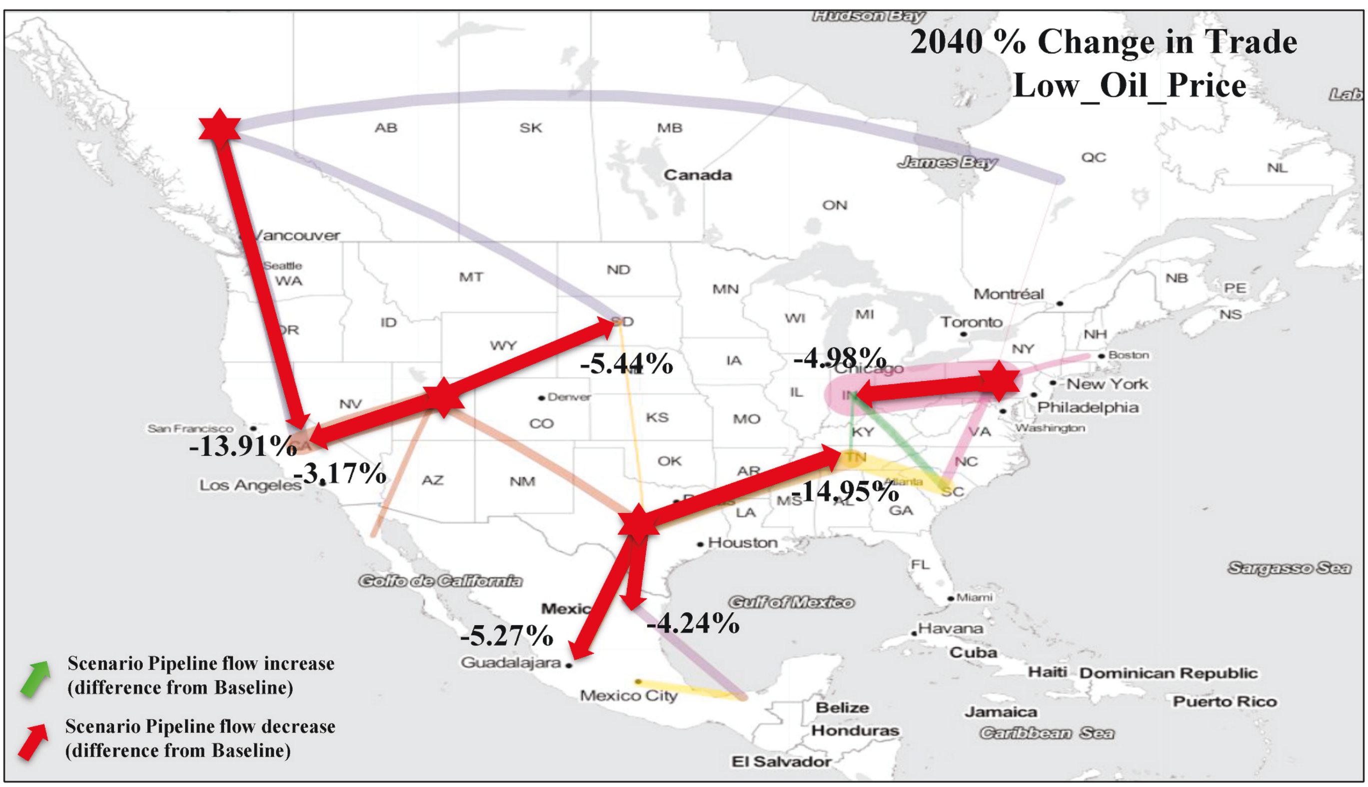

Fig. 7. Percentage change in natural gas trade between North American regions under the Low_Oil_Price scenario. Trade via major interconnections decreases.

and North-West Central, that in fact increase their investment in production infrastructure compared to the Reference. Nevertheless, Fig. 13 also reveals that all regions are able to use all existing and new capacity more efficiently. In fact, the regions that do not expand their production capacity infrastructure compared to Reference, such as Canada and Mexico, are the ones that are able to tap into the potential of existing available resources (see Fig. 14).

In conclusion, this scenario highlights the potential of Mexican production to grow by more than the U.S., given the technological circumstances. This comes as a result of more efficient utilization of existing production infrastructure. Growth of Mexican production however does not immediately imply that imports from the U.S. are decreased, given the strong trade relations between the two countries. On the contrary, total U.S. exports to Mexico remain unaffected and increase marginally.

5.3. Natural gas resources

The U.S. is the largest natural gas producer and consumer in North America with strong trade relationships with both Canada and Mexico. For that, shocks in the productivity of the U.S. propagate to the rest of North America. Naturally, in the High_NG_Res scenario, the U.S. gains a comparative advantage over the rest of the countries and for that it grows disproportionately more. On the other hand, at the Low_NG_Res scenario the U.S. becomes less competitive with respect to its neighbors, who expand their production at higher rates compared to Reference. We

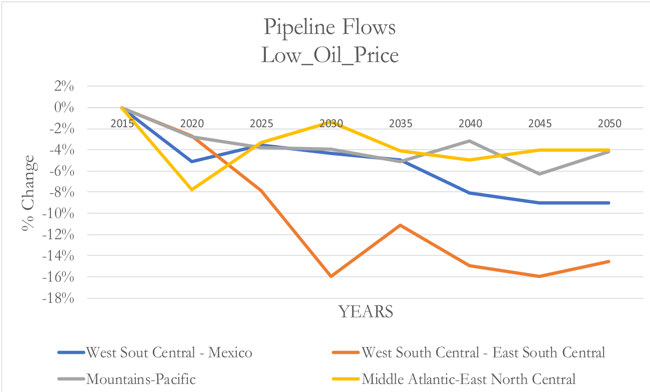

Fig. 8. Percentage inter-temporal change in natural gas trade between selected North American regions under the Low_Oil_Price scenario. Among major interconnections, the West-South Central – East South Central interconnection is affected the most.

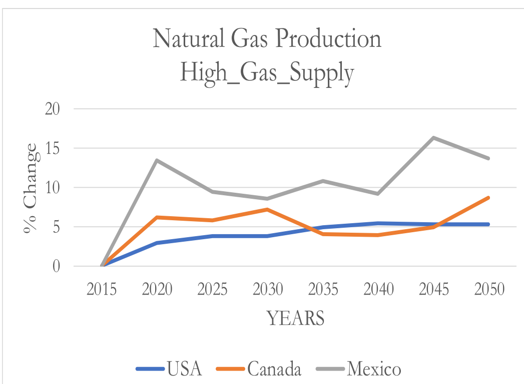

Fig. 9. Percentage change in natural gas production per country under the High_Gas_Supply scenario. Mexican production increases the most with respect to Reference.

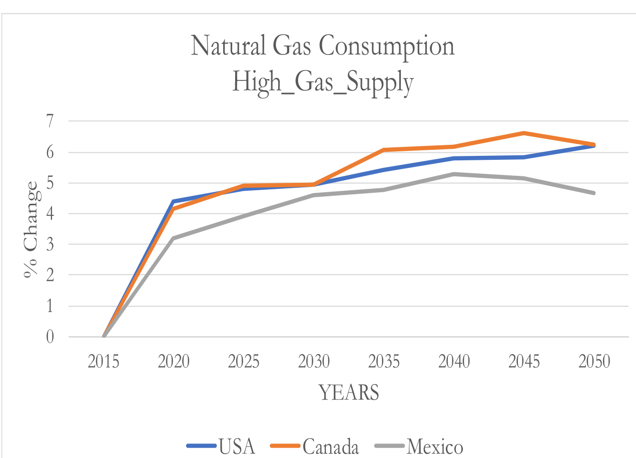

Fig. 10. Percentage change in natural gas consumption per country under the High_Gas_Supply scenario.

implement this scenario by constraining all infrastructure decisions by 2030 to their reference level (variables z^{P}_{ysne}, z^{A}_{ya} in (Feijoo et al., 2016)) and allowing them to adjust thereafter. Moreover, in 2030, we adjust the linear, quadratic, and Golombek terms of the marginal cost function (parameters lin^{P}_{ysne}, qud^{P}_{ysne}, gol^{P}_{ysne} in (Feijoo et al., 2016)) according to

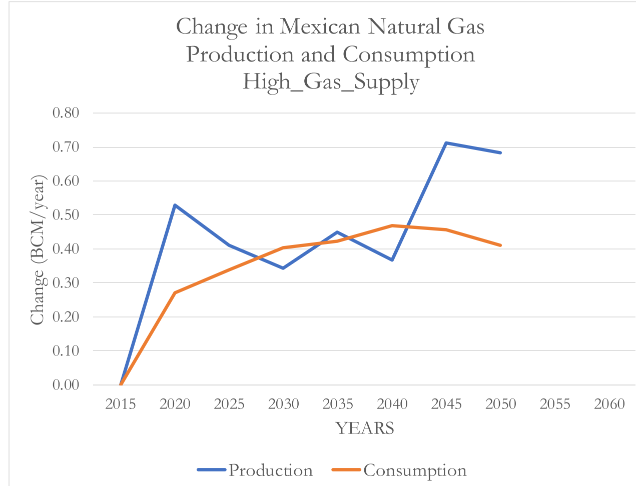

Fig. 11. Change in Mexican natural gas production and consumption in High_Gas_Supply. Mexican consumption expands due to greater availability of Mexican low-cost resources. The magnitude of the change in Mexican consumption is comparable to the change in Mexican production intertemporally.

each scenario's specifications.

In the High_NG_Res scenario, the higher availability of resources in North America results in higher consumption in all countries. Fig. 15 shows how consumption in the U.S. increases by 6% by 2050 in the High_NG_Res scenario, while consumption of Canada and Mexico increase by 4%. In the Low_NG_Res scenario, U.S. consumption decreases by 3.5% and Mexican and Canadian consumption decrease by more than 2% and 3% respectively.

Pipeline infrastructure allows Mexican and Canadian consumers to benefit from low-cost U.S. resources. In addition, in the High_NG_Res scenario, West-South-Central exploits its capabilities as the biggest producing region and at the same time the major trade partner of Mexico. Total exports from the U.S. to Mexico increase by 6.97%. Trade between other U.S. regions is depicted in Fig. 16. Notably, Mountains is capable of providing to Pacific all of the demand previously covered by West-Canada. Therefore, trade between West-Canada and the Pacific is eliminated and trade between Mountains and the Pacific region increases by 15.75%. To do so, the Mountains also need to curtail some of their supply to West-North-Central. Finally, Fig. 17 depicts how the flows from large U.S. producers (West-South-Central and Middle-Atlantic) to regions with limited production (South-Atlantic and North-East-Central respectively) serve as a means for expanding regional markets with limited resources.

Similarly, in the Low_NG_Res scenario, the scarcity of resources in the U.S. results in a decrease in trade. The reason is the need for producers to cover their regional demand. Therefore, exports from the U.S. to Mexico are reduced by 4.12%. In addition, West-Canada exploits the difficulty of the U.S. to cover their demand and increases both its production and its trade with the Pacific region. Finally, when producers prioritize covering their regional demand then flows to other regions are curtailed, resulting in a decrease in natural gas trade between West-South-Central and East-South-Central.

The changes in natural gas trade do not alter investment decisions in pipeline infrastructure compared to Reference in the High_NG_Res and Low_NG_Res scenarios respectively. The only pipeline interconnection that is affected is the Middle Atlantic to North-East Central. In the High_NG_Res scenario its capacity increases by 10.14 BCM/year and in the Low_NG_Res by 2.09 BCM/year by 2050. The reason is that 2015 pipeline infrastructure is sufficient for most interconnections. Fig. 18 shows that in Reference, the pipeline capacity infrastructure of many major interconnections is underutilized. Therefore, in response to changes in trade, pipeline operators adjust their utilization rate instead

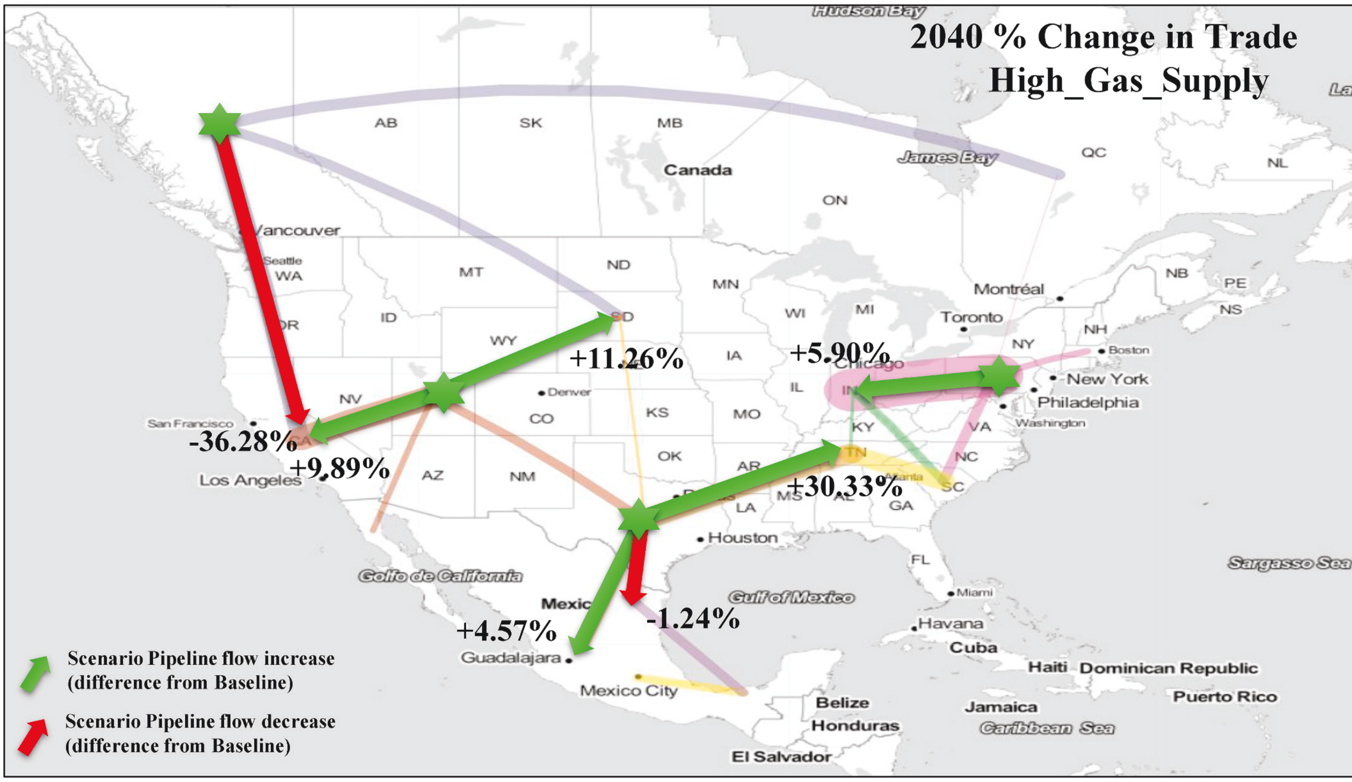

Fig. 12. Percentage change in natural gas trade between North American regions under the High_Gas_Supply scenario. Trade via most major interconnections increases. Change in trade varies regionally.

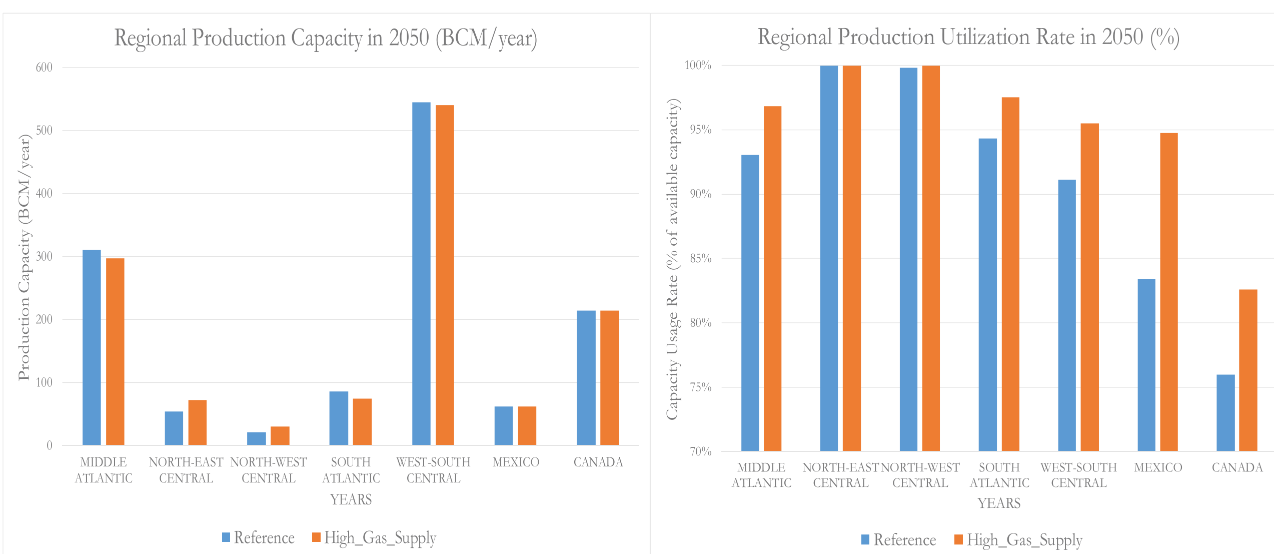

Fig. 13. Production capacity for selected regions (left) and regional production utilization rate (right) in 2050 in Reference and High_Gas_Supply scenarios. All producers use their capacity more efficiently.

of their capacity. The Middle Atlantic to North-East Central interconnection is always at capacity, which is the reason why investment in new infrastructure happens under all scenarios. Finally, the Canada West to Pacific interconnection appears to be very sensitive in these scenarios. The utilization rate becomes zero in 2040 in High_NG_Res but almost doubles in Low_NG_Res.

In conclusion, this scenario highlights that the availability of low-cost resources in the U.S. is exploited primarily by local consumers. When more resources are available in the medium and long-term for the U.S., U.S. producers increase their market share in North America. In addition, consumption increases in all three countries as a result of low-cost natural gas in North America overall. Due to the significance of the U.S., the shocks propagate to both Canada and Mexico via the pipeline system, increasing North American demand for natural gas overall. The opposite is true for scarce medium and long-term resource availability. U.S. production loses a fragment of its market share, while U.S. consumption decreases due to the overall increase in the price of natural gas. However, the impact on Canadian and Mexican production is less severe compared to that on U.S. production, which points to the ability of U.S. natural gas infrastructure to absorb the impact of such shocks

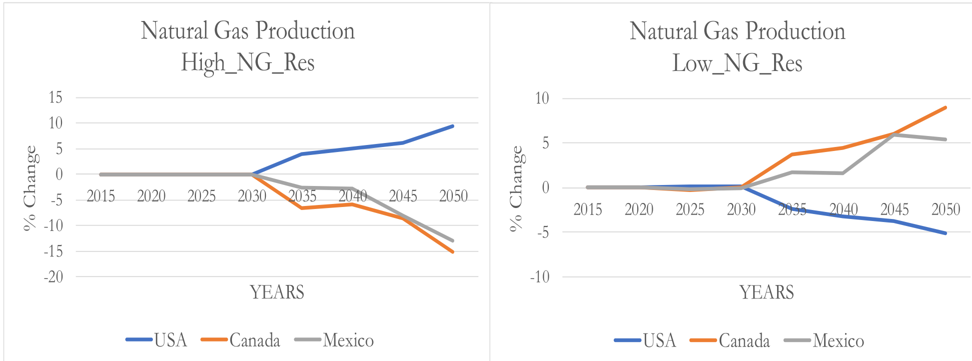

Fig. 14. Percentage change in natural gas production per country under the High (left) and Low (right) Natural Gas Resources scenarios. Greater availability of resources in the U.S. in High_NG_Res provides U.S. producers with a competitive advantage over Canadian and Mexican producers. The opposite is true in Low_NG_Res.

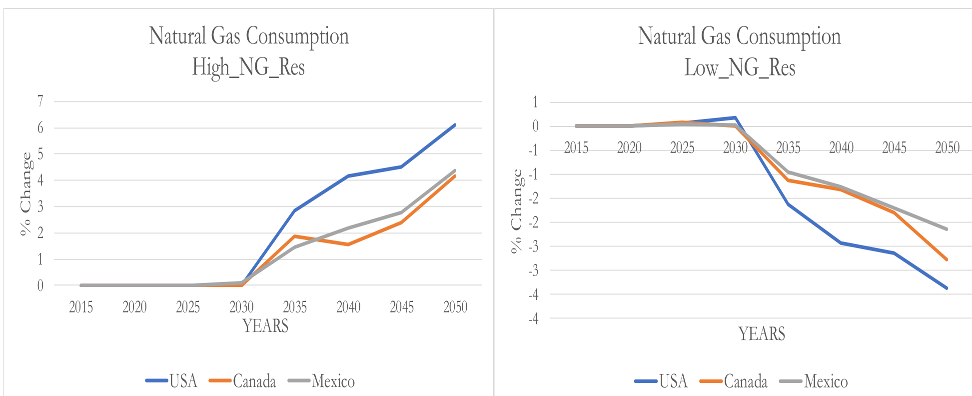

Fig. 15. Percentage change in natural gas consumption per country under the High (left) and Low (right) Natural Gas Resources scenarios. Greater availability of resources in the U.S. in High_NG_Res drives consumption higher in all three countries. The opposite is true in Low_NG_Res.

before exploiting inter-country trade. The vast majority of pipeline operators respond to changes in trade by adjusting the utilization rate of pipelines, since pipeline infrastructure is underutilized in Reference.

6. Conclusion and policy implications

This study explores the evolution of North American natural gas infrastructure under a variety of plausible scenarios. For the purpose of this paper we use NANGAM, a large-scale, bottom-up, game-theoretic model of the North American natural gas system that allows for the representation of market agents with competing objectives. We run a scenario where the low oil and gas prices observed after 2014 are preserved in the future, a scenario of higher supply due to technological change, and two scenarios of high and low availability of natural gas resources.

We show that when oil prices remain low all three countries' production decreases by more than 3% by 2040. Total investment in new production capacity infrastructure in the U.S. also decreases, but the impact varies regionally. Larger U.S. producers decrease their investment in production infrastructure, however certain smaller U.S. producers marginally increase their investment in new infrastructure. Moreover, the exposure of the U.S. to international trade leads to production decreasing faster in the short-term than in the long-term, as a response to the faster short-term decrease in consumption that is imposed in this scenario. Although Canada is not as exposed to international trade as the U.S., the decrease in production between the two is similar through 2050. Mexico on the other hand taps into its potential in the long-term and is able to offset the effects of the shock by 2050. The results suggest that the strong projected link of the U.S. with international markets renders the U.S. vulnerable to changes in international prices in the mid-term. Decreased demand also leads to decreased flows from major U.S. producing regions to traditional trade partners in mainland U.S. and Mexico.

More aggressive technological change in North America results in Mexican production growing by more than the rest of the countries. The disproportional growth of Mexico happens without any investment in new production infrastructure, as the reduced cost allows Mexico to exploit more efficiently its existing resources. However, Mexico continues to rely on the U.S., with U.S. exports to Mexico decreasing only marginally. The result suggests that the Mexican Energy Reform can succeed in exploiting Mexican natural gas resources if it manages to stimulate those market forces that would enhance the productivity of the Mexican natural gas industry by at least as much as the rest of the countries. At the same time, enhancing Mexican production does not necessarily imply that Mexico's dependence on U.S. natural gas is mitigated.

In the High_NG_Res (Low_NG_Res) scenarios where more (less) resources are available in the medium and long-term for the U.S., U.S. producers increase (decrease) their market share in North America. The results suggest that the (un)availability of resources in the U.S. affects primarily U.S. consumption and secondarily U.S. imports and exports. Given that pipeline infrastructure is underutilized in Reference, pipeline operators respond to changes in trade by adjusting the pipeline utilization rate. From the policy-makers' point of view, the U.S. would bare the benefits (costs) of resource availability. From a stakeholder's point of view, certain trade infrastructure might not be resilient to changes in its current and projected status.

Our results highlight the spatial distribution of the effect of plausible

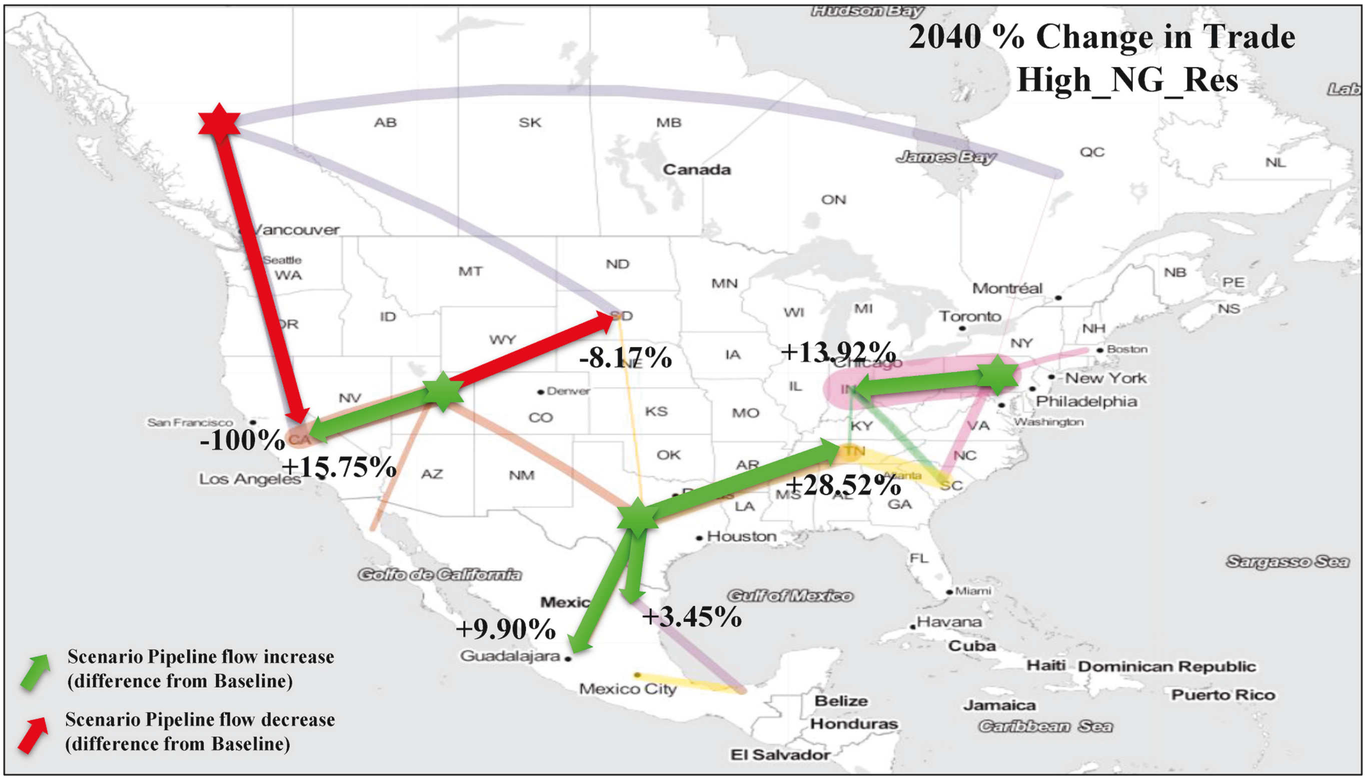

Fig. 16. Percentage change in natural gas trade between North American regions under the High Natural Gas Resources scenario. Trade via most major interconnections increases.

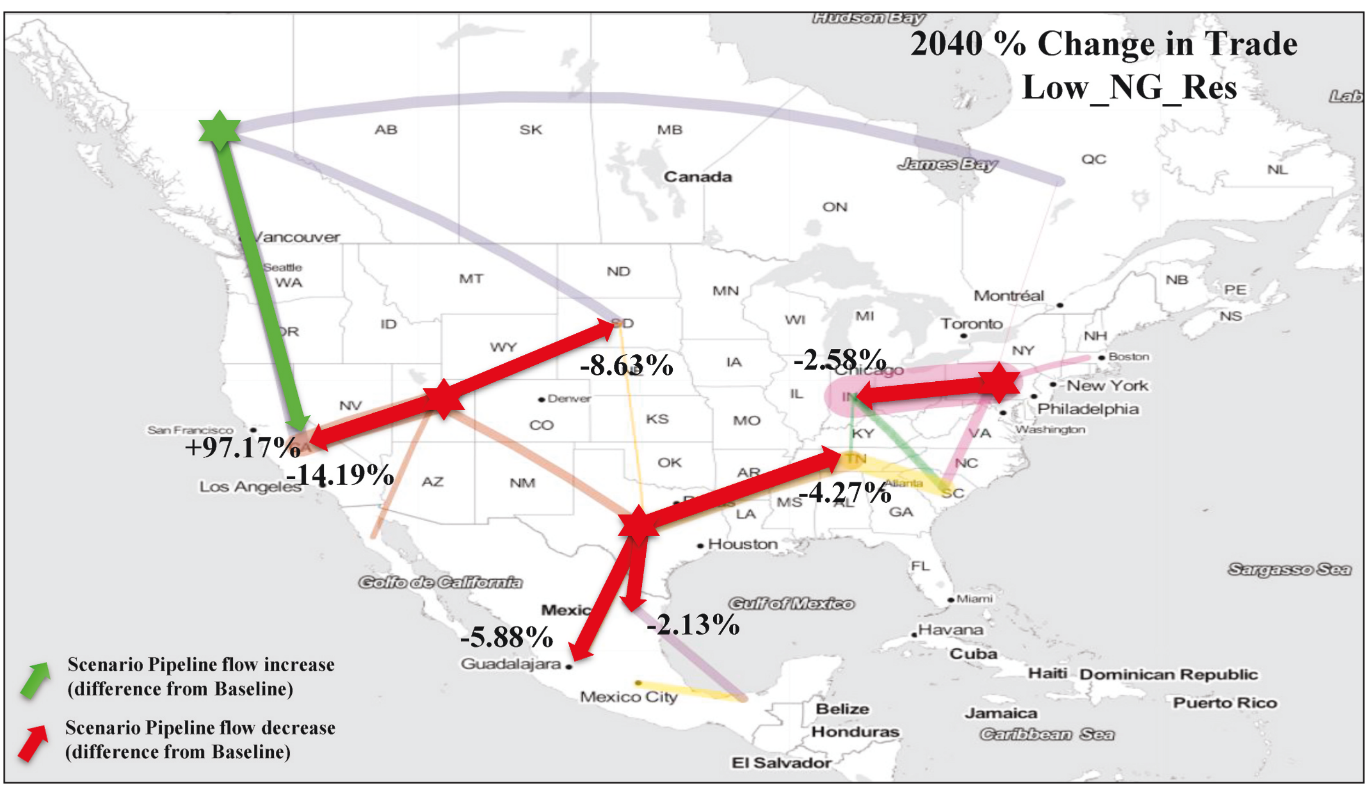

Fig. 17. Percentage change in natural gas trade between North American regions under the Low Natural Gas Resources scenario. Trade via most major interconnections decreases.

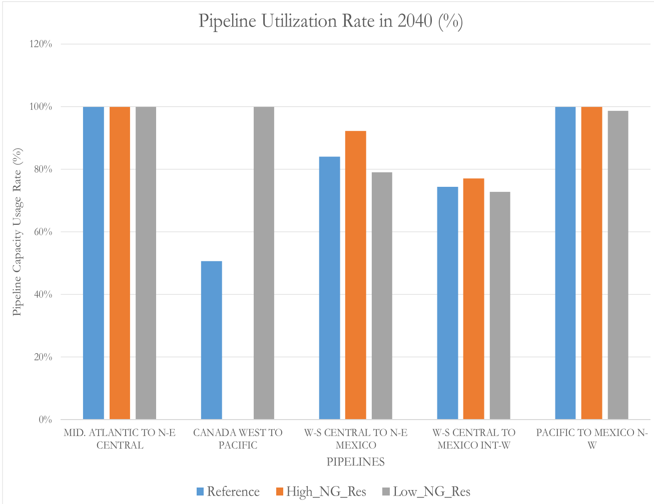

Fig. 18. Pipeline utilization factor (percentage with respect to pipeline capacity) in 2040 in the Reference, High_NG_Res, Low_NG_Res scenarios for selected pipeline. Pipeline operators respond to a surge in trade by exploiting underutilized capacity instead of expanding their capacity.

future development trajectories of the natural gas sector in North America. We stress the importance of using a framework that accounts for the interactions between competing market agents as a means to understand the transformation of the North American natural gas sector. We study three scenarios that explore the impact of low international oil prices, technological change in the natural gas sector, and availability of natural gas resources. By using NANGAM, we are able to provide policymakers and stakeholders with an informed outlook on North American regions and pipelines that are most affected both between countries, but also within the U.S. Our analysis focuses on the crucial role of natural gas on the ongoing transformation of the North American energy system towards a low-carbon economy in an attempt to inform future policy design.

CRediT authorship contribution statement

Charalampos Avraam: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing - original draft, Writing - review & editing. **Daniel Chu:** Data curation, Software. **Sauleh Siddiqui:** Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Writing - review & editing

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.

Acknowledgements

We would like to thank the entire EMF 34 Modeling Group for their discussions and feedback. Research support for C.A. and S.S. was funded in part by NSF Grant #1745375 [EAGER: SSDIM: Generating Synthetic Data on Interdependent Food, Energy, and Transportation Networks via Stochastic, Bi-level Optimization]. NANGAM is based in part on the multi-fuel energy equilibrium model MultiMod.[2] The MultiMod was developed by Dr. Daniel Huppmann at DIW Berlin as part of the RESOURCES project, in collaboration with Dr. Ruud Egging (NTNU, Trondheim), Dr. Franziska Holz (DIW Berlin) and others (see http://diw.de/multimod). We are grateful to the original developers of MultiMod for sharing their model.

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