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North American natural gas model: Impact of cross-border trade with Mexico

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A B S T R A C T

Natural gas gained significant attention due to its low carbon emissions and competitive prices in North America relative to other energy sources. The Annual Energy Outlook 2015 projects the U.S. as a net exporter by 2017. Recently, Mexico launched its energy reform, aiming to expand domestic production by opening the market to private investors. The success or failure of these policy changes will impact the development of the natural gas market in North America.

To analyze possible pathways of the Mexican energy reform, we develop the North American Natural Gas Model (NANGAM). NANGAM is a long-term partial equilibrium model that allows for endogenous infrastructure expansion and non-linear cost functions. NANGAM is calibrated using the most recent data available from U.S., Canadian, and Mexican sources.

We find that, in order to reduce pipeline imports, Mexico depends on economic incentives that lower barriers to infrastructure investment and keep production costs at competitive levels. If reforms to guarantee these incentives are not successfully implemented, growing gas demand in Mexico will be satisfied by further supply from Texas and neighboring states. This will cause a ripple-effect of increasing production in other regions in the U.S. and a shift in trade flows across the continent.

1. Introduction

The shale boom and new power plant regulations recently announced by the U.S. Environmental Protection Agency (U.S. EPA), aiming to curb greenhouse gas emission and mitigate global warming, have stimulated substantial academic debate and numerical simulation exercises to understand the future role of natural gas in North America [e.g., 1, 2]. Furthermore, the U.S. is expected to become a significant net exporter of natural gas over the next years [3], as China and Mexico are shifting from its reliance on coal to cleaner alternatives [3,4]. However, to date, there is very little academic focus on the role of Mexico on the North American natural gas market.

Natural gas demand grew by 64% in Mexico between 2004 and 2013, primarily led by the increasing consumption from the electricity sector. Due to a lack of investment incentives, production did not increase at the same pace as demand, and proven gas reserves in Mexico decreased from 2.0 trillion cubic meters in 1993, to 0.4 tcm in 2003 and 0.3 tcm in 2013 [5]. Production growth of natural gas in the South-Southeast Mexican region is projected to be 0.4% per year through 2019 [6]. Mexico's state-owned petroleum company, PEMEX, consumes increasing portions of this gas production for exploration, production, and refining activities.[1] Combining these circumstances with limited future LNG importing capacity, cheaper pipeline imports from the U.S. are crucial to meet growing national demand [7,8]. Natural gas from the U.S. accounted approximately 69% of total imports in 2014 [9]. Pipeline flows from the U.S. to Mexico averaged 2 billion cubic feet per day (Bcf/d) that year. Projects in Mexico to increase pipeline capacity are underway. These new pipelines are expected to import more than 5 Bcf/d of

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[1] See further details at https://www.eia.gov/todayinenergy/detail.cfm?id=16471. Accessed on January 19, 2016.

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natural gas by 2020 [8,10].

In order to promote natural gas production in Mexico and reduce reliance on U.S. imports, on December 20, 2013, the energy reform was approved by the Congress of the Union, modifying articles 25, 27 and 28 of the Mexican Constitution [11]. The legal framework established under this reform involves not only a transformation of the hydrocarbons (oil and gas) sector, but also a structural change of the national power sector [12]. In this manuscript, we mainly focus on the reforms in the natural gas sector. Details of the regulatory framework for oil and natural gas markets can be found in the annual SENER (*secretaria de energia*) report [13], Section 1.

The energy reform initiative opened up new opportunities for the private sector in the upstream (exploration, development, and production) and downstream (refining and marketing of the resource) sector of the oil and gas industry. The energy reforms also call for empowering the regulatory agencies of SENER and The National Hydrocarbon Commission (CNH), and for creating the *Agencia de Seguridad, Energia y Ambiente* (ASEA), which seeks to guarantee safety of the population and the integrity of the environment[2] [8].

Towards a better understanding of the future of the natural gas sector in North America, models need to account for a better representation of Mexico. Better depiction of Mexico is needed due to its increasing role in North America driven by the energy reform. Also, models need to be able to endogenously determine new infrastructure development as new pipelines and expansion of existing ones are underway. For models to be a valid representation of current trends, they need to be calibrated to up-to-date conditions, in particular focusing on new capacity investment and the shift of regional trade patterns, as the natural gas market is continuously changing. The main goal of this effort is to present a model with these features, entitled the North American Natural Gas Model (NANGAM). We use NANGAM to study the impacts (e.g., new capacity built and change of flows in the network) of the Mexican energy reform on North America. NANGAM is a long-term partial-equilibrium model of the natural gas markets of Canada, the U.S., and Mexico. This is the first natural gas model that considers a high granularity in terms of geography (regions) and infrastructure (pipelines and supply) in North America, specifically for Mexico. Details of NANGAM are presented in Section 2. The main characteristics that make NANGAM suitable for this study are:

1. Endogenous infrastructure capacity expansion for all players (suppliers, storage operators, and arc operators) with better representation of the cost (supply) function.
2. Representation of the Mexican gas market by five consumption-production regions and infrastructure (pipelines and supply).
3. Up-to-date data used for calibration and base case scenario (e.g., shale gas boom, higher Mexican demand and imports, and increased projected natural gas production in Alaska).

1.1. Literature review: natural gas models for North America and the world

Existing models in the literature, while also being large-scale numerical applications, do not consider a sufficiently high level of detail of the infrastructure in North America, in particular for Mexico. For instance, one of the first natural gas models with focus in North America is the Gas Trade Model [GTM, 14]. The GTM was developed in the late 80's and considered Mexico as a single demand-production node. A large scale linear complementarity model for North America was presented in Ref. [15]. Even though the model has a high granularity of the U.S., the Mexican gas market was not taken into account. Also, this model did not consider endogenous capacity expansion decisions. The World Gas Model (WGM) described in Refs. [16], an extension of the work developed in Refs. [15,17], considered six regions in the U.S and treated Mexico as a single region. The authors in Ref. [18] used the WGM to study the impact of a shale producer having market power. Authors expanded the number of regions in the U.S. to 10, but kept Mexico and Canada as single regions. A model similar in scope to the WGM is the Global Gas Model [GGM, 19], but it includes more features and functionality with regard to stochastic scenarios. The Rice World Gas Trade Model (RWGTM) [20] attempted to better describe Mexico. However, only two regions were considered. Of all these models, none of them was developed to study policy implications and regulations in Mexico. Their particular focus was on the U.S. or global market.

Table 1
Comparison of models.

Model	Mexican regions	Capacity expansion	Market power
NANGAM	Five regions	Endogenous[a]	Yes
GTM [14]	Single node	None	No
Gabriel et al. [15]	Not considered	None	Yes
WGM [16]	Single node	Endogenous[b]	Yes
GGM [19]	Not considered	Endogenous[b]	Yes
GaMMES [21]	Not considered	Endogenous	Yes
FRISBEE [22]	Not considered	Endogenous[c]	No
GASMOD [24]	Not considered	Endogenous	Yes
GASTALE [25,26]	Not considered	Endogenous[c]	Yes
ICF GMM	Not considered	Exogenous	No

[a] Endogenous capacity expansion is modeled for all market participants.
[b] Endogenous capacity expansion is not considered for natural gas suppliers.
[c] Endogenous capacity expansion is considered for natural gas suppliers only.

The Gas Market Modeling with Energy Substitution (GaMMES) developed in Ref. [21] (a generalized Nash Cournot model) did consider endogenous decisions for capacity expansion and long-term contracts but it was used to study the northwestern European natural gas trade. The FRISBEE model [22] is a recursively dynamic partial-equilibrium model with 13 global regions. However, Mexico is not considered among them. The model developed in Ref. [23] represents Europe by 15 nodes, of which eleven are European union (EU) member states (or aggregates thereof). The rest of the world is aggregated into thirteen nodes by continent or major regions. Models that have a focus on the European market include GASMOD [24], GaMMES [21], described earlier, and GASTALE [25,26]. Other models with a European focus that analyze imperfect competition a la Cournot among gas producers include [27–29]. Finally, Gridnet (www.rbac.com) and ICFs Gas Market Model (ICF GMM[3]) offer high details on U.S. coverage, but are designed to support short- and medium-term decisions. See Table 1 for a summary of the most relevant models discussed here. A different comparison of gas market models can be found in Ref. [30].

As mentioned above, different models have been used to study the global and the North American gas market (e.g., [15–18,30]). However, all of these models treat Mexico as a single node, or exclude it completely. A model with a better representation of the Mexican natural gas industry and infrastructure is essential to study the implications of the Mexican energy reform on North America. For instance, to date, none of the models currently available can determine the regional implications of production capacity

[2] http://www.asea.gob.mx/?pageid = 9894.

[3] http://www.icfi.com/insights/products-and-tools/gmm.

Fig. 1. Mexican market regions. Source: U.S. Energy Information Administration, http://www.eia.gov/todayinenergy/detail.cfm?id=16471. Last accessed on 5/16/2016.

increases and pipeline investment in Mexico (considering that demand, production, investment, and transportation costs vary from one region to other within Mexico) that will likely reduce imports from the U.S. In contrast, NANGAM accounts for more details of the Mexican territory by considering five consumption/production market regions as well as more details regarding gas infrastructure (pipelines) network (see Fig. 1 and Section 3.2 for details). Another important feature that distinguishes NANGAM from other previous natural gas models is that NANGAM incorporates endogenous capacity expansion for all market participants (e.g., production and pipeline infrastructure) while using a logarithmic cost function for gas supply [31]. Also, NANGAM considers up-to-date data and projections (used for calibration) and hence it better represents recent developments due to the shale gas boom, especially in the U.S. (see details in Section 2).

Modifying existing models to account for these distinctions is a task that considers significant effort and intractable under some conditions. It is well known that the calibration procedure of complex large scale systems is not trivial, reaching a computational complexity of NP-complete [32]. In the scenario that re-calibrating a model is suitable, existing models need to represent new regions, in particular in Mexico. Access to data collection and correct representation of Mexico is also a complex task. Lastly, adding endogenous capacity expansion requires a reformulation of the mathematical structure of the models. Any changes in terms of infrastructure, regions representation, and mathematical formulation will also require further re-calibration.

The rest of the paper is organized as follows. Section 2 describes the details of the NANGAM model. The methodology for analysis (base case calibration data and alternative scenarios) are presented in Section 3. Results of the future scenarios are presented in Section 4. Concluding remarks are in Section 5.

2. The North American natural gas model

NANGAM[4] is a long-term partial-equilibrium model of the United States, Mexican, and Canadian gas markets. There are currently a total of 17 nodes, of which nine correspond to U.S. census regions (see Fig. 2), one node to Alaska,[5] two nodes to Canada (East and West), and five to Mexico (Northwest, Northeast, Interior-West, Interior, and South-Southeast, as shown in Fig. 1). Of the above mentioned nodes, there are 13 nodes with natural gas (shale and non-shale) 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. There are also storage facilities at each node in the U.S. and Canada. The model allows for endogenous infrastructure expansion, and is built in five year time-steps starting in 2010 up to 2040, considering three seasons (low, high, and peak) for each time-step. See Figs. 2 and 1 for a graphical depiction of the geographical regions considered in NANGAM for the U.S. and Mexico, respectively. Table 2 presents the pipelines within Mexico and the cross-border pipeles with the U.S.

NANGAM is built based on the MultiMod framework. MultiMod is a spatial and dynamic multi-period representation of the global energy value chain with endogenous investment in infrastructure capacity [23]. MultiMod represents a market equilibrium between non-cooperative actors in a Nash game, where each player seeks to maximize its individual profit. It allows to include several types of regulatory interventions in the context of climate change mitigation and energy policy (e.g., greenhouse gas emission constraints and taxes, fuel mix mandates, average emission intensity restrictions). MultiMod is formulated as a Mixed Complementarity Problem and can hence include Cournot or conjectural variations, market power for some or all suppliers, as well as use dual variables (i.e., prices) in the players' objective functions.

The current version of NANGAM is calibrated using up-to-date data from the U.S. Energy Information Administration (EIA), Annual Energy Outlook 2015, the Canadian National Energy Board, Mexican Secretary of Energy (Secretaría de Energía) SENER, and PEMEX (National Mexican natural gas producer). Details about the

[4] NANGAM is written in GAMS and data can be accessed using Microsoft Access. The model will be available to all researchers free of charge under a creative commons license.

[5] Alaska technically belongs to census region 9. However, it was considered that Alaska belongs to a single region in order to model its own increasing supply projections.

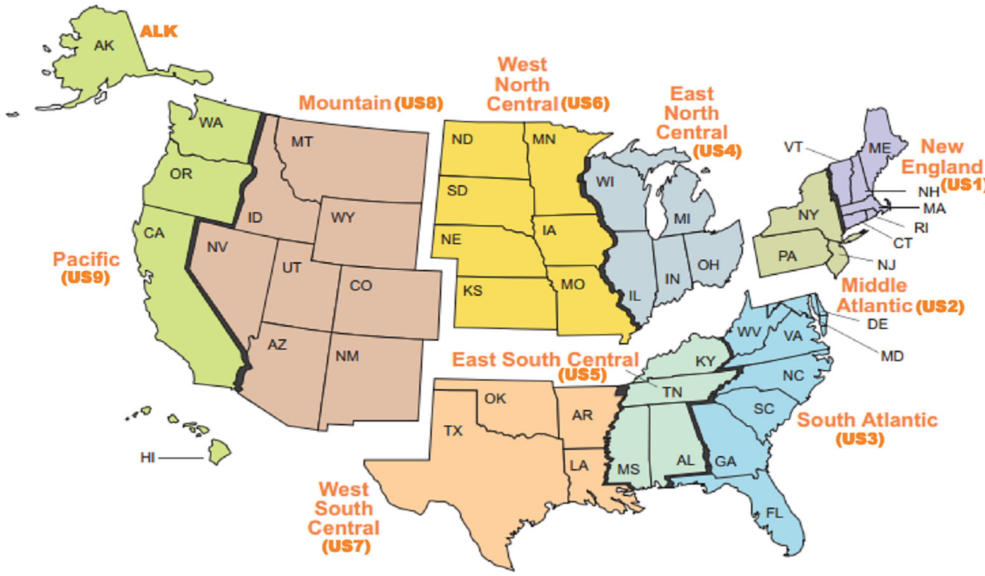

Fig. 2. U.S. census regions. Source: Annual Energy Outlook 2015.

Table 2
Pipelines among regions in Mexico and the U.S.

Pipelines
Northeast ↔ South-Southeast
South-Southeast ↔ Interior
Interior ↔ Interior-West
US7 ↔ Northeast
US8 ↔ Northwest

NANGAM data set are presented in Section 3. Note that we aim at matching supply and demand levels at each node for the base year (2010) and projections (until 2040) in the calibration process. The calibration procedure is performed automatically for the demand side using a searching procedure (iteratively, updating the willingness to pay of consumers). Calibration for all other players is performed manually by adjusting cost and capacity parameters.

The players in the natural gas supply chain (in NANGAM) include suppliers (upstream), service providers and infrastructure operators (midstream) such as arc operators for pipelines and storage operators, and a final demand (downstream) for an aggregated consumption sector. Each player in NANGAM is profit maximizer. Suppliers produce and sell natural gas. A logarithmic cost function is assumed for suppliers as it better models the costs associated to produce natural gas with low resources. Arc operators allocate possibly congested transmission capacity (based on an implicit auction). This player can be interpreted as a transmission system operator. Storage operators allow suppliers to shift natural gas between yearly seasons (time slices). Final demand for natural gas is modeled via a linear inverse demand curve by sector. For simplicity, NANGAM assumes an aggregated final demand sector. Different sectors (residential, industrial, energy, etc) will be addressed in future research. Also, the mathematical structure of NANGAM allows for extension to multi-objective programming to determine policies for energy and climate market, as studied in Refs. [33–35]. Further modeling details and the mathematical formulation can be found in Appendix A.

3. Methodology for analysis: base case calibration and alternative scenarios

In this section, the data sources utilized to calibrate NANGAM with are described as well as projections for U.S., Canada, and Mexico. Calibration serves as a validation step for NANGAM, as it replicates the market outputs (e.g., behavior of supplier) by matching the predictions performed by NANGAM with historical and projected supply and consumption. The data set is available upon request (Microsoft Access format). We then proceed to develop four future scenarios to analyze the impact of the Mexican energy reform.

3.1. Projections for the U.S.

Data for production and demand projection in the U.S. were obtained from the Annual Energy Outlook 2015 [EIA2015, 3] (hereafter AEO2015). Natural gas production in the United States increased by 35% from 2005 to 2013, with the natural gas share of total U.S. energy consumption rising from 23% to 28%. The increase in production resulted mainly from the development of shale gas resources in the Lower 48 states and Alaska. According to the AEO2015 reference case, more than 50% of the total increase in shale natural gas production comes from the Haynesville (southwestern Arkansas, northwest Louisiana, and East Texas) and Marcellus (Pennsylvania, west Virginia, southeast Ohio, and upstate New York) formations. Natural gas production in the U.S. increased from 24.4 Tcf in 2013 to 35.5 Tcf in 2040, a 45% increase. Growth in tight gas, federal offshore, and onshore Alaska production also contributes to overall production growth over the projection period. Fig. 3 shows the projection by census regions in the U.S. (see Fig. 2 for the division of the census regions considered by NANGAM), where the US7, US8, and US2 are the main producers (representing the Haynesville and Marcellus formations). Also, starting in 2030, there is an increase in Alaska's production (27.4 MMcm/d in 2010 to 89.21 MMcm/d in 2040). Natural gas demand increases in the U.S. from 1785.35 in 2010–2183.78 MMcm/d in 2040, with the highest demand being in US7 (512.02 MMcm/d in 2040).

Future dry natural gas production depends primarily on the size and cost of tight and shale gas resources, technology improvements, domestic natural gas demand, and the relative price of oil. According to the AEO2015, United States becomes a net exporter of natural gas in 2017, driven by increased pipeline exports to Mexico, reduced imports from Canada, and LNG exports.

3.2. Projections for Mexico

In order to expand the granularity of the Mexican market and infrastructure, information regarding market regions (with its production and consumption levels), capacities, and pipelines was needed. Information for the market regions were obtained from SENER (see Fig. 1 for a depiction of the market regions) [*Prospectiva de Gas Natural y Gas L.P. 2013–2027* 10]. Data for pipelines and capacities were obtained from the U.S. Energy Information Administration EIA, and Pemex [36].

The Northwest and Northeast regions receive all natural gas imports. The Northwest area does not have access to natural from other Mexican regions as pipelines are not existing or are under development [7]. Natural gas flowing south to Mexico has grown substantially since 2010. Exports to Mexico are projected to continue increasing according to the AEO2015, mainly because increasing Mexican production is not expected to keep pace with the country's growing demand. Demand is to increase 3.6% yearly [10] through 2027. The electric power generation is the main sector and accounts for 75% of consumption growth between 2012 and 2027 (57% of the national natural gas demand). The demand increase is shown in Fig. 4, where natural gas production is 2040 is approximately half of the national demand. Consumption growth in natural gas is projected for all five regions. The Northeast region (MEX2) is expected to become the largest consumer, overtaking the south-southeast region, accounting for 28.8% of the total natural gas demand. The south-southeast will represent 25% of the national demand.

Offshore oil platforms operated by Pemex in the South-Southeast account for 75% of the country's domestic natural gas production [7]. With the opening of Mexico's energy industry, shale development has been one of the areas gathering interest. Some gas formations in northern Mexico are attractive to U.S. companies due to their proximity to developments in Texas [6]. As an example, the Burgos Basin in the Northeast is an extension of the Eagle Ford Basin, a development in Texas with good recovery rates.

With the energy reform, which aims at addressing some of the above mentioned issues, the Peña Nieto government has optimistic projections, including a yearly GDP growth of 1%, lower energy prices, and 500,000 new jobs. Estimates indicate that foreign investments in the country are to increase $20 billion each year in 2016 and 2017 [6]. These investments are expected to take advantage of major unexplored reserves, particularly in the Gulf of Mexico [37].

3.3. Projections for Canada

Projections for production and demand of natural gas in Canada were obtained from the Canadian National Energy Board (NEB).

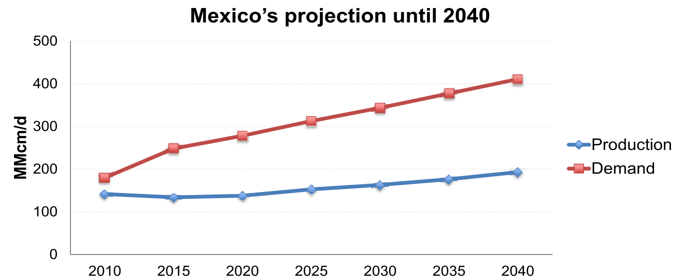

Fig. 4. Mexican projections used for NANGAM calibration. Data from SENER, PEMEX, and EIA.

Canada is the worlds fifth largest producer of natural gas and accounts for around 5% of global production. Natural gas production in Canada is predominantly from the Western Canadian Sedimentary Basin (WCSB) in British Columbia, Alberta, and Saskatchewan, although offshore natural gas is also produced from Nova Scotia and smaller amounts are produced in Ontario, New Brunswick, and Nunavut [38].

Fig. 5 shows the projection used in NANGAM for production and demand of natural gas in Canada. Declines in natural gas prices have reduced drilling activity for conventional gas in the WCSB in recent years. However production is expected to ramp up continuously until 2035, led by higher levels of tight and shale gas development. Demand for natural gas grows at an annual average rate of 1.7% over the projection period. This is an increase of over 5.20 Bcf/d over the projection period, with the largest increases in the industrial and power generation sectors [38].

3.4. Scenarios for Mexico's production and demand of natural gas

The Mexican energy reform is likely to change the future landscape of natural gas in North America. The Mexican energy reform mainly seeks to create economic incentives to address the high demand levels and to increase production of natural gas. Even though projection presented in the AEO2015 or NEB accounted for high demand of natural gas from Mexico, there is still huge uncertainty regarding future infrastructure investments. Therefore, in order to analyze the impact of different levels of capacity expansion and demand levels, we developed four scenarios (see Table 4 for a summary) which we compare against the reference case built based on our calibration to the data described previously. The following scenarios assess the impact of the success (higher resources and production of natural gas than the reference data) or failure (similar or lower levels of natural gas production than the reference data).

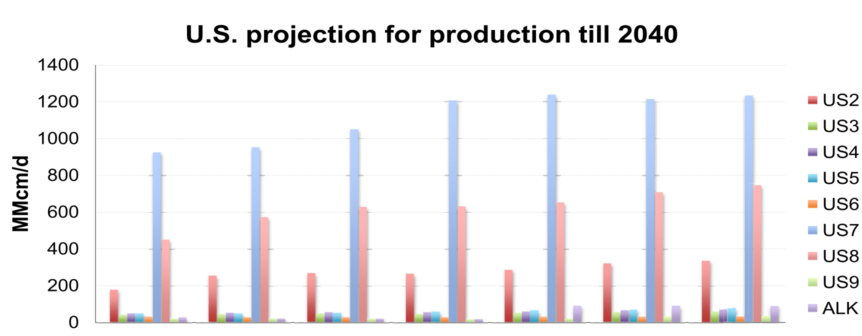

Fig. 3. Production projections based on the AEO2015 used for NANGAM calibration.

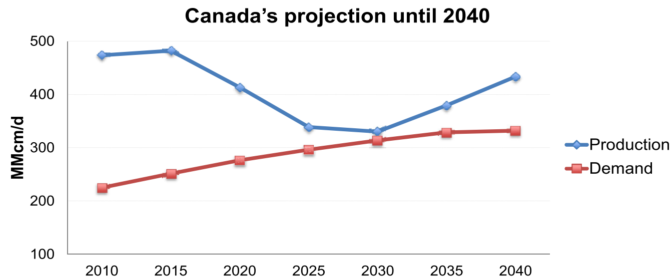

Fig. 5. Canadian projections used for NANGAM calibration. Data from the Canadian National Energy Board (NEB).

Table 3
Natural gas data sets.

Data source	Reference
U.S. Energy Information Administration EIA	[7,8,43]
Natural Gas Gross Withdrawals and Production (Dry Production)	
Pipeline projects	
Annual Energy Outlook 2015	[3]
Table: Natural Gas Supply, Disposition, and Prices (Dry Production)	
National Energy Board, NEB Canada's Energy Future 2013	[38]
Supply and Demand Projections to 2035 End-use Energy Demand	
Secretaria de Eneria SENER, Prospectiva de Gas Natural y Gas L.P. 2013-2027	[10]
Gas y Petroquimica Basica Pemex	[36]
Condiciones Generales para la Prestacion del Servicio de Transporte	

- Reference/base scenario) We calibrate NANGAM to the historical data and projections obtained from sources presented in Table 3. The calibration process creates the base scenario.
- Scenario 1) *High demand in Mexico without rise in production (failure of the energy reform and increasing demand in MEX2)*: As described in Section 3.2, there is an expected increase of demand for natural gas in Mexico, mainly at the Northeast (MEX2) region. Hence, we study the case in which demand increases in this region along with a lower increasing demand in the rest of regions. For MEX2, we assumed a rate of 15% increase in 2020 and 5% yearly based on 2020 thereafter. For the rest of the regions, we considered an increase of 10% starting on 2020 and 5% yearly based on 2020 thereafter. The rise of demand is assumed to be caused by the increasing demand from the energy sector. Production is considered to remain the same as in the reference scenario.
- Scenario 2) High demand and low resources in Mexico (failure of the energy reform, Burgos and Sabinas are more geologically complex than anticipated): In this scenario we assume that demand levels increase as in Scenario 1. However, as mentioned earlier, there is still uncertainty regarding future levels of infrastructure investments in Mexico, and hence, if imports from U.S. will still be a major source to satisfy increasing demand. To study this phenomena, we consider a yearly increase of production cost (for Mexican suppliers) of 5% starting in 2015. This scenario seeks to represent the case in which the energy reform does not attract private investors due to increasing cost generated by the complexity of extraction of natural gas at Burgos and Sabinas basins (northeast and southeast regions).
- Scenario 3) *High resources in Mexico (success of the energy reform)*: Contrary to Scenario 2, where we assume that capacity expansion does not take place as expected, Scenario 3 considers that the energy reform achieves economic incentives that expand infrastructure capacity. In particular in the northern region as U.S. companies may take advantage of developments close to Texas [6]. As described earlier, the Burgos Basin in the Northeast is an extension of the Eagle Ford Basin, a development in Texas with good recovery rates. To model this scenario, a 10% reduction in investment costs of production capacity at both Northeast and Southeast regions is considered. Also, there is a 5% reduction in production cost starting in 2020. Demand projections are kept as the reference values.
- Scenario 4) *High demand and high resources in Mexico (success of the energy reform)*: In this scenario we study the case in which infrastructure capacity and demand increase compared to the base case scenario. This scenario is of interest as both higher natural gas production (off-shore in the Southeast and shale in the Northeast) and demand (mainly from the electric sector) are expected. We assumed an increase demand for natural gas demand as in Scenario 1 as well as high resources as in Scenario 3.

Table 4
Natural gas market scenarios.

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
High demand	Yes	Yes	No	Yes
High resources	No	No	Yes	Yes
Low resources	No	Yes	No	No

4. Results and discussion

NANGAM is used to simulate and study the four scenarios described in Table 4. Remember that NANGAM is calibrated to match the data sets described earlier for U.S., Canada, and Mexico, for the considered horizon (2010 through 2040).

Private pipelines and pipelines owned by PGPB[6] (NANGAM does not differentiate between private and public pipelines) in the Northwest and Northeast regions transport all natural gas imports from the U.S (see Fig. 1). We focused our attention on the supply at the region US7 (Texas mainly), as it is the main producer of natural gas with direct pipelines to the Northwest (MEX2) region. According to the AEO2015 reference case, more than 50% of the total increase in shale gas production comes from the Haynesville formation. Fig. 6 shows the production levels over the time horizon for all scenarios for US7. Differences of up to 303 MMcm/d (1364 MMcm/d - 1061 MMcm/d) are observed from the scenarios of High demand and low resources in Mexico compared with the scenario of only high resources in Mexico (demand is the same as the reference case). Clearly, in the case where incentives are not enough for private investor to develop resources Mexico (modeled as higher production and investment costs), the increasing demand (mainly in the Northeast region) is accompanied with increasing supply in US7.

Capacity production constraints play a significant role in the determination of the natural gas supply. NANGAM allows for endogenous production capacity investment together with logarithmic cost functions for natural gas.[7] Figs. 7 and 8 show the capacity investment levels in MMcm/d (cumulative over the time horizon) for all scenarios for US7 and Mexico, respectively.

[6] The majority of pipelines were owned by PGPB. Pipelines have recently been passed on to *CENEGAS*, the new public agency in control of distribution of natural gas in Mexico.

[7] The study presented in Ref. [39] provides a proof that combining endogenous investment decisions and a logarithmic cost function yields a convex minimization problem.

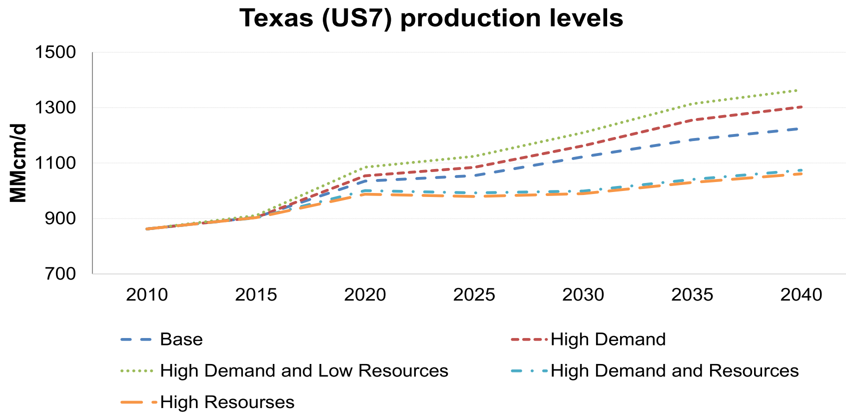

Fig. 6. NANGAM results: US7 supply of natural gas for each scenario.

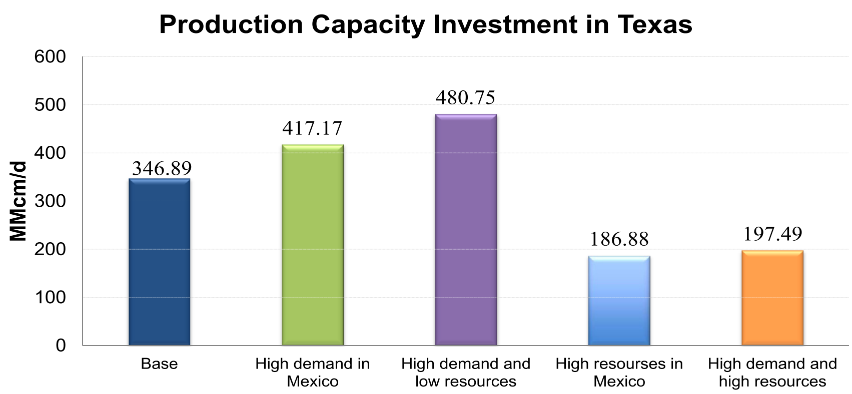

Fig. 7. Production capacity investment in U.S. census region 7.

Region US7 is significantly impacted by different scenarios in Mexico. Investment capacity is higher than in the reference case for scenarios with low resources in Mexico and high demand. A different pattern is observed in the cases where production and investment costs are lowered in Mexico. We lowered costs to attract private investors, which are expected to develop the infrastructure needed to spur natural gas production in the Northeast, South-Southeast and Gulf of Mexico [8,10].

As described above, expansion in production capacity in the Mexican regions is higher for the scenarios of high resources, which results in lower levels of capacity investment in US7. Note that Fig. 8 considers the combined investment of the Northeast and South-Southeast regions. Creating incentives that lower production and investment costs in Mexico will likely result in the development of the infrastructure and resources needed to decrease natural gas imports from United States. Table 5 presents these changes in imports from the U.S. and among nodes within Mexico for all scenarios. The changes are calculated as the deviation from the base or reference scenario (relative changes from the base scenario).

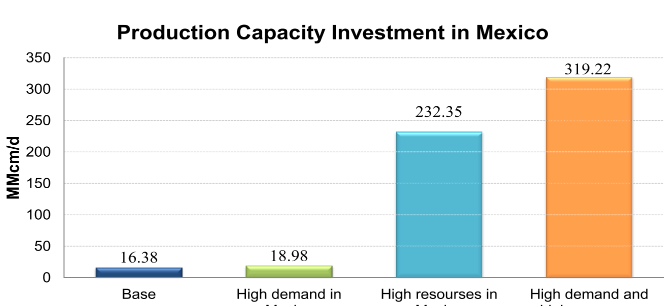

Fig. 8. Production capacity investment in Mexico (MEX2 and MEX5 combined).

As expected, higher demand in Mexico increases flows (imports) from US7 into the Northeast (MEX2) region. The increase over the horizon (2010–2040) accounts to 25% (see Table 5 for relative changes from base scenario). The increasing imports are accomplished by increased production (6% higher relative to the baseline scenario in 2040) in US7, as it was previously shown in Fig. 6. The relative changes in production for all nodes are presented in Tables 6 and 7. When there are low resources in the Northeast and South-Southeast, there is a further increase of imports, reaching a 53% growth, along with a 11% higher production in US7 in 2040 (see Table 6). On the other hand, if high resources of natural gas are available in Mexico, flows from US7 decline by 61% and production is reduced by 13% in 2040.

It was also noted that consumption levels in the U.S. are not highly impacted, whereas prices in the U.S. increased/decreased by 1–3% depending on the scenario. If natural gas production capacity is lower than in the base case, investment in pipelines from Texas and New Mexico will increase flows from the U.S. to satisfy increasing demand. Flows will further increase if there is no infrastructure investment (via incentives on reduced cost in our model). In this case, it was shown that flows from US7 to MEX2 increased by around 53% (see Table 5, high demand and low resources scenario). However, flows from US7 to connected U.S regions are reduced. Hence, we observed higher natural gas supply in nodes that are connected to US7, as shown in Table 6. Particularly, nodes US4, US5, and US6 are the most affected. Alaska's production and flows into US8 are also increased by 4% (increase starts in 2020) and 3%, respectively. Incoming flows from Alaska to US8 help to

Table 5
Relative changes from base scenario: Natural gas flows.

	High demand and low resources	High demand and resources	High demand	High resources
MEX20020 → MEX5	1.58	0.25	1.22	0.23
MEX5 → MEX4	1.11	1.13	1.11	1.01
MEX4 → MEX3	1.19	1.21	1.19	1.01
US7 → MEX2	1.53	0.39	1.25	0.33
US8 → MEX1	1.18	1.18	1.18	1.00
US7 → US4	0.99	1.02	0.99	1.02
US7 → US5	0.96	1.09	0.99	1.09
US7 → US6	0.98	1.04	0.99	1.04
ALK → US8	1.03	0.98	1.05	0.95

Table 6
Relative changes from base scenario: Natural gas production in scenario of low resources in Mexico.

	2010	2015	2020	2025	2030	2035	2040
ALK	**1.00**	**1.00**	**1.01**	**1.02**	**1.04**	**1.04**	**1.04**
CAE	1.00	1.00	1.00	1.00	1.01	0.99	1.00
CAW	1.00	1.01	1.00	1.00	1.01	1.00	1.00
US2	1.00	1.02	1.01	1.00	1.00	1.00	1.00
US3	1.00	1.00	1.00	1.00	1.01	1.01	1.01
US4	**1.00**	**1.01**	**1.02**	**1.02**	**1.03**	**1.02**	**1.03**
US5	**1.00**	**1.01**	**1.05**	**1.07**	**1.08**	**1.07**	**1.09**
US6	**1.00**	**1.01**	**1.06**	**1.07**	**1.09**	**1.08**	**1.10**
US7	**1.00**	**1.01**	**1.05**	**1.07**	**1.08**	**1.11**	**1.11**
US8	1.00	1.01	1.01	1.01	1.01	1.01	1.01
US9	1.00	1.00	1.01	1.02	1.01	1.01	1.01
MEX2	**1.00**	**0.83**	**0.87**	**0.82**	**0.78**	**0.71**	**0.75**
MEX5	**1.00**	**0.82**	**0.65**	**0.61**	**0.54**	**0.45**	**0.49**

Numbers in bold are to highlight regions with a significant variation from the reference scenario.

Table 7
Relative changes from base scenario: Natural gas production in scenario of high resources in Mexico.

	2010	2015	2020	2025	2030	2035	2040
ALK	**1.00**	**1.00**	**1.00**	**0.98**	**0.95**	**0.94**	**0.94**
CAE	1.00	1.00	1.00	1.00	1.00	0.99	0.97
CAW	1.00	1.00	1.00	0.99	0.99	0.99	0.98
US2	1.00	0.99	0.99	0.99	0.99	0.99	0.99
US3	1.00	1.00	1.00	1.00	1.01	1.00	1.00
US4	**1.00**	**1.00**	**0.99**	**0.97**	**0.97**	**0.97**	**0.97**
US5	**1.00**	**1.00**	**0.98**	**0.91**	**0.91**	**0.92**	**0.90**
US6	**1.00**	**1.00**	**0.97**	**0.90**	**0.90**	**0.91**	**0.89**
US7	**1.00**	**1.00**	**0.95**	**0.93**	**0.88**	**0.87**	**0.87**
US8	1.00	0.99	0.99	0.99	0.99	0.99	0.99
US9	1.00	1.00	1.00	0.99	1.01	1.01	1.01
MEX2	**1.00**	**0.99**	**1.13**	**1.66**	**2.39**	**2.44**	**2.49**
MEX5	**1.00**	**1.09**	**1.56**	**1.88**	**2.20**	**2.44**	**2.53**

Numbers in bold are to highlight regions with a significant variation from the reference scenario.

address increasing demand in the MEX1 region, which receives all the natural gas from the U.S. due to limited pipeline infrastructure within Mexico. Also, Alaska's productions help to address reduced flows from US7 to US4, US5, and US6. Opposite effects are observed in the case where investment and production costs are lowered in Mexico (for production regions MEX2 and MEX5), as in scenario 3 (high resources). In this case, natural gas production increases significantly in Mexico by 2040, whereas US4 through US8 and Alaska reduced their supply levels. The region US7 is the most affected, reducing its supply by 13% in 2035 and 2040. Even though supply was reduced in US7, its flows into US4, US5, and US6 are increased up to 9%, hence, lowering production in those regions (see Tables 5 and 7). In the case of Alaska, production is reduced by 6% in 2040 as well as the flows, which were decreased by 5% in the case of high resources and 2% in the scenario of high demand and resources in Mexico.

5. Conclusions and outlook

According to projections of the 2015 Annual Energy Outlook [3], the U.S. is expected to become a net exporter of fossil fuels due to strongly increasing shale gas and oil production. Natural gas, in particular, has gained significant importance due to its low carbon emissions and competitive prices compared to alternative and other fossil-fuel energy sources [40,41]. Mexico, through its ongoing energy reform, seeks to spur the development of gas resources by opening the market to private investors and hence reduce the increasing gas imports to northern Mexican regions from the U.S. Assessing the economic and policy implication of these new trends requires models with updated energy projections and higher granularity for Mexico. This paper presents the dynamic partial-equilibrium model NANGAM, which tackles all these issues.

In the current study, NANGAM is calibrated using the most recent data and projections. We assess the impacts of the Mexican energy reform on North America under different scenarios. We found that, in order to spur natural gas supply, Mexico highly depends on economic incentives that reduce barriers to infrastructure investment and keep production costs at competitive levels. As shown using NANGAM, an expansion of the Mexican gas market will reduce dependency on U.S. pipelines imports. NANGAM endogenously predicts investment strategies in Mexico that are sufficient to reduce imports to the Northeast region of Mexico. Hence, a corresponding reduction of production levels in the U.S. is also observed, mainly in Texas and Louisiana (census region US7). Reduced exports to Mexico results in higher flows within the U.S., as production volumes from US7 to Mexico are redirected eastwards and to the Midwest (in particular census regions US4, US5, and US6).

In an alternative scenario (scenario 2 in Table 4: low resources and high demand), we assume that the incentives created by the energy reform are not sufficient to generate the required capacity expansion in Mexico to reduce import dependence. As a consequence, growing natural gas demand in Mexico is satisfied by further increasing supply from US7. As flows from US7 to Mexico grow, a ripple effect of higher supply in Alaska, US4, US5, and US6 is observed. In this scenario, Alaska plays a key role in supplying gas to the Northwest region. The success of the Mexican energy reform will therefore play an important role in the further development of the natural gas sector in North America. It will determine whether the current flow of natural gas from north to south will prevail, or whether Mexico will increase its self-sufficiency with regard to natural gas, reversing the current flow pattern across the continent.

In any case, the Mexican energy reform will only be one step in an ongoing overhaul of the North American energy landscape: the technological revolution facilitating the shale gas boom is the pull factor in the current transformation. On the push side are growing concerns over climate change and emissions from fossil fuel combustion, whether in power generation, heating or transportation. The emission reduction targets recently announced by the U.S. EPA and the creation of the *Agencia Nacional de Seguridad Industrial y de Proteccion al Medio Ambiente del Sector Hidrocarburos* (ASEA), in charge of designing environmental regulations for the oil and gas sector, are examples of initiatives to manage the transition towards a clean and sustainable energy system.

This manuscript introduced NANGAM and used it to analyze new energy regulations in Mexico. We plan to extend the modeling framework of NANGAM to account for stochasticity and conflicting objectives in energy and climate policies via multi-objective optimization [33,35]. A stochastic framework is needed to tackle the ambiguity of available resources, technological developments, and constant environmental regulations that change the direction of the energy sector. These ambiguities create uncertainty in the choices that market participants will consider when making long-lived capacity investment decision. Also, we aim at integrating NANGAM with other energy models being developed, including electricity and oil models in order to develop a more comprehensive model of the energy sector. These models are important because changes in, for instance, oil prices change the dynamics of other energy sectors. Suppliers exerting market power and strategic behaviors from production of various form of gas (e.g., conventional and unconventional), different demand sectors, and environmental regulations (e.g., caps on emissions, taxes, quotas) are also in the outlook of research using NANGAM.

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Appendix A. Optimization problem for players in NANGAM

A.1. Definition of sets and mappings

Table 8
Sets, mappings, and subsets.

Sets	
$y \in Y$	Years
$h \in H$	Hours/days/seasons/representative periods (time slices)
$v \in V$	Loading cycles of storage (grouped time slices for injection and extraction)
$s \in S$	Suppliers
$n, k \in N$	Nodes (spatial disaggregation)
$d \in D$	Final demand sectors
$a \in A$	Transportation arcs
$o \in O$	Storage operators/technologies
$e, f \in E$	Energy carriers/fuels
$r \in R$	Regions
$g \in G$	Emission types (greenhouse gases)
Mappings and subsets	
$n, k \in N_r$	Node-to-region mapping
$r \in R_n$	Region-to-node mapping (any node can be part of several regions)
$a \in A^+_{ne}$	Subset of arcs ending at node n transporting fuel e
$a \in A^-_{ne}$	Subset of arcs starting at node n transporting fuel e
$e \in E^A_a$	Fuel(s) transported via arc a
$n^{A+}(a)$	End node of arc a (singleton)
$n^{A-}(a)$	Start node of arc a (singleton)
$e^O(o)$	Fuel stored by technology o (singleton)
$o \in O^E_e$	Subset of technologies storing fuel e
$h \in H^V_{vo}$	Mapping between loading cycle and hour/day/season/time slice
$v^H(h,o)$	Loading cycle of hour/day/season/time slice (singleton)
dur_h	Relative duration of hour/day/season h (with $\sum_h dur_h = 1$)

A.2. The supplier

Each natural gas supplier maximizes its profits from selling gas, considering costs for production, transportation and transformation.[8] Losses during production, transportation and transformation are considered by the supplier in the nodal mass balance constraint. Suppliers may behave as competitive (i.e., price-taking behavior) or act as a Cournot player; the parameter $cour^S$ is 1 in the latter case, and 0 in the former. Intermediate *conjectural variations* (CV) values are also possible. See Ref. [42] for a discussion on the (difficulties regarding the) interpretation of using CV as "exerting market power".

Table 9
Parameters and variables for the suppliers.

Parameters	
df^S_{ys}	Discount factor of supplier s
$cour^S_{ysnd}$	Cournot market power parameter of supplier s at node n regarding sector d
$cost^P_{yhsne}(\cdot)$	Production cost function faced by supplier s at node n for fuel e
lin^P_{ysne}	Linear term of the production cost function ($lin^P \geq 0$)
qud^P_{ysne}	Quadratic term of the production cost function ($qud^P \geq 0$)
gol^P_{ysne}	Logarithmic (Golombek) term of the production cost function ($gol^P \geq 0$)
cap^P_{ysne}	Gross initial production capacity
avl^P_{yhsne}	Availability factor of production capacity
exp^P_{ysne}	Production capacity expansion limit
inv^P_{ysne}	Production capacity expansion (per-unit) costs
$dep^P_{yy'sne}$	Production capacity expansion depreciation factor
hor^P_{sne}	Production horizon (reserves)
$loss^P_{sne}$	Loss rate during production of fuel e at node n
ems^P_{ysneg}	Emission of type g during production of fuel e at node n by supplier s
Variables	
q^P_{yhsne}	Quantity produced of fuel e by supplier s at node n
q^A_{yhsae}	Quantity transported through arc a
q^{O-}_{yhsno}	Quantity injected into storage o
q^{O+}_{yhsno}	Quantity extracted from storage o
q^D_{yhsnde}	Quantity sold to final demand sector d
z^P_{ysne}	Expansion of production capacity
α^P_{yhsne}	Dual for production capacity constraint
α^O_{yvsno}	Dual for injection/extraction constraint
γ^P_{sne}	Dual for production horizon constraint
ζ^P_{ysne}	Dual for production capacity expansion limit
ϕ_{yhsne}	Dual for mass-balance constraint

$$\begin{aligned}\max_{\substack{q^P,q^A,q^C \\ q^{O-},q^{O+},q^D,z^P}} \sum_{\substack{y\in Y,h\in H \\ n\in N,e\in E}} df^S_{ys} dur_h \Bigg(\sum_{d\in D} \Big[cour^S_{ysnd} \Pi^D_{yhnde}(\cdot) + \Big(1 \\ - cour^S_{ysnd}\Big) p^D_{yhnde} \Big] q^D_{yhsnde} - cost^P_{yhsne}(\cdot) - \sum_{a\in A^+_{ne}} p^A_{yhae} q^A_{yhsae} \\ - \sum_{o\in O^E_e} \left(p^{O-}_{yhno} q^{O-}_{yhsno} + p^{O+}_{yhno} q^{O+}_{yhsno} \right) - \sum_{g\in G} p^G_{yng} ems^P_{ysneg} q^P_{yhsne} \\ - inv^P_{ysne} z^P_{ysne} \Bigg)\end{aligned} \tag{1a}$$

[8] Note that emissions cost are not studied in the current version of NANGAM. However we still provide the complete mathematical formulation for NANGAM, including emissions cost for each player.

$$st \quad q^P_{yhsne} \le avl^P_{yhsne}\left(cap^P_{ysne} + \sum_{y'<y} dep^P_{y'ysne} z^P_{y'sne}\right) \quad \left(\alpha^P_{yhsne}\right) \tag{1b}$$

$$\sum_{h\in H^V_{vo}} dur_h q^{O+}_{yhsno} = \sum_{h\in H^V_{vo}} dur_h\left(1 - loss^{O-}_o\right) q^{O-}_{yhsno} \quad \left(\alpha^O_{yvsno}\right) \tag{1c}$$

$$\left(1 - loss^P_{sne}\right) q^P_{yhsne} - \sum_{d\in D} q^D_{yhsnde} + \sum_{a\in A^+_{ne}} \left(1 - loss^A_{ae}\right) q^A_{yhsae} - \sum_{a\in A^-_{ne}} q^A_{yhsae} + \sum_{o\in O^E_e}\left(q^{O+}_{yhsno} - q^{O-}_{yhsno}\right) = 0 \quad \left(\phi_{yhsne}\right) \tag{1d}$$

$$z^P_{ysne} \le exp^P_{ysne} \quad \left(\zeta^P_{ysne}\right) \tag{1e}$$

$$\sum_{y\in Y, h\in H} dur_h q^P_{yhsne} \le hor^P_{sne} \quad \left(\gamma^P_{sne}\right) \tag{1f}$$

The production cost function extends the one proposed by Refs. [31], which yields the marginal cost function given below (Equation 2(a)–(c)). For conciseness, $\widehat{cap}^P_{yhsne}$ defines the available capacity including prior expansions as defined in Equation (1b).

$$cost^P_{yhsne}(\cdot) = \left(lin^P_{ysne} + gol^P_{ysne}\right) q^P_{yhsne} + qud^P_{ysne}\left(q^P_{yhsne}\right)^2 + gol^P_{ysne}\left(\widehat{cap}^P_{yhsne} - q^P_{yhsne}\right)\ln\left(1 - \frac{q^P_{yhsne}}{\widehat{cap}^P_{yhsne}}\right) \tag{2a}$$

$$\frac{\partial\, cost^P_{yhsne}(\cdot)}{\partial\, q^P_{yhsne}} = lin^P_{ysne} + 2qud^P_{ysne} q^P_{yhsne} - gol^P_{ysne}\ln\left(1 - \frac{q^P_{yhsne}}{\widehat{cap}^P_{yhsne}}\right) \tag{2b}$$

$$\frac{\partial\, cost^P_{yhsne}(\cdot)}{\partial z^P_{\hat{y}sne}} = gol^P_{ysne} avl^P_{yhsne} dep^P_{\hat{y}ysne}\left(\ln\left(1 - \frac{q^P_{yhsne}}{\widehat{cap}^P_{yhsne}}\right) + \frac{q^P_{yhsne}}{\widehat{cap}^P_{yhsne}}\right) \text{ if } \hat{y} < y \tag{2c}$$

$$\text{where} \quad \widehat{cap}^P_{yhsne} = avl^P_{yhsne}\left(cap^P_{ysne} + \sum_{y'<y} dep^P_{y'ysne} z^P_{y'sne}\right)$$

See Ref. [39] for a discussion that this yields a convex problem.

A.3. The arc operator

By assumption, there is one independent operator for each arc.[9] Each arc can carry multiple gas types, with a weight factor to align different units of measurements if necessary. For simplicity, the emission price is always paid at the starting node of the arc.

Table 10
Parameters and variables for the arc operator.

Parameters	
df^A_{ya}	Discount factor of arc operator a
trf^A_{yae}	Tariff for using arc a to transport fuel e
cap^A_{ya}	Gross initial capacity of arc a
exp^A_{ya}	Arc capacity expansion limit
inv^A_{ya}	Arc capacity expansion (per-unit) costs
$dep^A_{yy'a}$	Arc capacity expansion depreciation
wgt^A_{ae}	Weighting factor for distinct fuels in arc capacity
$loss^A_{ae}$	Loss rate during transportation through arc a of fuel e
ems^A_{yaeg}	Emission of type g during transportation through arc a of fuel e
Variables	
f^A_{yhae}	Quantity transported by the arc operator
z^A_{ya}	Expansion of arc capacity
τ^A_{yha}	Dual for arc capacity constraint
ζ^A_{ya}	Dual to arc capacity expansion limit
p^A_{yhae}	Market-clearing price of arc capacity

$$\max_{f^A, z^A} \sum_{y\in Y, h\in H} df^A_{ya} dur_h\left(\left(p^A_{yhae} - tr\, f^A_{yae}\right) f^A_{yhae} - \sum_{g\in G} p^G_{yng} ems^A_{yaeg} f^A_{yhae} - inv^A_{ya} z^A_{ya}\right) \tag{3a}$$

$$st \quad \sum_{e\in E^A_a} wgt^A_{ae} f^A_{yhae} \le cap^A_{ya} + \sum_{y'<y} dep^A_{y'ya} z^A_{y'a} \quad \left(\tau^A_{yha}\right) \tag{3b}$$

$$z^A_{ya} \le exp^A_{ya} \quad \left(\zeta^A_{ya}\right) \tag{3c}$$

Market clearing

$$\sum_{s\in S} q^A_{yhsae} = f^A_{yhae} \quad \left(p^A_{yhae}\right) \tag{4}$$

A.4. The storage operator

The storage operator allows suppliers to transfer natural gas between different seasons (low, high, peak) within a year. The capacity constraint (i.e., maximum quantity stored) is the summation over all gas injected over a loading cycle. We assume that all costs (losses and emissions) are accounted for during injection. The storage operator only assigns the available capacity. The balancing of gas that is extracted and injected (after losses) is modeled in the

[9] Given that the infrastructure service providers are price takers, this yields the same model functionality as when there would have been a single arc operator for all the arcs in the system.

supplier's optimization problem.

Table 11
Functions and parameters for the storage technology operator.

Parameters	
df^{O}_{yno}	Discount factor of operator of storage technology *o* at node *n*
trf^{O-}_{yno}	Tariff for injecting into storage technology *o*
cap^{O}_{yno}	Gross initial capacity for fuel stored in technology *o* over one loading cycle
exp^{O}_{yno}	Yearly storage capacity expansion limit
inv^{O}_{yno}	Yearly storage capacity expansion (per-unit) costs
$dep^{O}_{yy'no}$	Yearly storage capacity expansion depreciation
cap^{O-}_{yno}	Initial capacity for fuel injection into storage
exp^{O-}_{yno}	Storage injection capacity expansion limit
inv^{O-}_{yno}	Storage injection capacity expansion (per-unit) costs
$dep^{O-}_{yy'no}$	Storage injection capacity expansion depreciation
cap^{O+}_{yno}	Initial capacity for fuel extraction rate from storage technology *o*
exp^{O+}_{yno}	Storage extraction capacity expansion limit
inv^{O+}_{yno}	Storage extraction capacity expansion (per-unit) costs
$dep^{O+}_{yy'no}$	Storage extraction capacity expansion depreciation
$loss^{O-}_{o}$	Loss rate of storage technology *o* (accounted at injection)
ems^{O-}_{yog}	Emission of type *g* of storage technology *o* (accounted at injection)
Variables	
f^{O-}_{yhno}	Quantity injected into storage
f^{O+}_{yhno}	Quantity extracted from storage
z^{O}_{yno}	Expansion of yearly storage capacity
z^{O-}_{yno}	Expansion of injection capacity
z^{O+}_{yno}	Expansion of extraction capacity
ζ^{O}_{yno}	Dual to yearly storage capacity expansion limit
ζ^{O-}_{yno}	Dual to injection capacity expansion limit
ζ^{O+}_{yno}	Dual to extraction capacity expansion limit
p^{O-}_{yhno}	Market-clearing price for injection into storage
p^{O+}_{yhno}	Market-clearing price for extraction from storage
τ^{O}_{yvno}	Dual for capacity constraint of storage technology in loading cycle *v*
κ^{O-}_{yhno}	Dual for injection capacity constraint of storage technology
κ^{O+}_{yhno}	Dual for extraction capacity constraint of storage technology

$$\max_{\substack{f^{O-},f^{O+}\\ z^{O},z^{O-},z^{O+}}} \sum_{y\in Y,h\in H} df^{O}_{yno}dur_h\Bigg(\left(p^{O-}_{yhno}-tr\,f^{O-}_{yno}\right)f^{O-}_{yhno}+p^{O+}_{yhno}f^{O+}_{yhno} - \sum_{g\in G} p^{G}_{yng}ems^{O-}_{yog}f^{O-}_{yhno} - inv^{O}_{yno}z^{O}_{yno} - inv^{O-}_{yno}z^{O-}_{yno} - inv^{O+}_{yno}z^{O+}_{yno}\Bigg) \tag{5a}$$

$$st \sum_{h\in H^{V}_{vo}} dur_h f^{O-}_{yhno} \le cap^{O}_{yno} + \sum_{y'<y} dep^{O}_{y'yno}z^{O}_{y'no} \quad \left(\tau^{O}_{yvno}\right) \tag{5b}$$

$$f^{O-}_{yhno} \le cap^{O-}_{yno} + \sum_{y'<y} dep^{O-}_{y'yno}z^{O-}_{y'no} \quad \left(\kappa^{O-}_{yhno}\right) \tag{5c}$$

$$f^{O+}_{yhno} \le cap^{O+}_{yno} + \sum_{y'<y} dep^{O+}_{y'yno}z^{O+}_{y'no} \quad \left(\kappa^{O+}_{yhno}\right) \tag{5d}$$

$$z^{O}_{yno} \le exp^{O}_{yno} \quad \left(\zeta^{O}_{yno}\right) \tag{5e}$$

$$z^{O-}_{yno} \le exp^{O-}_{yno} \quad \left(\zeta^{O-}_{yno}\right) \tag{5f}$$

$$z^{O+}_{yno} \le exp^{O+}_{yno} \quad \left(\zeta^{O+}_{yno}\right) \tag{5g}$$

Market clearing

$$\sum_{s\in S} q^{O-}_{yhsno} = f^{O-}_{yhno} \quad \left(p^{O-}_{yhno}\right) \tag{6}$$

$$\sum_{s\in S} q^{O+}_{yhsno} = f^{O+}_{yhno} \quad \left(p^{O+}_{yhno}\right) \tag{7}$$

A.5. Final demand

The current version of NANGAM considers an unique demand sector. This sector maximizes its utility from the total energy consumption, after accounting for gas and emission costs. We assume the final demand to be a price-taker. For notational convenience, in the utility maximization problem below, the decision variables of final demand (energy consumed) is denoted by Q^D whereas the final demand price is denoted by p^{D}_{yhnde}.

Table 12
Functions and parameters for the demand sector.

Pi^{D}_{yhnde}	Inverse demand curve of sector *d* for fuel *e*
int^{D}_{yhnd}	Intercept of inverse demand curve of sector *d* at node *n*
slp^{D}_{yhnd}	Slope of inverse demand curve of sector *d* at node *n*
eff^{D}_{ynde}	Efficiency of energy service demand satisfaction of sector *d* by fuel *e* at node *n*
$eucc^{D}_{yhnde}$	Constant end use cost parameter of sector *d* regarding fuel *e*
$eucl^{D}_{yhnde}$	Linear end use cost parameter of sector *d* regarding fuel *e*
ems^{D}_{ydeg}	Emission of type *g* during consumption of fuel *e* at node *n*

$$\max_{Q^D} \sum_{\substack{y\in Y,h\in H\\ n\in N,e\in E}} \Bigg\{\Bigg[int^{D}_{yhnd} - \frac{1}{2}slp^{D}_{yhnd}\Bigg(\sum_{f\in E} eff^{D}_{yndf}Q^{D}_{yhndf}\Bigg)\Bigg] \times \left(eff^{D}_{ynde}Q^{D}_{yhnde}\right) - p^{D}_{yhnde}Q^{D}_{yhnde} - eucc^{D}_{yhnde}Q^{D}_{yhnde} - \frac{1}{2}eucl^{D}_{yhnde}\left(Q^{D}_{yhnde}\right)^2 - \sum_{g\in G} p^{G}_{yng}ems^{D}_{ydeg}Q^{D}_{yhnde}\Bigg\} \tag{8}$$

The linear inverse demand curve is obtained by taking the first-order condition of the quadratic utility maximization problem.

$$p^{D}_{yhnde} = ef\,f^{D}_{ynde}\Bigg[int^{D}_{yhnd} - slp^{D}_{yhnd}\Bigg(\sum_{s\in S,f\in E} ef\,f^{D}_{yndf}q^{D}_{yhsndf}\Bigg)\Bigg] - eucc^{D}_{yhnde} - eucl^{D}_{yhnde}\Bigg(\sum_{s\in S} q^{D}_{yhsnde}\Bigg) - \sum_{g\in G} p^{G}_{yng}ems^{D}_{ydeg} \tag{9}$$

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