Energy Policy 156 (2021) 112378

Contents lists available at ScienceDirect

Energy Policy

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

Mexico and U.S. power systems under variations in natural gas prices

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ARTICLE INFO

Keywords:
Natural gas
Power system
Integrated modeling framework
United States
Mexico

ABSTRACT

This study examines the impact of natural gas prices on the power systems of Mexico and the United States. For this, we develop an integrated modeling framework by soft linking three different techno-economic bottom-up models of the power and energy systems, one partial equilibrium model of the natural gas sector, and a partial equilibrium model of the Mexican energy sector. Our results show several interesting results: high natural gas prices raise the use of carbon-intensive technologies in the short-term and boost renewable investments at longer time intervals, increasing emissions in earlier periods and reducing them thereafter. Regarding system costs, because of more capital-intensive green power and lower expenditures in raw energy carriers, capital costs rise and operating costs decrease in the long haul. Furthermore, we see an increase in natural gas demand when its price is low, reducing long-term capital and operating costs through cheaper energy inputs in natural gas facilities and a lower share of capital-intensive renewable facilities in the power system. Concerning emissions, low natural-gas prices decrease coal use in the United States, reducing anthropogenic emissions until the last stages of the optimization period. For Mexico, they show heterogeneous results across models. Policymakers can use this study's results to understand the influence of natural gas prices in the Mexican and United States energy sectors.

1. Introduction

The North American energy and power sectors are under constant change. New technologies, climate commitments, and geopolitical circumstances continuously alter the structure of the energy mix and have significant implications in terms of emissions, costs, and the overall design of the energy market. Specifically, integrating a large share of renewable energy alongside the low price of natural gas across the continent call for a detailed assessment of how cross-national energy systems react to current technological circumstances.

Notably, the power sectors of Mexico and the United States (U.S.) are experiencing significant alterations due to the exploitation of unconventional natural gas reserves trapped in shale formations. These newly exploitable reserves increase supply, lower prices, and increase natural-gas power production while decreasing emissions due to the switching off of coal and fuel-oil technologies. Additionally, the demand for gas in the power and industrial sectors will continue growing because of the high availability of shale reservoirs in the south and northwest of the United States (United States Energy Info, 2019a).

Another relevant effect of the shale revolution is the integration of the Mexican and U.S. energy systems. Historically, energy trade consisted of shipping Mexican crude oil to the United States, processing it, and then shipping it back to Mexico (United States Energy Info, 2019b). However, the natural gas market is gaining in relevance: between 2005 and 2015, U.S. exports to Mexico increased by more than six-hundred percent (United States Energy Info, 2019b; of Energy, 2015a).

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https://doi.org/10.1016/j.enpol.2021.112378
Received 20 January 2020; Received in revised form 13 February 2021; Accepted 13 May 2021
Available online 1 June 2021
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Additionally, the current approval of the United States–Mexico–Canada Trade Agreement (USMCA) by the Mexican Senate and the U.S. House of Representatives gives certainty to the energy integration of the North American continent. Among the main energy-clauses in the USMCA are: (1) Zero tariffs in energy products between all three nations; (2) it considers any movement of hydrocarbons by pipelines originating from the continent as long as any foreign diluent does not constitute more than 40% of the good's volume; (3) U.S. liquefied natural gas exports will receive automatic approvals; and (4) the USMCA locks Mexican legislation regarding investment and operating restrictions in its energy sector (David, 1719).

This paper aims to analyze the effect of natural gas prices on the power systems of Mexico and the U.S. To do so, we construct an integrated modeling framework by soft linking five different energy models: four techno-economic models of the power and energy sectors — ReEDS 2.0, *GENeSYS-MOD*, *urbs*-MX, and TIMES-MXR-Regional— plus one long-term partial equilibrium model of the natural gas market — NANGAM. We optimize the power system of both countries under three different natural gas price scenarios: *Reference ('Reference')*, *Low Price ('Low')*, and *High Price ('High')*. Each model specifies the natural gas prices in the *'Reference'* case and adjusts them for the *'High'* and *'Low'* scenarios by changing their growth rate according to the price evolution of the high and low natural gas supply scenarios of the American Energy Outlook (AEO) 2019 (United States Energy Info, 2019c). For each scenario, we analyze differences in the structure of the power sector, variations in system costs, shifts to the infrastructure of natural gas markets, and changes in the emissions of the electric industry.

Three of the techno-economic models deal with the Mexican energy system (*urbs*-MX, *GENeSYS-MOD*, TIMES-MXR), one studies the impact for the U.S. and Mexico (ReEDS 2.0), and the final one studies the natural gas market outcomes across both nations (NANGAM). Moreover, by integrating five different models, we offer a more detailed analysis of the effects and reduce the risk of having model-dependent results.

The effect of natural gas prices on the costs, demand, and structure of the power sector depends on several factors, including prices, dispatchability, availability, and intertemporal efficiency of alternative energy carriers. In principle, it is challenging to have *a priori* assessments on these effects as the temporal pathway of these factors is difficult to predict. For instance, high natural gas prices could increase the demand for carbon-intensive fossil fuels or renewable technologies. The direction of the effect depends on the cross-technological elasticity of substitution across energy carriers that, in turn, depend on all the above factors. It is because of this high level of complexity on the interactions between natural gas prices and the power system that it becomes necessary to perform numeric approximations of the effect that different price levels could impose on the electricity sector.

Conclusions from this study can advise policymakers on the short and long term effects of natural gas prices on the power system. We structure the rest of the paper as follows. Section 2 provides a short literature review of works analyzing the relationship between the natural gas and the power sectors. Section 3 provides a general overview of natural gas and electricity markets in Mexico and the U.S. Section 4 explains the integrated modeling framework used in this study; it starts with a short description of the five energy models, followed by the model coupling approach and scenario design. Section 5 presents and discusses the results of the optimization routine on electricity demand, natural gas consumption, natural gas market outcomes, electricity generation mix, and CO_2-emissions for the three natural gas price scenarios. Finally, Section 6 wraps up essential findings and concludes.

2. Literature on power and gas

TThe development of natural gas markets and their relationship to the power system has produced a significant number of academic papers mainly focusing on three essential aspects: the relationship between natural gas and electricity infrastructure (Zlotnik et al., 2016; Diagoupis et al., 2016; Qiao et al., 2017), the relationship between natural gas demand and distribution infrastructure (Touretzky et al., 2016; of Energy, 2015b), and the contribution of natural gas electricity generation in the transition toward a low-carbon energy system (Mignone et al., 2017; McJeon et al., 2014; Davis and Shearer, 2014).

Zlotnik et al. (Zlotnik et al., 2016) formulate some coordination scenarios and computational implementations as techniques for improving natural gas and power infrastructures optimization. The authors conclude that it is imperative to analyze security and efficiency feasibility under high-stress conditions in these networks. Likewise, Diagoupis et al. (Diagoupis et al., 2016) present a planning approach based on Monte Carlo sequential simulations to deal with a failure scenario in the supply of natural gas to the electric system. They analyze the possible impacts of failures and propose new natural gas storage facilities in the United States. Qiao et al. (Qiao et al., 2017) explore natural gas system's operation in the presence of wind-power generation uncertainty, arriving at important conclusions regarding the relationship between the whole power system and natural gas by anticipating the instability of primary inputs in the production of electricity.

Regarding natural gas infrastructure, Touretzky et al. (Touretzky et al., 2016) demonstrate the superiority of a centralized operation strategy between the distributed generation of natural gas and the electric grid. Nevertheless, they assess that this process could be quite challenging without assuming a single entity that owns the distributed generation resources. In terms of infrastructure stock, the U.S. Department of Energy concludes that having a demand expansion for natural gas in the power sector will increase the need to develop U.S. interstate pipelines (of Energy, 2015b).

Concerning the relation between natural gas and renewables, Mignone et al. (Mignone et al., 2017) analyze the impact of Natural Gas Combined Cycle (NGCC) facilities on emissions abatement under scenarios that vary with the level of carbon prices. The authors find that none of the scenarios affect NGCC deployment before 2030. However, McJeon et al. (McJeon et al., 2014) show that the abundant use of natural gas in substitution of coal does not necessarily reduce CO_2 emissions. According to these authors, there are two counteracting forces: a substitution — more production with renewables —- and a scale effect – more generation with natural gas. Additionally, Davis and Shearer (Davis and Shearer, 2014) refer to this paper and motivate further studies evaluating the strategic use of natural gas to complement the use of renewable energy technologies.

This paper contributes to the current literature in several ways. First, it is the first article analyzing the effect of natural gas price shifts on the structure and costs of the power mix in the U.S. and Mexico. Second, it develops insights regarding the impact of these prices on power-sector emissions of carbon dioxide. And third, it analyzes the consequences of different price structures on the cross-national infrastructure of natural gas between both countries.

3. Background

3.1. The U.S. Natural gas market

Since the 1990s, natural gas production in the U.S. has experienced a sudden transformation. Fracking and horizontal drilling technologies paved the way to the competitive extraction of unconventional reservoirs trapped in shale formations by injecting high volumes of water, sand, and additional chemicals into the ground. In 2018, U.S. production of natural gas reached 101.3 billion cubic feet per day (an 11% increase over 2017) (United States Energy Info, 2019d). Fig. 1(a) shows the monthly production of natural gas in the U.S. between 2000 and 2019. The plot shows the constant and steady increase in production consequence of the use of unconventional reserves. For example, between 2000 and 2017, the extraction of natural gas grew by an astonishing 39.7% (International Energy Agen, 2008), driven to a great extent by the discovery of cheap shale gas in Pennsylvania (Kirschbaum et al., 2012)

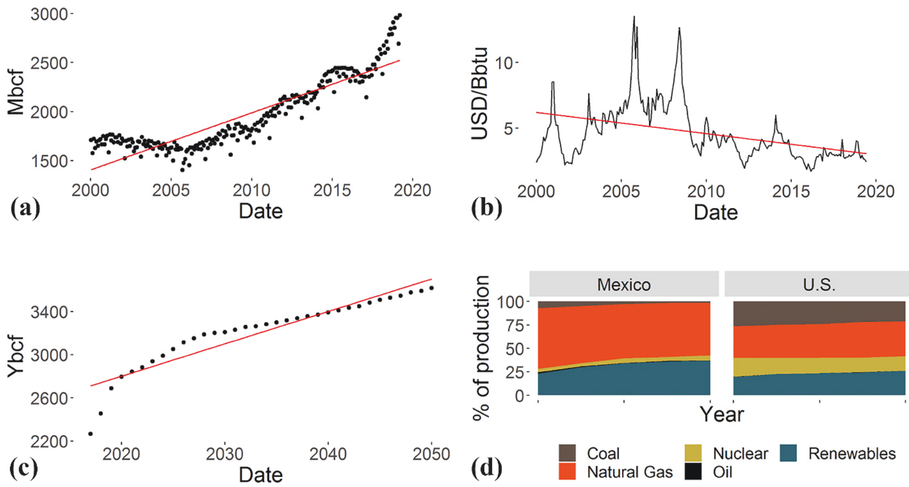

Fig. 1. Statistics on the U.S. natural gas sector.
Note: This figure shows descriptive statistics of the U. S. natural gas sector. Panel (a) plots the monthly production of natural gas between January 2000 and November 2019. Figure (b) shows the price behavior of natural gas in the Henry Hub. Image (c) exhibits the yearly projections of natural gas production, according to the U.S. Energy Outlook 2019. Finally, panel (d) shows the power mix of Mexico and the United States between 2017 and 2040 – Acronym clarification: Monthly billion cubic feet (Mmcf), Yearly billion cubic feet (Ybcf), Billion British thermal units (Bbtu).

and the shift of the power sector toward cleaner fossil-fuel technologies.

The new abundance of natural gas pushed down the Henry Hub spot price from $4.31 in 2000 to $2.82 in 2019 (see Fig. 1(b)). Furthermore, the AEO 2019 suggests a continuous growth of natural gas production by pointing toward a reference case where it steadily grows from 29.57 trillion cubic feet in 2017 to 43.41 in 2050 (see Fig. 1(c)). Additionally, the International Energy Agency estimates that natural gas will continue to play a decisive role in the power mix of Mexico and the U.S. (International Energy Agen, 2016). Fig. 1(d) plots the IEA assessment of power generation between 2017 and 2040. It shows how both countries will rely on natural gas to produce electric power, increasing the relevance of studies examining the effect of the natural gas sector on the power system.

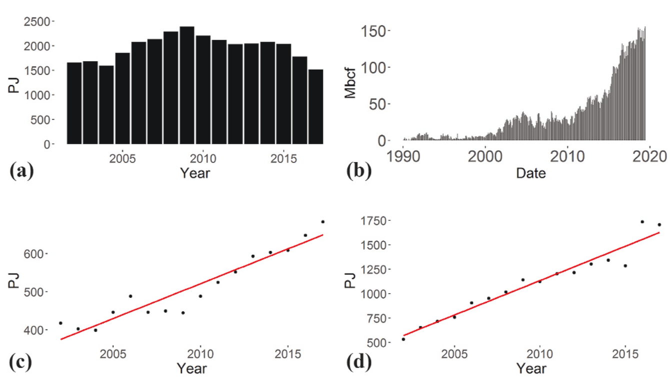

Fig. 2. Statistics on the Mexican natural gas sector.
Note: This figure shows descriptive statistics of the Mexican natural gas sector. Panel (a) plots the yearly production of natural gas between 2000 and 2019. Figure (b) shows the total trade of natural gas between the United States and Mexico from 1990 to 2019. Image (c) exhibits the demand for natural gas in the industrial sector between 2000 and 2019, and figure (d) does it for the power sector — acronym clarification: Petajoules (PJ).

3.2. *The Mexican natural gas market*

Although Mexico ranks 6th among the top 10 countries with technically recoverable shale gas (Congressional Research Se, 2015), its production has been consistently decreasing since 2010. Fig. 2(a) shows natural gas production in Mexico between 2002 and 2017. The extraction of natural gas consistently increases until reaching its peak in 2009. After that, the trend reverses, with production dropping from 2390 to 1518 PJ in eight years.[1] Furthermore, Fig. 2(c) and (d) show the linear increment in the demand for natural gas in the Mexican power and industrial sectors. Alongside the previously mentioned drops in national supply, these demand-side pressures increased the exports of U.S. natural gas to Mexico. Fig. 2(b) shows the increase in trade flows between the two countries for the 1990–2019 period.

In Mexico, the price of natural gas traditionally links to gas price references from the Southwest of the U.S., like the Houston Ship Channel and Henry Hub gas prices. The Mexican natural gas pipeline system physically connects to the U.S. precisely in the Southwest Texas region. Therefore, given the physical nature of natural gas, the Southwest price provides the opportunity cost for Mexican gas resources, mainly produced in Southeast Mexico as a byproduct of oil extraction. In fact, for more than two decades (from 1996 to 2017), the price of natural gas produced by the state-owned monopoly firm (Petroleos Mexicanos – PEMEX) was linked to the price at the Houston Ship Channel hub through a netback formula. The price of gas in Ciudad Pemex, Tabasco (Southeast Mexico), was then equal to Houston's rate plus transport costs from Houston to the arbitrage point at Los Ramones, Nuevo León (Northeast Mexico) minus transport costs from the arbitrage point to Ciudad Pemex.

In a series of papers, Brito and Rosellón explain the economic fundamentals of such natural-gas price regulation (Brito and Rosellón, 2002). They show that the netback formula was an application of the Little-Mirrlees principle (Little Mirrleeset al., 1968) and relied on the fact that the Houston hub had a liquid market of future contracts to hedge against externalities. However, the formula could also lead to incentives to increase domestic natural gas prices by diverting production from the regulated market. PEMEX could sell gas to its subsidiaries

[1] In 2013, Mexican energy reform allowed, for the first time in almost a century, the participation of private entities in the production of natural gas. Allowing private involvement in the sector has the goal of reverting the continuous plummeting of natural gas production in the country. The Mexico Energy Outlook (2016) (International Energy Agen, 2016) estimates a ramp-up of production by the late 2020s due to the reform, putting additional uncertainty on the prices of natural gas across the region.

or reduce its production to bring the arbitrage point south and increase domestic prices. These shortages in domestic gas production, in part, explain the continuing increasing trend of natural gas imports.

3.3. System reliance on natural gas

Price shifts in natural gas have noticeable impacts on the power mix; low prices increase gas generation and decrease production with other technologies (Levitan et al., 2014). For the U.S., electricity generation from natural gas grew from 897 to 1296 TW-hours [TWh] between 2007 and 2017 (United States Energy Info, 2019c). For Mexico, only in combined-cycle gas-turbine power plants, power generation[2] increased from 101 to almost 129 TWh for the same time-period (Secretaría de Energía and Si, 2019). Fig. 3 shows the power mix of Mexico and the United States across models in the reference year 2015.

Both power systems show a marked reliance on natural gas capacity. For the U.S., natural gas capacity represents 36.8% of the total installed capacity, followed by coal at 27.2% and nuclear at 9.6%. For Mexico, the share of natural gas capacity is, on average, 44.9%. Furthermore, Sarmiento et al. (Sarmiento et al., 2019) estimate that, even without attaining climate goals, the 2050 natural gas capacity-share in Mexico will remain around 40% while the International Energy Agency expects this share close to 46% in the U.S. (International Energy Agen, 2019; International Energy Agen, 2016).

4. Methodology

This study uses an integrated model assessment to analyze how different paths for the evolution of natural gas prices can change the power system and natural gas sectors of Mexico and the United States. For this, the proposed modeling framework integrates five different energy models: three of them of the power sector (GENeSYS-MOD, ReEDS 2.0, and *urbs*-MX), one model of the North American natural gas market (NANGAM), and one model of the Mexican energy system (TIMES-MXR-Regional) to evaluate and compare three different scenarios of natural gas prices.

4.1. Model integration

We divide the loose integration (soft link) of the five models into three steps. First, TIMES-MXR-Regional and ReEDS 2.0 determine the national electricity demand for Mexico and the U.S. between 2015 and 2050. A harmonized assumption in this regard allows a better comparison of results.[3] Second, the power sector models GENeSYS-MOD, ReEDS 2.0, and *urbs*-MX use this demand to calculate the optimal energy-mix for each of their modeled countries across all three scenarios. We aggregate the results into eight different energy sources: coal, natural gas, oil, nuclear, hydro, wind, solar, and other renewables. After the optimization, the model-wise computed demand for natural gas in the power sector is used as input in NANGAM to assess the evolution of gas production, prices, and trade between the U.S. and Mexico. Finally, we conduct a multi-model comparison of all three techno-economic models across all three scenarios. Fig. 4 portrays the loose coupling of all four models.

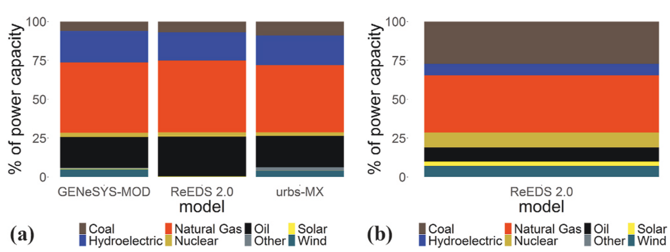

Fig. 3. Technological share in the power mix.

GENeSYS-MOD, ReEDS 2.0, and *urbs*-MX perform a cost-linear optimization subject to capacity, dispatch, transmission, and trade constraints. Additionally, each model imposes exogenous conditions in the form of policies, prices, or resource availability. Each team develops its model independently. Consequently, assumptions regarding the modeling structure and the technical and economic postulates on generation, costs, storage, transmission, distribution, and technological potentials are independent across models. However, despite marked differences in each model's scope, characteristics, and detail, the multi-model comparison approach allows us to understand and analyze a more extensive set of possible outcomes while reducing the risk of drawing model-dependent conclusions.

4.2. Models description

Table 1 summarizes the main characteristics of the models. It is possible to see the solution approach, the number of regions, the number of time slices, covered countries, and modeled sectors. The appendix section contains the full description of each model.

4.3. Scenario design

We evaluate and compare three different scenarios of natural gas prices: *'Reference'*, *'High'*, and *'Low'*. Since the models optimizing the power sectors (GENeSYS-MOD, ReEDS 2.0, and *urbs*-MX) have different absolute fuel prices, we model the scenarios as a shift in the price of natural gas. Hence, the input to the optimization models is a percentage change in the reference price of natural gas, as derived from the High and Low Oil and Gas Resource and Technology scenarios of the AEO 2019 (United States Energy Info, 2019c). In this way, we harmonize the trend of natural gas prices across GENeSYS-MOD, ReEDS 2.0, and *urbs*-MX.

Table 2 presents the natural gas prices from AEO 2019 and the calculated percentage change concerning the reference price. For example, if the 2017 price of natural gas for the *'Reference'* case of ReEDS 2.0 were one dollar per unit of measure, its price in the *'High'* scenario for 2020 would be 1.198 and in the *'Low'* case 0.896. In a sense, we keep the initial price level of each model *'Reference'* scenario and only shift its trend.

In addition to harmonizing the electricity demand and the shift in the natural gas prices, the three models also agree on the national renewable energy penetration targets. For Mexico, these are set to 30% by 2020, 35% by 2024, and 50% by 2050. The renewable share for all three models forces the system to produce at least the specified percentage of power with renewable resources. Naturally, the system can generate even more renewable energy. The technologies considered for the

[2] Includes the electricity generation from the state-owned electric utility (Comisión Federal de Electricidad – CFE.) and independent power producers. Other generation modalities, such as self-supply, are not considered.

[3] We integrate the TIMES-MXR regional demand from TIMES-MXR (5 regions) into GENeSYS-MOD (9 regions), ReEDS 2.0 (49 regions), and urbs-MX (9 regions) by proportional rules. For instance, if TIMES-MXR reports a demand of 100 for the combined GENeSYS-MOD region A-B, and GENeSYS-MOD region A represents 20% of regions A-B, the demand in A would be equal to 20 and of B to 80.

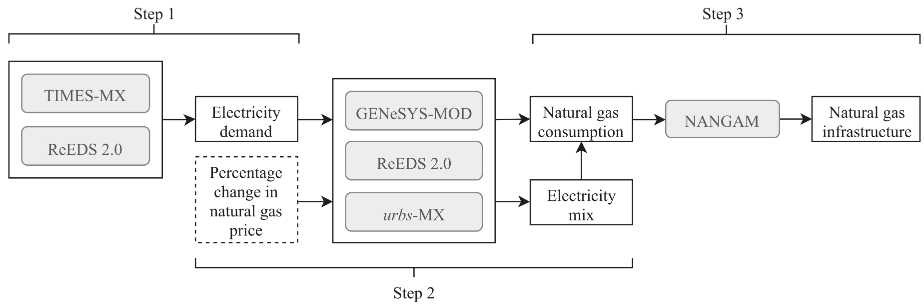

Fig. 4. Loose coupling of five energy models.
Note: This figure shows the soft-link diagram of the models we implement in our study: GENeSYS-MOD, ReEDS 2.0, *urbs*-MX, NANGAM, and TIMES-MXR.

Table 1
Main characteristics of energy models.

Model acronym	Sectors	Solution approach	Countries	Regions	Time slices	Institute
GENeSYS-MOD	Power Transport Heat	Perfect Foresight	Mexico	9	16	TU Berlin
NANGAM	Natural Gas	Perfect Foresight	U.S. Mexico Canada	9	16	JHU
ReEDS 2.0	Power	Sequential Myopic	U.S. Mexico Canada	73	17	NREL
TIMES-MXRRegional	Power Industry Transport Buildings	Perfect Foresight	Mexico	5	16	UCL
urbs-MX	Power	Perfect Foresight	Mexico	9	Full year (8760 h)	TU Munich

Note: This table summarizes the main characteristics of the models in our study. Acronym clarification — GENeSYS-MOD: Global Energy System Modeling, NANGAM: North American Natural Gas Model, ReEDS 2.0: Regional Energy Deployment System 2.0, TIMES-MXR: The Integrated MARKAL-EFOL System for Mexico. TU Berlin: Technische Universität Berlin, JHU: John Hopkins University, NREL: National Renewable Energy Laboratory, UCL: University College London, TU Munich Technische Universität Munich.

Table 2
Absolute natural gas price and percentage change for 'Reference', 'High Price' and 'Low Price' scenarios.

	Reference	High Price	Low Price	High Price	Low Price
Year	USD MMBtu	USD MMBtu	USD MMBtu	Perc change	Perc. change
2017	3.08	3.08	3.08	–	–
2020	3.08	3.69	2.76	19.8	−10.4
2025	3.53	4.66	2.90	26.3	5.1
2030	3.76	5.60	3.02	20.2	4.1
2035	4.02	6.19	3.14	10.5	4.0
2040	4.21	6.70	3.16	8.2	0.6
2045	4.45	7.14	3.24	6.6	2.5
2050	4.87	8.24	3.39	15.4	4.6

Note: This table shows the percentage adjustment in the price of natural gas for the *'High'* and *'Low'* scenarios across all models. The second to fourth columns show the price of natural gas under the high and low price scenario of the AEO. These scenarios correspond to the Low Oil and Gas Resource and Technology and High Oil and Gas Resource and Technology cases from the AEO 2019 (United States Energy Info, 2019c), respectively. The fifth and sixth columns show the percentage adjustment in the reference price of each model for each scenario.

renewable targets are solar, wind, hydro (large and small), geothermic, and bio-energy. In the case of renewable targets for the U.S, state-level renewable portfolio standards dictate the minimum share of renewables for each jurisdiction while including renewable energy credits plus trading and anti-laundering constraints.

5. Results and discussion

5.1. Electricity demand

We use TIMES-MXR to estimate Mexico's power sector demand as a component of the energy mix to 2050. TIMES-MXR meets energy service requests by combining fuels and technologies on a system cost optimization framework. The model decides the electrification level endogenously by sector and region while considering the climate targets in place. In TIMES-MXR, the power system has to meet end-user demand for electricity at each optimization period while working with a regional representation of installed capacity across 53 transmission regions that consider scheduled retirements and techno-economic data of each power facility. The model disaggregates electricity demand across six periods based on three seasons and three diurnal time slices. This temporal disaggregation allows us to represent load changes on each of the sectors' demand profile, and although this temporal resolution is relatively low, the model's integrated system approach provides insights not available to conventional dispatch models (particularly concerning the pace of end-use electrification).

ReEDS 2.0 defines the end-use electricity load projection for the U.S. based on scenarios from AEO 2019. Additionally, it sources hourly load profiles directly from regional transmission organizations (RTO) and independent system operators (ISO) websites, requesting load data at the most granular resolution level available. Hourly profiles for transmission zones are summarized and averaged to the 17 time-slice load profiles for the model balancing areas. These profiles are then scaled to ensure a match with the state-level annual retail energy load data from EIA's Electricity Data Browser. Within each state, ReEDS 2.0 further adjusts load profiles with county-level load participation factors from Ventyx (HattachiB and Velocity Su, 2014). Furthermore, the model calculates the regional growth factors after 2010 from AEO electricity consumption scenarios by census division. ReEDS scales the regional load profiles by regional growth factors for each year and scenario while assuming a constant load profile's shape throughout the study period. Fig. 5 portrays the harmonized inelastic demand for the optimization period 2015–2050 in Mexico and the U.S.

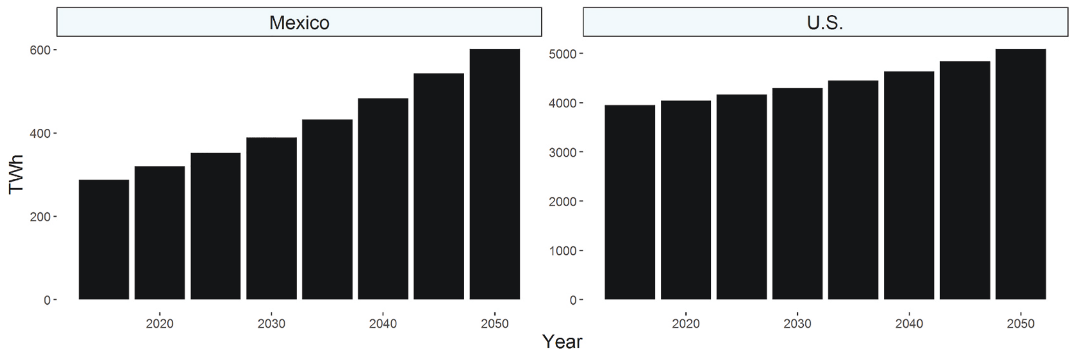

Fig. 5. Demand for electricity.
Note: This figure shows the harmonized demand for power in Mexico and the United States throughout the study period.

5.2. The power sector

This subsection analyses the effect of the *'High'* and *'Low'* scenarios in the power mix of Mexico and the United States. In principle, increasing the price of natural gas under demand constraints can have three different effects: increasing power generation with alternative fossil fuel technologies, boosting the share of renewables in the power mix, or, if the price change is not big enough, having no influence on the electric system. The effect depends on several factors like each technology's costs, efficiency, dispatchability, regionalization of demand, supply centers, intermittency, and policy commitments. Furthermore, because these factors change with time, e.g., technology costs, the effect has an intertemporal component that depends on each model's assumptions and exogenous data sources.

5.2.1. Electricity generation mix in Mexico

Fig. 6 shows the Mexican power mix across all three models and scenarios for the years 2020, 2030, 2040, and 2050. Each row represents a model and each column a year. The individual graphs plot the production of electric power in TWh as a function of each scenario.

Because we homologize all model's power demands with TIMES-MXR, their total consumption at the early stages of the optimization is quite similar, i.e., 288 (*urbs*-MX), 291 (ReEDS 2.0), and 297 (GENeSYS-MOD) TWh in 2020. However, GENeSYS-MOD deviates from ReEDS and *urbs*-MX at later periods due to its integration with the transportation and heating sectors. This difference is due to the sector coupling paradigm behind GENeSYS-MOD. In this model, the transportation and heating sectors link with electric power and increase its demand through electric vehicles and power to gas technologies. The power system meets this new demand with cost-competitive renewable facilities that increase overall systems production and green technologies' share.

Independent of the model and scenario, natural gas, solar, and wind generation represent the largest share of power production in the Mexican power mix at the end of the optimization period. In the *'High'* scenario, the production of electricity with natural gas decreases and is substituted with a combination of solar and wind facilities. The timing of the reduction differs across models: for GENeSYS-MOD, production starts decreasing in 2040; for ReEDS 2.0 in 2030; and for *urbs*-MX in 2050.

The replacement year of natural gas by renewables in the *'High'* scenario depends on the cross elasticity of substitution among generation technologies. This cross elasticity of substitution depends on each model's exogenous assumptions on costs, dispatchability, and efficiency. By the end of the modeling period, GENeSYS-MOD, ReEDS 2.0, and *urbs*-MX reach shares of natural gas power production of 12.4%, 26.0%, and 40.5% in this scenario. Such shares imply decrements with respect to the *'Reference'* case of 15.2, 19.96, and 7.07 percentage points. Overall, we observe that increasing the price of natural gas expands electric power's long-run production with green technologies. For the *'Low'* scenario, the percentage change in the generation of electricity with natural gas does not fluctuate by more than 2.5%.

Fig. 7 shows the temporal evolution of power production for natural gas, coal, and renewables. Each column of the plot ensemble refers to a particular model and each row to a technology. Individual graphs show the percentage share of production as a function of time for the three different specifications.

For all models, the power production of natural gas facilities decreases under the *'High'* and increases under the *'Low'* scenarios. This outcome follows pure economic intuition; demand negatively correlates with prices. In the *'High'* scenario, for GENeSYS-MOD, the trend in the share of production with natural gas facilities remains pretty similar to the trend of the *'Reference'* case and only shifts in levels. By the end of the modeling period, the share of natural gas production is 8.38 percentage points lower than in the *'Reference'* scenario and 60.44% less than at the start of the modeling period. The trend in ReEDS 2.0 changes in the first periods of the optimization routine, with its 2050 share of natural gas production 15.38 percentage points below the *'Reference'* scenario and 48.75% lower than in 2015. Finally, *urbs*-MX reveals common trends across scenarios. By 2050, the share of natural gas production decreases by 27.2%, 5.73 percentage points less than in the *'Reference'* design. For the *'Low'* scenario, all models show small variations concerning the *'Reference'* case. These results imply that the demand for natural gas in the power sector is more sensitive to price increments than decrements, suggesting that further lowering the price of natural gas would have little effect on its overall demand in the Mexican power sector.

We observe a downward trend in coal-fired electricity generation across scenarios and, as expected, a higher production level from coal facilities when natural gas prices are high. *urbs*-MX presents an increase in the short-term electricity production with coal for the 'High' scenario; still, after this initial short-term increase, its generation decreases, reaching minimum output by the end of the optimization period. Additionally, in the 'Low' case, ReEDS 2.0 exhibits a negative shock to coal-production. For GENeSYS-MOD and *urbs*-MX, the effect of lower natural gas prices on coal production is marginal.

Concerning the penetration of renewables, all models show a significant share of green energy throughout the optimization period. In the *'High'* scenario, renewable sources reach as much as 84% of electricity production for GENeSYS-MOD, 65% for ReEDS 2.0, and 50% for *urbs*-MX. The difference in renewable investments between the *'Low'* and *'Reference'* cases is almost indistinguishable. For GENeSYS-MOD, renewable investments deviate between the *'High'* scenario and the other two cases from 2030 onwards, the same for ReEDS 2.0, while for *urbs*-MX, the deviation happens a bit further in the optimization period.

5.2.2. Electricity generation mix in the U.S

The optimal energy mix of the U.S. has similar and interesting implications. Fig. 8 shows the evolution of the U.S. power mix across the

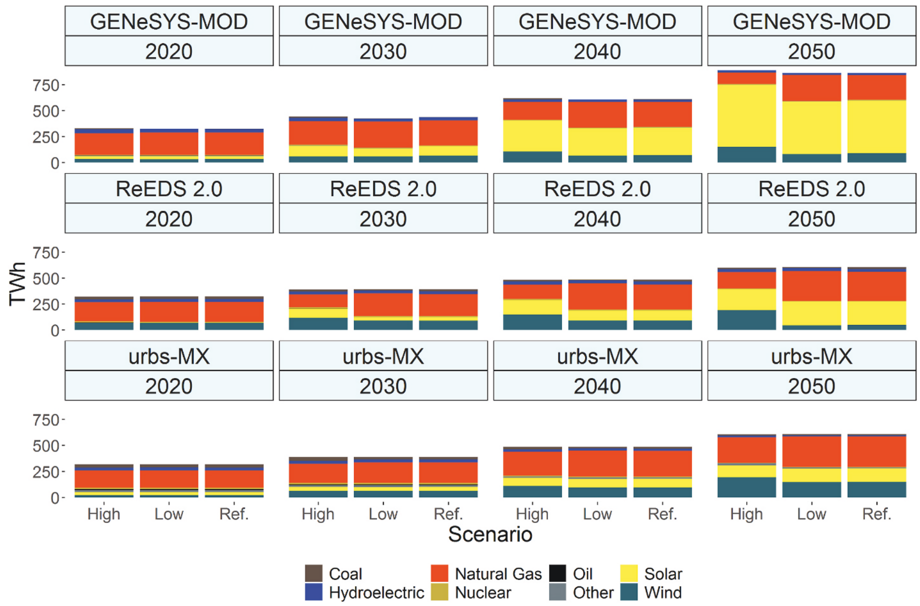

Fig. 6. Value of electricity production per technology across models and scenarios in Mexico.
Note: This figure shows the production of electricity between 2020 and 2050 in Mexico across three different techno-economic models: GENeSYS-MOD, ReEDS 2.0, and *urbs*-MX, for three different scenarios varying in the evolution of natural gas prices: high price, low price, and reference.

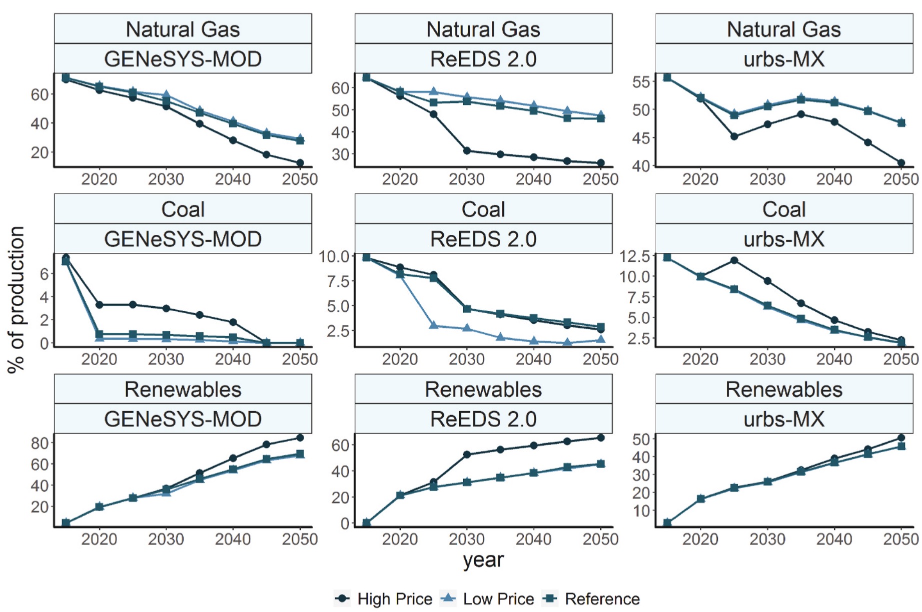

Fig. 7. Value of electricity production per technology across models and scenarios in Mexico.
Note: This figure shows the share of electricity production in the Mexican power mix between 2015 and 2050 for natural gas, coal, and renewable technologies across three models: GENeSYS-MOD, ReEDS 2.0, *urbs*-MX and three scenarios varying in the evolution of natural gas prices: high price, low price, and reference.

optimization period for ReEDS 2.0.

The U.S. mix seems to be more sensitive to swings in natural gas prices than its Mexican counterpart. At the end of the modeling period, in the *'Reference'* scenario, the production of power with natural gas represents 27.1% of the mix. The rest of the production comes from solar (33.0%), coal (16.9%), and wind (9.0%) technologies. The shares in the *'High'* scenario for natural gas, solar, wind, and coal are, respectively, 7.6%, 31.2%, 28.5%, and 16.9%. In this scenario, the generation by natural gas power plants drops by 19.5% and is fully compensated by wind energy. Finally, in the *'Low'* scenario, the power generation of natural gas grows by 24.9%. The growth in natural gas production reduces wind, solar, and coal production by 6.7%, 14.2%, and 4.5%, respectively, showing a higher downward sensitivity of coal to negative shifts in natural gas prices.

Analogous to the analysis of Mexico, Fig. 9 shows the temporal evolution of energy production for coal, natural gas, and renewables across all scenarios.

Higher natural gas prices decrease the demand for natural gas in the power system. The difference between all three scenarios is quite substantial. For the *'High'* scenario, by the end of the modeling period, demand for natural gas is 25.8 percentage points lower than in the *'Reference'* case. For the *'Low'* case, it is 19.54 higher. Concerning coal, a higher price of natural gas increases its share in the first years of the optimization routine. After these initial years, power production with

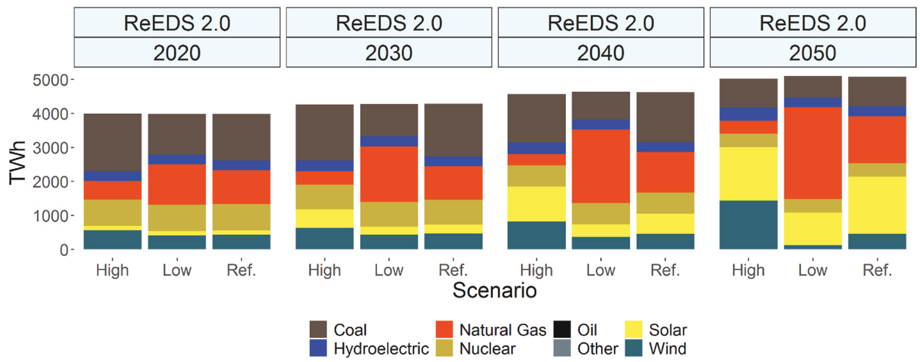

Fig. 8. Value of electricity production per technology across models and scenarios in the U.S.
Note: This figure shows the production of electricity between 2020 and 2050 in the United States for ReEDS 2.0 across three different scenarios varying in the evolution of natural gas prices: high price, low price, and reference.

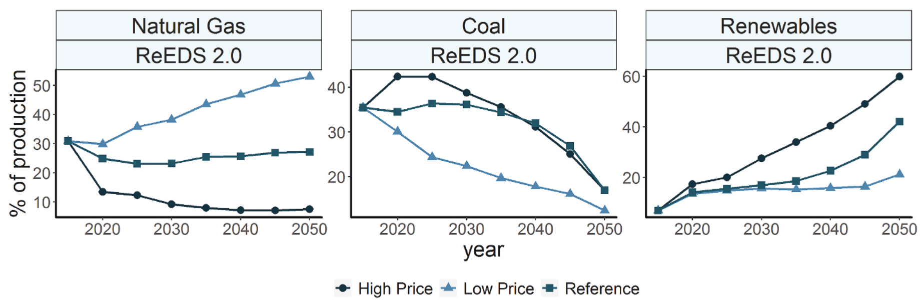

Fig. 9. Value of electricity production per technology across models and scenarios in the U.S.
Note: This figure shows the share of electricity production in the U.S. power mix between 2015 and 2050 in the ReEDS 2.0 model, for three technologies: natural gas, coal, and renewable technologies across three scenarios varying in the evolution of natural gas prices: high price, low price, and reference.

coal converges to the *'Reference'* case. On the other hand, a lower gas price decreases coal's power production share throughout the optimization period. For renewables, the higher penetration of renewables appears in the *'High'* scenario. As expected, when the price is low, natural gas pushes renewables out of the mix. At the end of the modeling period, renewables production in the *'High'*, *'Low'*, and *'Reference'* scenarios is 58.85%, 21.17%, and 42.08%, respectively.

5.2.3. CO_2-emissions in Mexico

Concerning anthropogenic emissions, overall results show a short-term positive and long-term negative relationship between natural gas prices and carbon dioxide. Fig. 10 displays the ratio of emissions with respect to 2015 as a function of time. Values below one mean that the system emits less equivalent CO_2, while values above one indicate more emissions.

All models show short-term CO_2 increments when the price of natural gas is high. This increment happens because, in the short term, the power system substitutes natural gas electricity production with coal. However, in the long haul, the coal-natural gas relationship changes due to the increasing penetration of intermittent renewables in the power system.

Renewables begin substituting natural gas and coal at different stages within each model's optimization period. Specifically, GENeSYS-MOD exhibits, between 2020 and 2030, higher emissions in the *'High'* scenario compared to the *'Low'* case. After 2030, this trend changes, and emissions show a continuous decrease until they become 63% lower than those in the base year.

GENeSYS-MOD emission trajectory emerges because up-until 2030, the model uses current coal generation capacity to substitute natural-gas facilities. However, once the model decommissions these power plants, it covers their supply with cost-efficient renewable technologies that lead to reduced CO_2 emissions. Contrary to ReEDS 2.0 and urbs-MX, the emissions trend continuously decreases up until 2050. This difference happens because, on the one hand, the effect of natural gas-coal

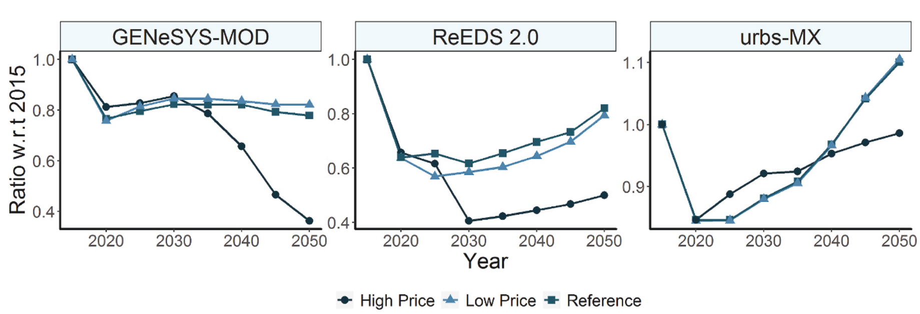

Fig. 10. Power system emissions throughout the optimization period.
Note: This figure shows the anthropogenic CO_2 emissions in the Mexican power mix between 2015 and 2050 as a ratio of emissions in 2015 across three models (GENeSYS-MOD, ReEDS 2.0, and *urbs*-MX) and three scenarios varying in the evolution of natural gas prices (high price, low price, and reference).

substitution in ReEDS 2.0 and urbs-MX is strong enough to lead to an increase in emissions (although still significantly lower than in the other two scenarios), while on the other, the lower share of natural gas production in GENeSYS-MOD reduces the adverse effects of this substitution.

We can observe a similar trend in ReEDS 2.0. Up until 2025, the model uses the current capacity of oil and coal facilities to produce electricity. However, after 2025, emissions in the *'High'* case sink by 60% (then increase linearly until reaching 50% in 2050) because of decommissioning and the introduction of renewable facilities.

Concerning *urbs*-MX, from 2020 to 2035, the emissions in the *'High'* scenario deviate and surpass the *'Low'* and *'Reference'* cases because of the substitution of natural gas production with coal. After 2040, the system adjusts as in GENeSYS-MOD and ReEEDS 2.0 by substituting decommissioned coal facilities with renewable power plants and by the end of the modeling period emissions in the *'High'* scenario are almost 50% lower than in the *'Reference'* case.

For the three models, the evolution of emissions in the *'Reference'* and *'Low'* scenarios in Mexico are remarkably similar, with both scenarios reaching the lowest level of emissions within the first decade of the optimization period. However, GENeSYS-MOD and *urbs*-MX show higher emissions for the *'Low'* case compared to the *'Reference'* (this difference is almost insignificant for *urbs*-MX). On the contrary, ReEDS 2.0 calculates a higher ratio for the CO_2-emissions in the *'Reference'* scenario. The reason behind the difference in results is that in the *'Low'* scenario, ReEDS 2.0 substitutes coal with natural gas in the first years of the optimization period; additionally, Mexico imports slightly less electricity from the US, thus increasing total generation. If the price drops, the production of natural gas grows, and the generation of coal drops. However, in ReEDS 2.0, the decline in coal dominates the increase in natural gas, and as a consequence, the system shows lower emissions in the *'Low'* scenario. For GENeSYS-MOD and *urbs*-MX, the relationship goes in the other direction.

Another difference worth noting is the range of emission reductions. While GENeSYS-MOD and ReEDS 2.0 show decrements in the *'Reference'* case of 22.11% and 17.96%, *urbs*-MX exhibit an increment of 10.21%. In the latter model, electricity generation with natural gas still accounts for almost 48% in the *'Low'* and *'Reference'* scenarios because of the weak elasticity of substitution between natural gas and renewable energy technologies alongside the absence of carbon capture and storage technologies in the modeling design.

Overall, increasing the price of natural gas increases short term anthropogenic emissions because of the substitution of natural gas with coal, while at the same time decreasing the long term emission trends due to the introduction of more competitive renewable sources. When natural gas prices decrease, models exhibit mixed results. GENeSYS-MOD and *urbs*-MX report higher emissions in the *'Low'* scenario because the scale effect – more production with natural gas — is higher than the substitution effect — more production with renewables. For ReEDS 2.0, the substitution effect dominates and, as a consequence, emissions are lower in the *'Low'* scenario.

5.2.4. CO_2-emissions in the U.S

Concerning the CO_2-emissions of the power sector in the United States, Fig. 11 plots the ratio of 2015 emissions as a function of time.

In the *'High'* scenario, emissions increase until they peak in 2030. After 2030, the slope decreases until reaching a reduction of 50% concerning the base year. The reason behind the short term increase in emissions is the substitution of natural gas with coal. For most of the optimization period, the *'Reference'* scenario shows higher emissions than the *'Low'* scenario, with only a substantial change in 2050 due to a significant drop in the emissions of the *'Reference'* case. The emission dominance behavior of the *'Reference'* scenario shows that for the *'Low'* scenario, the substitution effect is more significant than the scale effect: the increase in natural consumption because of lower prices is offset by the decommissioning of coal generation and the introduction of renewable sources. The relation holds until 2040, when the system installs a large share of photovoltaic parks to comply with state-specific renewable mandates.

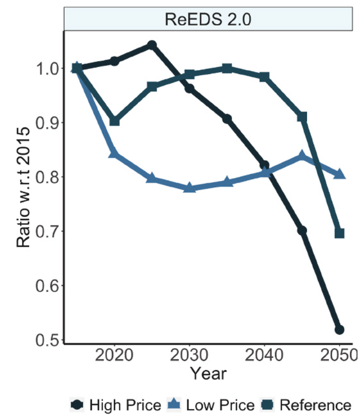

Fig. 11. Power system emissions throughout the optimization period.
Note: This figure shows the anthropogenic CO_2 emissions in the U.S. power mix between 2015 and 2050 as a ratio of emissions in 2015 across three models (GENeSYS-MOD, ReEDS 2.0, and *urbs*-MX) and three scenarios varying in the evolution of natural gas prices (high price, low price, and reference).

5.2.5. Capital and operational costs in Mexico

Investments in renewable energy technologies should increase capital costs and reduce operating costs due to the high capital requirements of renewable facilities and their almost marginal operating costs. Fig. 12 shows each scenario's effect on investment, operating, and total costs. Each row represents a model, each column a cost type, and each graph exhibits the percentage change of cumulative system costs with respect to the *'Reference'* case for the *'Low'* and *'High'* scenarios.[4]

In the *'High'* scenario, all models exhibit long term higher investment costs than in the *'Reference'* case. However, for GENeSYS-MOD and *urbs*-MX, the first periods of the optimization routine also show a decrease in capital investments. These reductions in capital costs come because GENeSYS-MOD and *urbs*-MX stop the construction of new natural gas facilities and start producing electricity with coal when the natural gas price is too high. For both models, cumulative investment costs are higher after 2030 because of the introduction of renewables, particularly solar and wind facilities. By 2050, cumulative costs in GENeSYS-MOD, *urbs*-MX, and ReEDS 2.0 are 8.84%, 11.24%, and 27.00% higher than in the *'Reference'* case. These results point toward long to medium term increments of investment costs because of the introduction of capital intensive renewables when the price of natural gas is high.

For the *'Low'* scenario, we see mixed results. Because of the introduction of new natural gas facilities, GENeSYS-MOD presents higher investment costs until 2025. After 2025, investment costs remain lower than in the *'Reference'* case due to the substitution of capital intensive renewable facilities with natural gas power plants. By the end of the optimization period, capital investments in the *'Low'* scenario are 0.02% lower than in the *'Reference'* case. ReEDS 2.0 show lower investment costs throughout the optimization routine. Its lower investment costs also come from fewer renewable facilities. By 2050, the capital investment of ReEDS in the *'Low'* scenario is 2.29% lower than in the *'Reference'* case — finally, *urbs*-MX exhibit higher investment costs across the

[4] Each value comes from aggregating costs according to.

$$Costs_{jT} = \frac{\sum_{t=0}^{T} Costs^{j} - \sum_{t=0}^{T} Costs^{Ref.}}{\sum_{t=0}^{T} Costs^{j}} \quad \forall T \in (2020, ..., 2050) \land \forall j \in (Highprice, LowPrice)$$

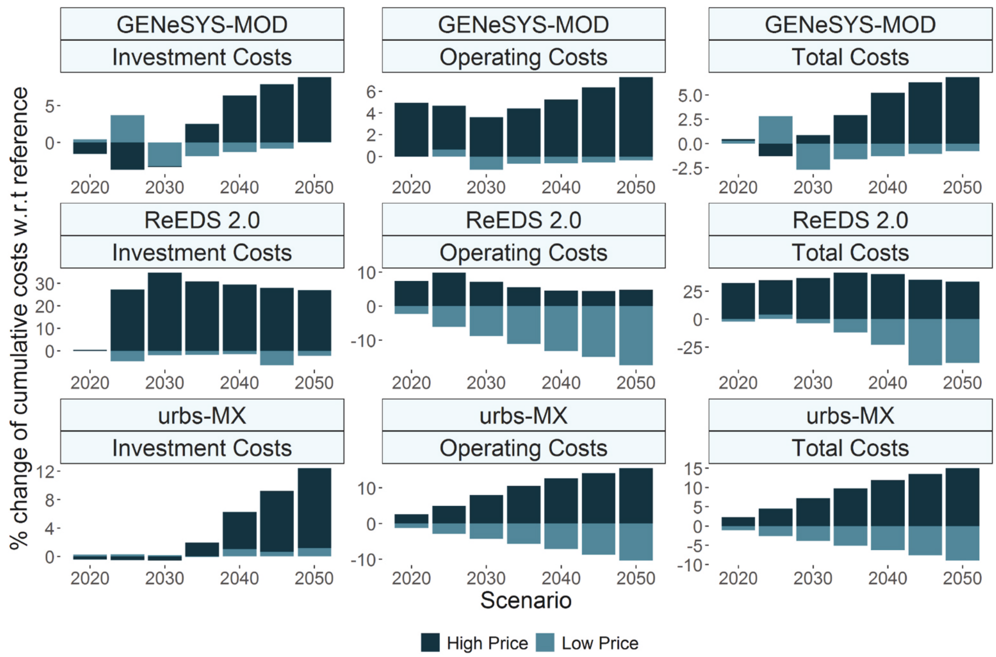

Fig. 12. Optimization results for power system costs in Mexico across scenarios.
Note: This figure shows the percentage change in investment, operating, and total costs (cumulative) concerning the base year. The values come from the optimization of GENeSYS-MOD, ReEDS 2.0, and *urbs*-MX under the *'High'* price, *'Low'* price, and *'Reference'* scenarios.

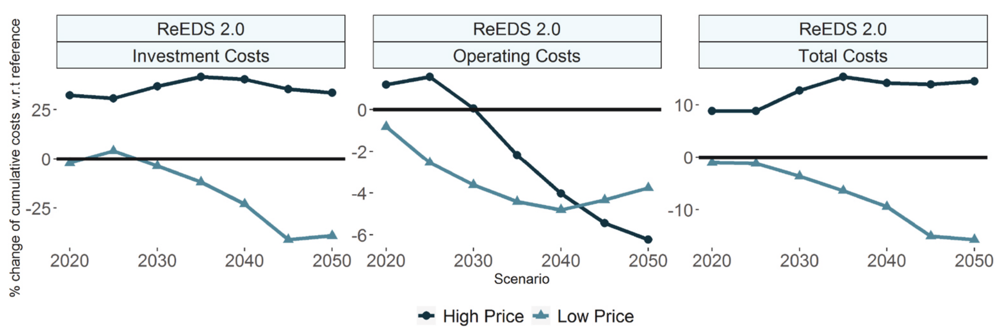

Fig. 13. Optimization results for power system costs in the U.S.
Note: This figure shows the percentage change in investment, operating, and total costs (cumulative) concerning the base year. The values come from the optimization of ReEDS 2.0 under the *'High'* price, *'Low'* price, and *'Reference'* scenarios.

optimization routine. Higher costs come from more investments in natural gas facilities. For *urbs*-MX, the difference between the *'Low'* and *'Reference'* cases is only 1.18% at the end of the optimization period. These results show minimal effects of low prices on the capital costs of the energy system.

Concerning operating costs, the three models show a marked increase in the *'High'* scenario because of higher input prices for natural gas and the use of more expensive fossil fuels in the initial years of the optimization period. The cumulative share increases by 7.29% in GENeSYS-MOD, 4.80% in ReEDS 2.0, and 15.5% in *urbs*-MX by 2050. Regarding the *'Low'* scenario, the effect of lower natural gas prices on the cumulative operating costs of GENeSYS-MOD is significantly smaller (−0.38%) than for *urbs*-MX (−10.37%) and ReEDS 2.0 (−18.29%). This difference is due to the higher shares of renewable energy in GENeSYS-MOD.

All models conclude higher natural gas prices lead to increments in operating costs. This increase comes from two primary sources. First, when natural gas prices are higher than those of substitute technologies, i.e., coal and oil, the models shift production to more expensive fossil fuels. And second, even with substitution, the share of natural gas in the system remains high, further increasing operating costs through the price channel. Concerning the *'Low'* scenario, ReEDS 2.0 and *urbs*-MX show a substantial decrease in their operating costs because of a higher share of natural gas facilities throughout the optimization period. For GENeSYS-MOD, the larger share of renewable technologies only leads to a modest reduction.

Finally, we aggregate the operational costs, capital investments, and additional model-dependent costs to compute the total cumulative percentage change in system costs between the *'Reference'* case and the *'Low'* and *'High'* scenarios. Cumulative costs at the end of the optimization period in GENeSYS-MOD are 6.83% higher in the *'High'* scenario than in the *'Reference'* case. For ReEDS 2.0 the same figure oscillates close to 33.38%, while for *urbs*-MX it reaches 15.03%. The constant increment in operating costs mostly drives the higher value for *urbs*-MX, and the high rise in capital investments does it for ReEDS 2.0. With respect to the *'Low'* scenario, cumulative costs for GENeSYS-MOD, ReEDS 2.0, and *urbs*-MX are −0.80%, −39.02%, and −8.98%, respectively. As can be noticed, the costs of ReEDS 2.0 are more sensitive to variations in the price of natural gas than the costs in the other two models.

5.2.6. Capital and operational costs in the U.S

Fig. 13 shows each scenario's effect on investment, operating, and total costs for the United States. Each column represents a cost type, and each graph exhibits the percentage change of cumulative system costs with respect to the *'Reference'* case for the low and *'High'* scenarios.

For the United States, the optimization exercise in the *'High'* scenario exhibits an increment of 33.38% in cumulative investment costs because of higher shares of renewable power plants in the power system. Concerning the *'Low'* scenario, the relationship goes in the other direction, with a decrease of 39.02% by the end of the optimization period. The *'Low'* scenario also exhibits a small increase in 2025 because of the installation of new natural gas facilities.

Regarding the operating costs, the *'High'* price scenario shows an increment at the start of the optimization period, only to drop after 2025. The operating costs increase in the short term because of either more costly natural gas or more expensive substitute fossil fuels. After this short term increase, renewables enter the power sector and reduce power generation's operating costs. In the *'Low'* scenario, although operating costs drop because of lower input prices, it is possible to see a small increase after 2040 due to the introduction of new natural gas power plants. However, costs remain lower than in the *'Reference'* case for all the periods of the optimization routine. Finally, total costs show the same trend in the United States as in Mexico. In the *'High'* scenario, they raise because of more investments in capital-intensive renewable technologies and higher operating costs up-until 2030; this short-term rise in operating expenses comes from generating electricity with more expensive fossil fuels alongside price-driven increments in natural gas facilities operating costs. Concerning the *'Low'* scenario, overall costs decrease for two reasons. First, as the competitiveness of natural gas facilities rises, investment in capital-intensive renewables falls. Second, even with more natural gas facilities, the price reduction in the *'Low'* scenario still decreases operating costs leading to a further reduction in total costs.

5.3. The natural gas sector

5.3.1. Natural gas demand in Mexico

Fig. 14 shows the percentage change in Mexican natural gas demand in the power sector between the base year and all subsequent periods for all three models and scenarios.

As expected, there is an inverse relationship between the prices of natural gas and its demand. In the *'Reference'* scenario, all three models exhibit an increase in the consumption of natural gas. The rates vary depending on the model-wise share of natural gas facilities in the power mix. In the last period, the percentage of natural gas consumption for GENeSYS-MOD, ReEDS 2.0, and *urbs*-MX are 3.69%, 28.60%, and 79.93% higher than in the base year.

For the *'High'* scenario, GENeSYS-MOD exhibit a decreasing trend in the consumption of natural after 2030. ReEDS 2.0 reaches its lowest level in 2030 only to slightly increase thereafter. And *urbs*-MX, contrary to the other two models, still exhibits an increasing trend, although at lower levels than in the *'Reference'* case. By 2050, the shares of natural gas consumption in the *'High'* scenario for GENeSYS-MOD, ReEDS 2.0, and *urbs*-MX are −51.13%, −29.02%, and 52.87%, respectively. This is, 54.82, 57.62, and 26.47 percentage points lower than in the *'Reference'* case.

For the *'Low'* scenario, all three models show a higher demand for natural gas than in the *'Reference'* case. The respective percentage change with respect to 2015 for GENeSYS-MOD, ReEDS 2.0, and *urbs*-MX in the *'Low'* scenario are 9.22%, 35.13%, and 80.43%. This is, 54.82, 57.62, and 26.47 percentage points lower than in the *'Reference'* case.

5.3.2. Natural gas demand in the U.S

Fig. 15 shows the percentage change of natural gas demand for the power sector with respect to the base year 2015 in the United States.

The U.S. demand for natural gas is quite price-sensitive. In the *'Low'* scenario, the need for natural gas between the base year and the end of the optimization period increases by 106.7%, while in the *'Reference'* case, it moves by only 6.2%. On the other hand, the *'High'* case also exhibits a substantial shock, although in the opposite direction: by the end of the optimization period, the demand for natural gas is 70.1% lower than in the *'Reference'* scenario. The higher sensitivity of the U.S. energy system may be due to easier substitutability of production across technologies or the fact that current political uncertainty leads to no national renewable targets or climate goals for the power system.

5.3.3. North American natural gas market outcomes

In this section, we use NANGAM to evaluate the propagation of the impact of decreased natural gas consumption from the electricity sector on regional natural gas production, consumption, and retail prices. NANGAM inputs are the percentage change of natural gas consumption in each model and scenario concerning the *'Reference'* case. NANGAM then applies the percentage change in natural gas consumption to its baseline consumption values.

NANGAM is an intertemporal, game-theoretic model of the U.S., Canada, and Mexico's interconnected natural gas sectors. It comprises

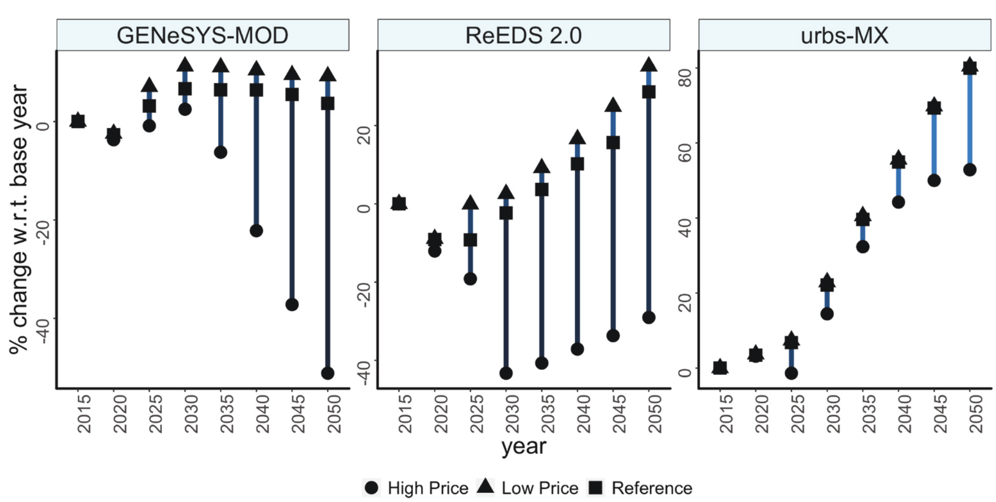

Fig. 14. Optimization results for the demand of natural gas in Mexico.
Note: This figure shows the year-wise percentage deviation in the power-sector demand of natural gas concerning 2015. The values come from the optimization of GENeSYS-MOD, ReEDS 2.0, and *urbs*-MX for the *'High'* price, *'Low'* price, and *'Reference'* cases.

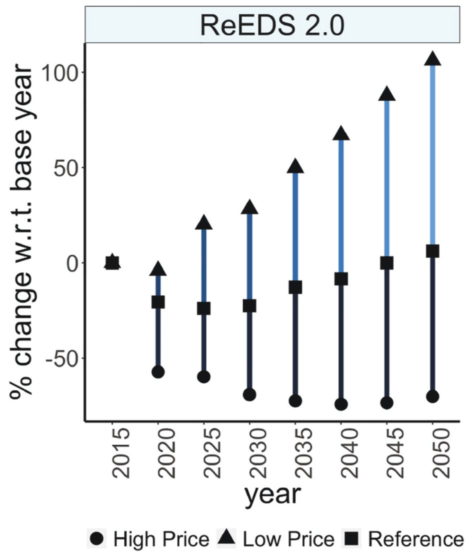

Fig. 15. Optimization results for the demand of natural gas in the U.S.
Note: This figure shows the year-wise percentage deviation in the power-sector demand of natural gas concerning 2015. The values come from the optimization of GENeSYS-MOD, ReEDS 2.0, and *urbs*-MX for the *'High'* price, *'Low'* price, and *'Reference'* cases.

13 production regions, 17 consumption regions, and 69 links between these regions representing the inter-regional pipeline interconnections. Moreover, it also accounts endogenously for regional natural gas suppliers' production and investment decisions, trade and capacity expansion decisions of regional pipeline operators, and consumers' response to natural gas prices. The soft-link approach implies that the electricity models' natural gas price inputs are not updated based on the new natural gas prices computed in this iteration. Subsequently, the electricity sector agents can-not adjust their decisions based on the least-cost natural gas production and pipeline infrastructure development path calculated using NANGAM. Therefore, the impact of the original natural gas price shock on the fuel mix is a limit-scenario for natural gas demand.

In this version of NANGAM, baseline natural gas production, consumption, and trade are consistent with AEO2017 for the U.S. (United States Energy Info, 2017), and the "Natural Gas Outlook 2016–2030" of the Mexican Secretary of Energy (Secretaría de Energía) SENER for Mexico (R (Secretaria de Ener, 2016). Table 3 includes baseline natural gas production in the U.S. and Mexico, as well as net U.S. natural gas exports to Mexico via pipelines.

Natural gas flows and production adjust in all three scenarios due to the change in demand from the electricity sector. Fig. 16 shows the percentage change in U.S. production of natural gas concerning the base year (2015).[5] Production of natural gas increases concerning the *'Reference'* case for all three models in the *'Low'* scenario and decreases in the *'High'* scenario for both the U.S. and Mexico.

Fig. 17 highlights the difference in natural gas production across the United States and Mexico for all three models. ReEDS exhibits the most significant change in the production of natural gas. Specifically, because it takes into consideration the U.S. market and its associated growth in production of 116% in the *'Low'* scenario and 18% in the *'Reference'* case. On the other hand, the production of GENeSYS and *urbs*-MX grows by 59%, very close to the increase in the baseline scenario. Similar to the U.S., Mexican production in ReEDS grows by 100% in the *'Low'* scenario but only by 49% in the *'High'* case. GENeSYS and *urbs*-MX production is s again similar to baseline.

By comparing Fig. 16 with Fig. 15, we can observe that the production of the U.S. increases disproportionately more in the *'Low'* scenario than the increase of its demand for all three models. As described in Section 3, Mexico is highly dependent on imports from the U.S. to cover its demand, and this dependency is also prevalent in this scenario.

Fig. 18 shows how U.S. exports to Mexico change between all models and scenarios. Although the shock on consumption and the subsequent adjustment of production varies between models, in the*'Low'* scenario, all three models' exports seem to be close to baseline exports until 2040, suggesting that the Mexican sector can expand fast enough to cover the mid-term change in demand. However, the U.S. does pick up a part of the market after 2040, suggesting the depletion of cheap Mexican resources. In the *'High'* scenario, exports to Mexico either remain close to the baseline, for GENeSYS and *urbs*-MX, or decrease in the mid-term, for ReEDS 2.0. For all three models, trade between the U.S. and Mexico rebounds to a level close to the baseline by 2050.

Finally, Fig. 19 shows the change in natural gas prices concerning the base year 2015. Each column represents a scenario, each row a country, and each plot portrays the difference in prices as a function of time.

Prices adjust less than demand, with prices increasing more in the U. S. than Mexico in the *'Low'* scenario. The constant exports from the U.S. to Mexico in the *'Low'* scenario suggest that Mexican producers become more competitive in the mid-term compared to the baseline. Therefore, the Mexican marginal cost of production increases less, leading to smaller price adjustments for consumers.

6. Conclusion and policy implications

Natural gas already plays a crucial role in the energy systems of Mexico and the United States. The high availability of cheap fuel, mainly driven by the shale revolution in the U.S., resulted in a marked dependence on natural gas. This trend is likely to continue for the foreseeable future, with 2050 estimates of natural gas production ranging between 40% and 75% of total power output (Sarmiento et al., 2019; International Energy Agen, 2019; International Energy Agen, 2016).

Because of the current and future reliance of the U.S. and Mexican power systems on natural gas, it is crucial to analyze the impact of different natural gas prices in the power generation matrix across both nations. However, due to the many interdependencies between electricity generating technologies, the influence of natural gas price changes is difficult to predict without modeling the power system in its entirety. For instance, the elasticity of substitution between natural gas and other energy sources depends on costs, dispatchability, availability, distance to demand centers, and technological trends.

This article presents an integrated model approach to analyze the effect of natural gas prices in the power and natural gas sectors of Mexico and the United States. For this, we soft link five energy models: three of the power sector (GENeSYS-MOD, ReEDS 2.0, and *urbs*-MX), one model of the North American natural gas market (NANGAM), and one model of the Mexican energy sector (TIMES-MXR-Regional). Three scenarios of natural gas prices are evaluated and compared: *'Reference'*, *'High'*, and *'Low'*. We model the scenarios as a shift in natural gas prices derived from the High and Low Oil and Gas Resource and Technology scenarios of the Annual Energy Outlook 2019 (United States Energy Info, 2019c). In this way, we harmonize the trend of natural gas prices across models and analyze the effect of each scenario on the structure of the power mix, CO_2-emissions, costs, and natural gas production, exports, and infrastructure.

6.1. Mexico

Our model results show exciting insights on the interdependencies

[5] It is important to notice that even though the figure contains all three models, it comes from the optimization of NANGAM over the U.S. natural-gas system. The data from GENeSYS-MOD and urbs-MX only comes from their optimization of the Mexican power system, while the data for ReEDS 2.0 from both systems; this is why there is no significant change in the NANGAM production of U.S. natural gas with GENeSYS-MOD and urbs-MX.

Table 3
Baseline natural gas production and trade via pipelines between the U.S. and Mexico in NANGAM.

Baseline values (BCF-year)	2015	2020	2025	2030	2035	2040	2045	2050
U.S. production	70.0	81.3	88.7	93.9	98.3	102.6	107.1	109.6
Mexico production	4.3	4.0	4.3	4.0	4.1	4.0	4.3	5.9
Net U.S. exports to Mexico via pipelines	3.0	4.7	4.5	5.0	4.9	5.0	4.7	3.9

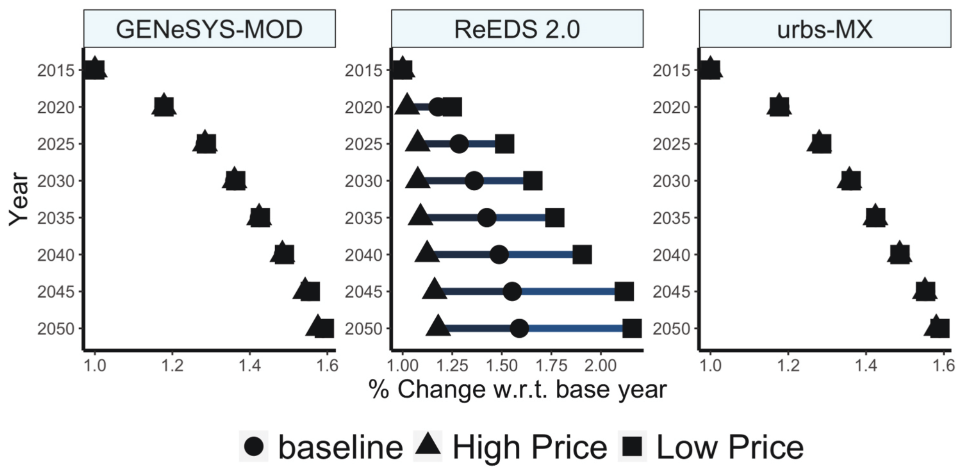

Fig. 16. NANGAM results concerning the U.S. production of natural gas.
Note: This figure shows the results from NANGAM regarding the percentage change with respect to 2015 in the production of natural gas due to the change in natural gas demand steaming from the power system optimization scenarios (high price, low price, and reference) of GENeSYS-MOD, ReEDS 2.0, and *urbs*-MX).

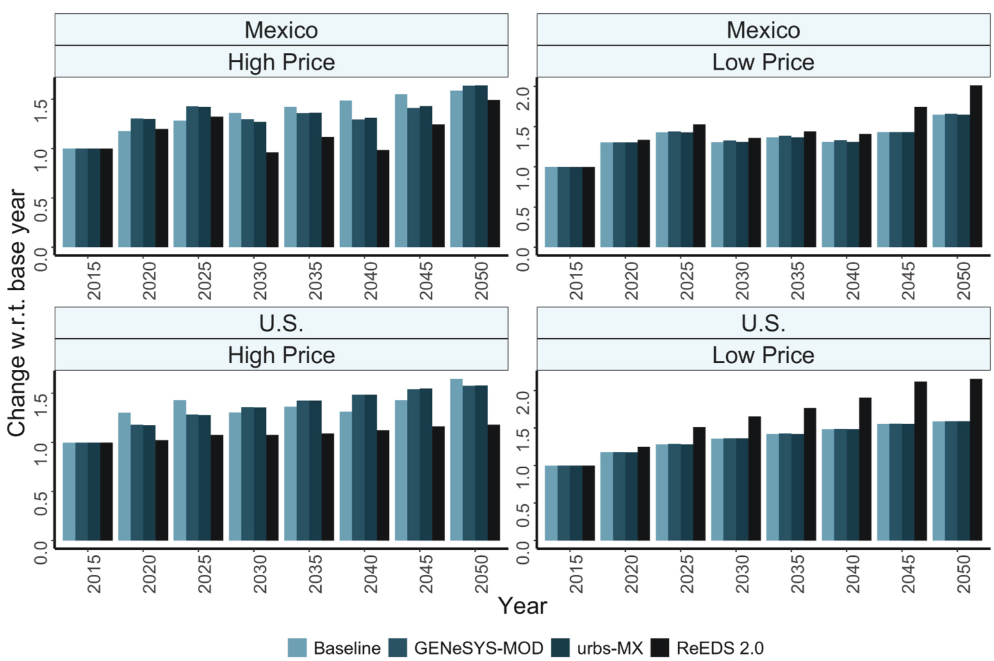

Fig. 17. NANGAM changes in natural gas production concerning the reference scenario.
Note: This figure shows the NANGAM reported percentage change of total natural gas production between the *'High'* and *'Low'* price scenarios and the reference case. Results come from optimizing NANGAM under six different natural gas demand values arising from the power-system optimizations of GENeSYS-MOD, ReEDs 2.0, and urbs-MX for the *'High'* price, *'Low'* price, and *'Reference'* cases.

between natural gas prices and the power system. Mexico shows an explicit dependency on natural gas, wind, and solar technologies across models and scenarios. Concerning scenario effects, high natural gas prices increase the short-term use of coal for electricity generation. However, by the end of the modeling period, the production of coal facilities mimics the output of the *'Reference'* case. On the other hand, Renewables exhibit a clear mid-to-long-term increase across all gas price scenarios. Concerning the *'Low'* scenario, GENeSYS-MOD and *urbs*-MX show no changes in the Mexican production of electricity with coal facilities. For both models, coal production remains almost the same between the *'Low'* and *'Reference'* cases. However, ReEDS 2.0 does report a reduction in the production of electricity with coal. The difference across models in the *'Low'* scenario accrues to a higher elasticity of substitution between natural gas and coal in ReEDS 2.0. For renewable energy technologies, all models exhibit a small reduction in the penetration of renewables in the energy mix for the *'Low'* scenario.

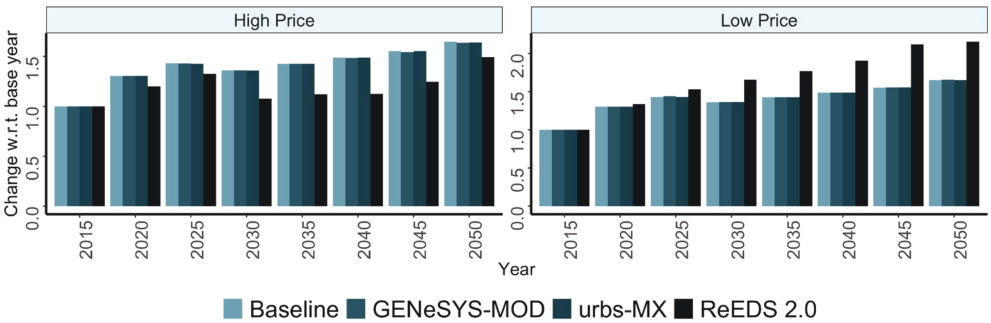

Fig. 18. Natural gas exports from the U.S. to Mexico.
Note: This figure shows the NANGAM reported percentage change of U.S. exports of natural gas to Mexico between the *'High'* and *'Low'* price scenarios and the reference case. Results come from optimizing NANGAM under six different natural gas demand values arising from the power-system optimizations of GENeSYS-MOD, ReEDs 2.0, and urbs-MX in the *'High'* price, *'Low'* price, and *'Reference'* cases.

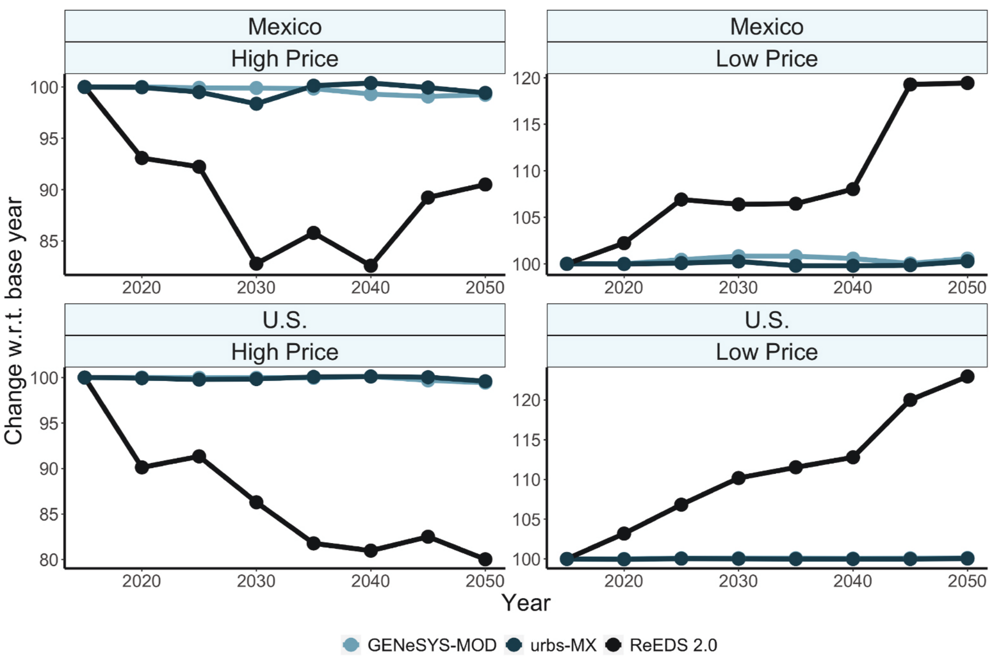

Fig. 19. NANGAM results for natural gas retail prices in the U.S. and Mexico.
Note: This figure shows NANGAM reported percentage change of natural gas retail prices concerning the base year for the U.S. and Mexico. Results come from optimizing NANGAM under six different natural gas demand values arising from the power-system optimizations of GENeSYS-MOD, ReEDs 2.0, and urbs-MX in the *'High'* price, *'Low'* price, and *'Reference'* scenarios.

These changes in the power system signal the effects of our scenarios on both emissions and system costs. For instance, the *'High'* scenario exhibits a short-term increase in CO_2-emissions followed by a mid to long-term reduction with respect to the *'Reference'* case. Furthermore, in this scenario, cumulative emissions show lower levels for all models at the end of the optimization period (2050), suggesting that although there is a short-term increase in coal use, all models agree that higher efficiencies of renewable energy technologies will trump the short-term spike in coal production and reduce emissions toward 2050. The *'Low'* scenario, on the contrary, exhibits mixed results. GENeSYS-MOD and *urbs*-MX show higher emissions in the *'Low'* scenario because of the higher production of natural gas and almost no changes for coal. ReEDS 2.0, however, presents higher emissions in the *'Reference'* case. These heterogeneous outcomes result from a greater change in the production of coal facilities in ReEDS 2.0, pointing toward an ambiguous effect of low gas prices on the anthropogenic emissions of CO_2. Concerning the costs of the power sector, system costs are higher in the *'High'* scenario compared to the *'Low'* and *'Reference'* cases because of substantial capital investments in renewable technologies and more expensive generation from fossil fuels.

The 2013 Mexican energy bill envisaged that the Mexican power sector should reach a 50-50% split between renewable and natural-gas power technologies by 2050. This policy goal depends on the long-term supply of U.S. shale gas, which appears sound and even modest when low shale-gas prices are forecasted. Notably, the 50-50% split has already implied short-run fast developments of natural gas and renewable infrastructure in the country. On the former, the national pipeline system increased in 2012–2019 from 11,347 km to close to 19,000 km, with pipelines mainly built by private investors to meet demand from independent power producers. On the latter, various auctions for solar and wind generation took place between 2015 and 2017, attracting more than 40 winning projects and delivering record-setting prices of less than USD 20 per MWh. But what would be the public policy implications in the long run? A first insight is that market-opening reforms in Mexico have implied growing reliance on U.S. shale gas based on sound economic arguments of liberalization, competition, and cost minimization. That is, importing shale gas from the U.S. would be an economically efficient solution to meet the growing demand for natural gas in Mexico, mainly demand linked to the development of combined-cycle power generation. Reforms should then remain and evolve to achieve expected positive economic effects while considering the impact of price fluctuations in natural gas on the Mexican power system.

However, an opposite interpretation would point out the Mexican electrical system's high geopolitical dependence on imported energy inputs. Which, by its nature, would put at risk the energy security of the country. Would this be a sufficient reason to reverse the Mexican energy sector's opening-up reforms and turn back to a vertically integrated state-owned monopoly? Such public policy –which is currently pursued by the López-Obrador's administration– would not be cost-minimizing nor environmentally friendly.

The research in this paper sustains that a more sensible policy –which reconciles energy sovereignty with economic and environmental efficiency in Mexico—might rely on an accelerated decarbonization process under any scenario of future natural-gas prices in North America.

6.2. U.S

The ReEDS 2.0 optimization results for the U.S. mimic several of the same trends as Mexico. Overall, the U.S. power matrix relies upon more generation technologies than the Mexican counterpart, with most power supply coming from natural gas, solar, wind, nuclear, and coal facilities. As in Mexico, the high price scenario increases the short-term use of coal and long-term use of renewables. Regarding the *'Low'* scenario, when natural gas prices are low, the optimization model shows a consistent and significant reduction in the generation of electricity with coal, solar, and wind power technologies.

The short-term increase in the production of electricity with coal for the *'High'* scenario leads to a short term increase in CO_2 emissions accompanied by a renewable driven long-term decrease. For the *'Low'* scenario, and contrary to Mexico, Emissions in the U.S. are lower than in the *'Reference'* case. This unexpected outcome is a consequence of two different effects: substitution and scale. When natural gas prices are high, the model reduces electricity production with natural gas power plants (scale effect). However, this production is substituted by a higher generation in coal facilities (substitution effect). Even though the output of renewable energy technologies also increases, their increase is not high enough to overcome the impact of higher coal generation. Conversely, when natural gas prices are low, the power system uses more natural gas (scale effect) and reduces both coal and renewable technologies (substitution effect). The higher use of natural gas emits more emissions than the reduction in coal production and, thus, the *'Low'* scenario pollutes more than the *'Reference'* case.

The effect of all three scenarios on the U.S. power sector's cost structure mimics the optimization results for the Mexican power matrix. Overall system costs are higher in the *'High'* scenario, lower for the *'Reference'* case, and the lowest for *'Low'* natural gas prices. These differences come from higher capital investments in renewable technologies and more expensive generation from fossil fuel facilities in the *'High'* scenario. On the contrary, when natural gas prices are low, producing electricity with fossil fuel facilities is cheaper and more competitive than constructing new capital intensive renewable power plants.

The optimization results of NANGAM concerning the natural gas sector show reductions in U.S. production of natural gas in the *'High'* scenario across all models and for both nations. Regarding the *'Low'* scenario, the relation goes in the other direction. We can find model variation in the sensitivity to different natural gas prices. Overall, ReEDS 2.0 shows a higher sensitivity in natural gas production due to exogenous changes in the price of natural gas. An additional result is the Mexican natural gas sector's ability to cope with demand pressures through 2040 when its cost-efficient resources are depleted. Furthermore, in the *'High'* scenario, exports show no inter-scenario variation.

This study shows the U.S. power matrix composition's sensitivity to changes in natural gas prices. Importantly, higher natural gas prices lead to short-term increments in coal generation, while lower prices drive the system to a significant reduction in renewable investments.

Biden's climate package reverses the Trump administration's efforts to disassemble policies designed to lower emissions while withdrawing the U.S. from the Paris climate deal. Biden executive actions will revise existing oil and gas leasing drilling on federal land, cease new leases on public lands and offshore waters, and eliminate current fossil fuel subsidies.

As this study points out, before entirely removing fossil fuel subsidies, the administration should look closely at the inter-temporal elasticity of substitution between technologies to reduce the possibility of unwanted short-term price-driven consequences. For instance, banning fracking and shale-gas extraction can reduce natural gas supply, increasing its price and leading to short-term increments in power generation with coal and fuel-oil facilities for both Mexico and the United States.

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

This work was authored in part by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U. S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by the U.S. Department of Energy Office of Policy. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes. Research support for C.A. and S.S. was funded in part by NSF Grant number 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 multifuel energy equilibrium model MultiMod. 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. GENeSYS-MOD is based on OSeMOSYS (Open-Source Energy Modeling System). It was developed by Konstantin Löffler, Karlo Hainsch, Thorsten Burandt, Pao-Yu Oei, Claudia Kemfert, and Christian Von Hirschhausen of the work-group for infrastructure and policy of the Berlin Institute of Technology and the Department of Energy, Transportation, and Environment of the German Institute of Economic Research (DIW Berlin) We are grateful to the original developers of both OSeMOSYS and GENeSYS-MOD for sharing their frameworks and helping us throughout the implementation of their model.

Appendix A. Description of the models

(1) GENeSYS-MOD (Global Energy System Model) is an extended and refined version of the techno-economic OSeMOSYS model (Open-Source Energy Modeling System). It includes new functionalities, such as a prolonged power system, the sector coupling of transportation and heating, improved trade, enhanced focus on environmental budgets, finer time slices, and the addition of storage technologies. In broad terms, GENeSYS-MOD uses a system of linear equations as constraints and inputs to minimize the aggregated cost of the energy system, while securing the supply of energy in a specific region. The model works on a block-type framework divided into eleven principal blocks (Objective function, cost, storage, capacity adequacy, energy balance, constraints, emissions, transport, heating, renewable targets, and trade). The capacity of GENeSYS-MOD to subdivide the energy system into sectors, technologies, and regions, its ability to account for sector coupling, and its high

degree of technological features differentiate it from traditional bottom-up power models. for More information on the model, we suggest (Löffler et al., 2017).

(2) NANGAM is a long-term partial-equilibrium model of the U.S., Mexican, and Canadian gas markets. NANGAM considers a total of 17 nodes, of which nine correspond to U.S. census regions 1–9, one node to Alaska, two nodes to Canada (East and West), and five to Mexico (Northwest, Northeast, Interior-West, Interior, and South-Southeast). Of the nodes mentioned above, there are 13 nodes with natural gas production capacity (census regions 2–9 for the lower-48 states, one for Alaska, two for Canada, and two for Mexico). The 17 production-demand nodes currently connect through 69 pipelines. NANGAM also considers storage operations in the U.S. and Canada. The model allows for endogenous infrastructure development and expansions while building on five-year time-steps up to 2050 with three seasons for each time-step. For more information on NANGAM, refer to (Feijoo et al., 2018; Feijoo et al., 2016).

(3) ReEDS 2.0 was developed from the original ReEDS model in 2018 to incorporate several improvements. The regional dimensionality remains the same in that there are a total of 205 balancing areas for Canada, Mexico, and the U.S., with an additional 454 resource regions that provide a detailed representation of wind (both onshore and offshore) as well as CSP technologies. The model represents seventeen-time slices corresponding to the morning/afternoon/evening/night periods for the four seasons as well as a super-peak period. The primary constraints in the model, non-exhaustively, include a planning reserve margin, operating reserve provisions, as well as state and federal policies (e.g., state renewable portfolio standards, production, and investment tax credits).

(4) TIMES-MXR-Regional is a bottom-up, technology-rich, linear programming, dynamic partial equilibrium model with an inter-temporal objective function, minimizing the discounted cost of the Mexican energy sector. Base-year energy-service demand is exogenous and is projected for the future using drivers such as GDP, population, households, and industrial output by sector. The model has five interconnected regions with trade in fossil fuels, petroleum products, biomass, and electricity. Each modeled region covers its energy supply, conversion, and end-use sectors. For more information on TIMES-MXR-Regional, refer to (Solano-Rodriguez, 2017).

(5) *urbs*-MX is a nine-region model of the Mexican power system based on *urbs*, an open-source linear optimization framework for capacity expansion and unit commitment analyses (Technical University of M, 2019). The model minimizes the annual system costs, which comprise all investment costs by their annualized depreciation as well as the operational and environmental costs. As a result, the least-cost portfolio of generators, storage, and transmission that meet the electricity demand at every hour of the modeled year under capacity and environmental constraints, is calculated. It allows the integration of multiple inputs and output commodities, resulting in a detailed representation of the energy conversion processes. A high temporal resolution of 8760 h per year is used to ensure the chronological tracking of storage and the detailed matching of intermittent supply and electricity demand. Additional information on the model is in (Molar-Cruz et al., 2018).

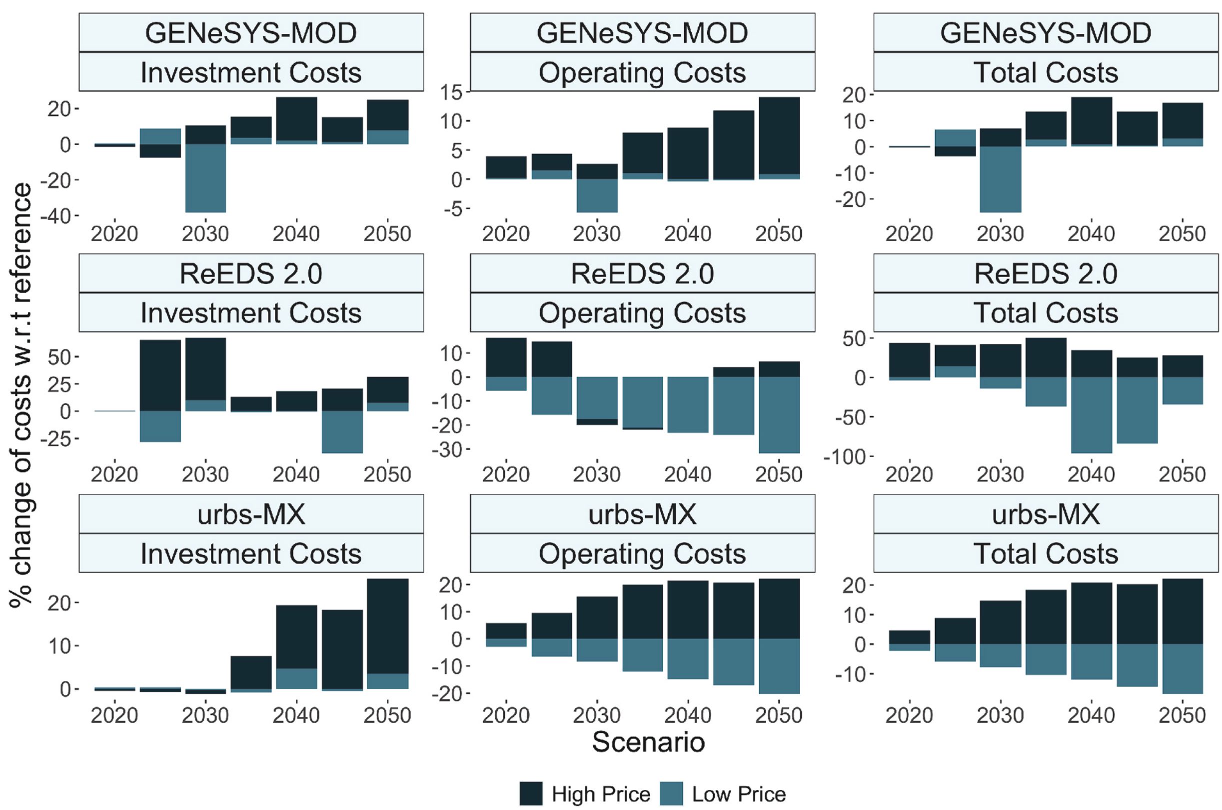

Fig. A.20. Optimization results for power system costs in Mexico across scenarios

Note: This figure shows the percentage change in investment, operating, and total costs concerning the base year. The values come from the optimization of GENeSYS-MOD, ReEDS 2.0, and *urbs*-MX under the *'High'* price, *'Low'* price, and *'Reference'* scenarios.

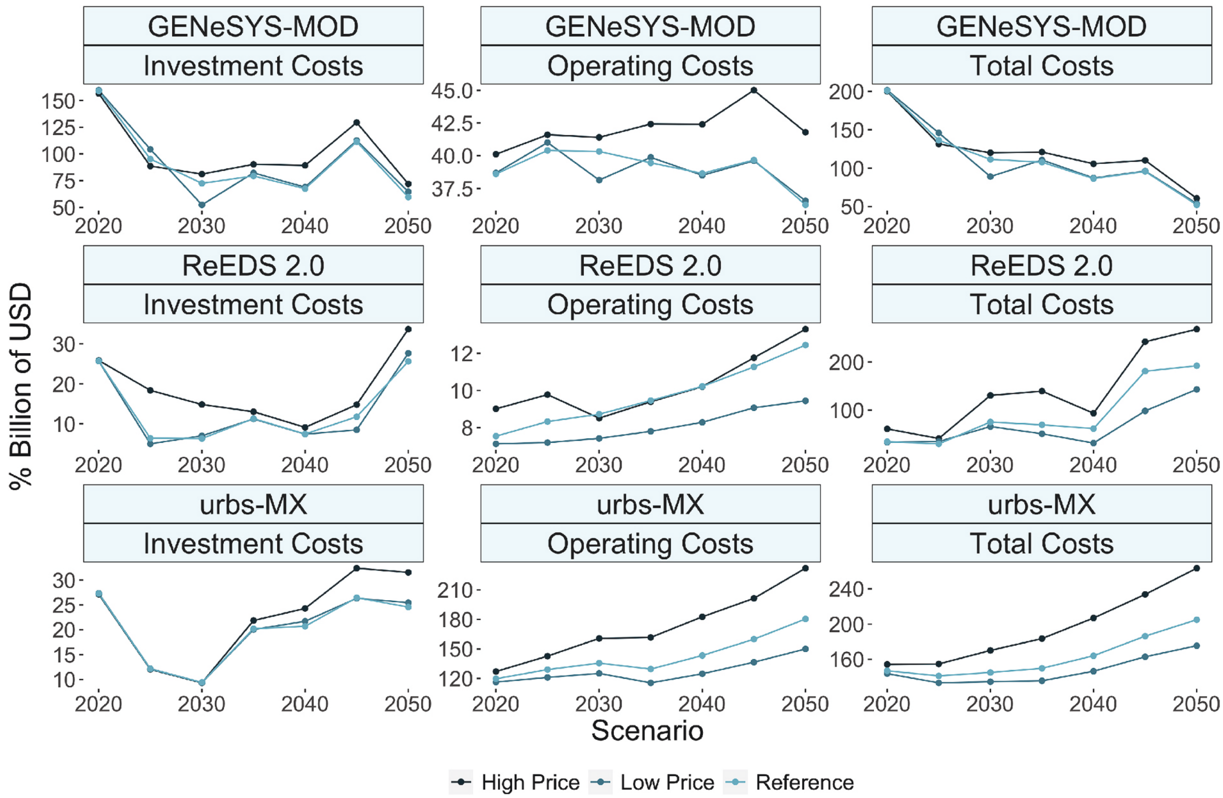

Fig. A.21. Optimization results for power system costs in Mexico across scenarios.

Note: This figure shows the value of investment, operating, and total costs across models and scenarios. The values come from the optimization of GENeSYS-MOD, ReEDS 2.0, and *urbs*-MX under the *'High'* price, *'Low'* price, and *'Reference'* scenarios. This figure should be read with care, we did not homologize costs across models and thus only changes within the same model are valid.Additionally, Figure A20 shows the same graph for non-cumulative costs according to:

$$Costs_{jt} = \frac{Costs_{jt} - Costs_{Ref.,t}}{Costs_{jt}} \quad \forall t \in (2020, \ldots, 2050) \wedge \forall j \in (HighPrice, LowPrice)$$

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