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The future of natural gas infrastructure development in the United states

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HIGHLIGHTS

- Inter-state natural gas infrastructure investment across socioeconomic context.
- Existing pipeline capacity is insufficient to satisfy future demand for natural gas.
- Geographic distribution of investments within the U.S. is heterogeneous.
- Risks of under-utilization of pipeline capacity in a low-carbon future economy.

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ABSTRACT

Changes in the natural gas market have spawned the need for pipeline infrastructure planning. Previous studies have analyzed natural gas infrastructure development largely independent of the interactions of the natural gas sector with the broader economy. However, natural gas infrastructure development is strongly influenced by broader domestic and international socioeconomic conditions. We couple a global Human-Earth system model with state-level detail in the United States (GCAM-USA) that provides the broader socioeconomic context for natural gas supply and demand with a natural gas infrastructure investment model (NANGAM) to examine inter-state natural gas pipeline infrastructure development in the U.S. under a range of socioeconomic scenarios. Here we show that existing pipeline infrastructure in the U.S. is insufficient to satisfy the increasing demand for natural gas and investments in pipeline capacity will be required. However, the geographic distribution of investments within the U.S. is heterogeneous and depends on the capacity of existing infrastructure as well as the magnitude of increase in demand. Our results also illustrate the risks of under-utilization of pipeline capacity, in particular, under a scenario characterized by long-term systemic transitions toward a low-carbon economy. More broadly, our study highlights the value of integrated approaches to facilitate informed decision-making.

1. Introduction

Natural gas is gaining increasing importance in global energy markets primarily because of competitive prices driven by the shale gas boom. Indeed, in the U.S. natural gas surpassed coal to become the leading source of electricity generation in 2016, the most important sector consuming natural gas in the U.S.[1] In addition, U.S. pipeline and liquefied natural gas (LNG) exports have increased significantly over the last five years and are expected to continue to increase through the mid-century.[2] For example, pipeline natural gas exports to Mexico in 2016 were roughly four times the exports in 2010. Furthermore, LNG is projected to dominate U.S. natural gas exports,[3] increasing total U.S. liquefaction capacity by roughly ten times between 2016 and 2019 [1]. In this context, the U.S. is expected to become a net exporter of natural

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

2 Today in Energy: U.S. natural gas exports to Mexico continue to grow. Available at: https://www.eia.gov/todayinenergy/detail.php?id=28932.

3 The top importers of U.S. LNG (Bcf in 2016) were Chile (29.4), Mexico (27.5), China, (17.2), India (16.9) and Argentina (16.7). See https://www.eia.gov/todayinenergy/detail.php?id=30052 and https://www.eia.gov/dnav/ng/ng_move_expc_s1_m.htm.

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Table 1
Summary of previous literature on natural gas infrastructure planning.

Author	Regional/ Geographic scope	Sectoral scope	Key insights
U.S. Department of Energy [9]	U.S.	Natural gas sector only. Demand is modeled from power sector only	Increased demand for natural gas in the power sector will lead to pipeline capacity additions. However, these additions will occur at a slower pace than historical expansion of pipelines
Liu et al., Zhang et al., and Barati et al. [13–15]	Not explicit (These studies consider sample networks such as the IEEE bus test networks)	These studies assess power sector unit commitment with natural gas transportation constraints. Supply from natural gas sector is not modeled explicitly	Combined coordination of the power sector and network operators of both the power and gas transportation network is required to avoid shortages and congestions, and for planning of new transportation infrastructure
Oliver at al, Brown et al., and M. Oliver [16–18]	U.S.	Natural gas sector only. Demand for natural gas is not modeled from individual sectors, but rather, in an aggregate manner	Lack of pipeline capacity results in network congestion and increased transportation costs. The increased prices could be managed by increased storage or additional pipeline capacity
Dieckhöner et al., Egging et al., Holz et al., [19–22]	Europe	Natural gas sector only. Demand for natural gas is not modeled from individual sectors, but rather, in an aggregate manner	The European natural gas market shows high integration. However, network congestions and need for new pipeline capacity was observed in Germany, Denmark and eastern Europe. Europe will also depend on exports from Africa and Caspian region, leading to added import pipeline capacity
Zhang et al. [23]	China	Natural gas sector only. Demand for natural gas is not modeled from individual sectors, but rather, in an aggregate manner at the provincial level	Scenarios with high imports in China show a substantial pipeline infrastructure expansions in the south-western regions. Pipeline imports replace LNG imports when international prices increase
Egging et al. [24]	World gas model	Natural gas supply sector only. Demand for natural gas is modeled by sector	Share of LNG and pipeline change over time and region. The European region will require new pipeline import capacity due to proximity to major gas suppliers. LNG will play a major role in the Asian market
Feijoo et al. [12]	North America (U.S., Canada, and Mexico)	Natural gas sector only. Demand for natural gas is not explicitly modeled from individual sectors, but rather, in an aggregated manner at the sub-national and regional level	Increased Mexican natural gas demand from the power sector results in higher U.S. pipeline exports. Exports to Mexico are possible under a shift of flows in the U.S. and pipeline capacity expansions in both the U.S. and Mexico

gas in 2017 and a net exporter of total energy by 2020[4]. Another example of increased importance of natural gas is the Chinese energy market. Natural gas production in China has grown rapidly in the last decade, increasing by 500% between 2000 and 2016 (27.2 bcm in 2000 to 136.9 bcm in 2016). However, as in many other countries (e.g., Mexico), the growth in demand (which increased about 850% over the same period) has surpassed supply capacity. The gap between Chinese natural gas demand and supply has been projected to continue to increase, reaching a gap ranging between 225 and 807 bcm in 2050 [2]. The increasing importance of natural gas in energy markets worldwide underline the need for adequate natural gas infrastructure and planning (e.g., see [3–8]) to not only proactively utilize this resource, but also protect from adverse implications for energy security. Indeed, the development of natural gas infrastructure has seen an expansion in the recent years. For example, in the U.S., recently completed or upcoming pipelines (e.g. the Rover pipeline and the Atlantic Coast Pipeline Project) connect newly emerging supply hubs such as the Middle Atlantic region (due to the increased supply from the Marcellus and Utica shale basins) to the rest of the U.S. In addition, new pipelines (e.g. Atlantic Coast Pipeline and the Valley Crossing Pipeline, Appendix A, Sections A1 and A2) also connect the West South Central region to Mexico to facilitate increased exports.

The increasing importance of natural gas and the emerging boom in investments in pipeline capacity raise several important questions such as: *Is the existing pipeline infrastructure in the sufficient to satisfy the increasing demand for natural gas in the future? What is the plausible range of the magnitude of future investments in pipeline capacity? How are these investments regionally distributed? Are there conditions under which the pipelines are underutilized?*

Answering these questions requires us to understand how future infrastructure development will be determined by broader domestic and international socioeconomic conditions. For example, the character of technology deployment in demand sectors such as the electric power sector, demographics, and economic growth patterns within the U.S. could shift natural gas demand centers resulting in shifts in infrastructure investment patterns compared to observed historical trends [9]. Likewise, changes in the energy and environmental policy landscapes in Mexico and Canada could affect U.S. pipeline and LNG exports, and thus U.S. energy security. Such interactions underscore the need for an integrated approach to study future natural gas infrastructure development—one that captures the complex *regional and sub-national* factors that affect investments in infrastructure while maintaining consistency with the broader *national* and *global* processes, and conditions.

We answer the above questions in the context of the U.S. We couple a global multi-sector Human-Earth system model with state level detail in the U.S. (GCAM-USA) [10] and a natural gas sector infrastructure investment model with updated data on the newest pipelines in North America (NANGAM) [11,12]. Using this coupled framework, we explore five socioeconomic scenarios of the future that vary across domestic and international natural gas demand patterns. The first scenario, labeled *Reference*, represents a counterfactual scenario to compare other scenarios against. The remaining scenarios are constructed as sensitivity cases of the *Reference* scenario representing high, low, and regionally variegated domestic demand (*High domestic demand*, *Low domestic demand* and *Heterogeneous domestic demand* scenarios respectively) and high international demand (*High international demand*) for natural gas.

Our study makes two important methodological contributions to the literature. First, although a number of previous studies examine future natural gas infrastructure development both in the U.S. and rest of the world [9,12–27] (see Table 1 and Appendix A3 for a literature review summary), they do not consider the broader socioeconomic context. GCAM-USA includes state-level representations of the supply and demand of natural gas along with interactions of the natural gas sector

[4] EIA's AEO2017 projects the United States to be a net energy exporter in most cases. Available at: https://www.eia.gov/todayinenergy/detail.php?id=29433.

with other sectors of the economy under one consistent framework. NANGAM represents natural gas supply and demand in nine regions within the U.S. and includes explicit representation of production, pipeline, LNG, and storage infrastructure, as well as the ability to endogenously determine investment in these infrastructures. Coupling these models enables us to study the development of future inter-state natural gas infrastructure in the U.S. under scenarios of natural gas demand that are internally consistent with domestic as well as international socioeconomic conditions. Second, NANGAM has explicit representations of existing and future pipelines in the U.S updated to the state to state data released by the U.S. Energy Information Administration (EIA) on May 2017. This allows us to credibly track future investment needs under various socioeconomic futures within the context of existing pipeline capacity. Therefore, the main contribution of this study lies on the significance of having an integrated framework to project natural gas infrastructure. This approach allows to perform studies from a completely new modeling perspective that simultaneously considers not only the constraints imposed by global markets and sectors of the economy but also those constraints imposed by existing infrastructure access.

In addition, our study also provides a framework to provide scientific decision-support to natural gas infrastructure planners and agencies (e.g. Federal Energy Regulatory Commission) to be able to assess investment needs and potential risks under various plausible socioeconomic futures. It is important to note that even though our paper focuses on the U.S., the methodology and scenarios developed in this study can be applied to other geographical contexts.

The rest of the paper proceeds as follows. We first provide an overview of the models used in this study (GCAM-USA and NANGAM) and explain the coupling method. We then discuss our scenarios in detail. The subsequent sections describe the results of our analysis and provide broader insights into our findings.

2. Methodology

2.1. Overview of GCAM-USA

GCAM-USA is a multi-sector, multi-scale, human-Earth system model with state-level detail in the U.S [10,28,29]. GCAM-USA includes representations of the energy, economy, and agriculture and land-use systems for 32 geopolitical regions (including the U.S.) across the globe under one integrated framework (Appendix, Sections A4-A5). GCAM-USA further breaks the energy and economy components of the U.S. into 50 states and the District of Columbia in addition to modeling the simultaneous interactions of 31 geopolitical regions outside of the U.S. GCAM-USA is a dynamic-recursive, partial equilibrium model and operates in 5-year time-steps from 2010 (calibration year) to 2100 by solving for the equilibrium prices and quantities of various energy, agricultural, and greenhouse gas (GHG) markets in each time period and in each region. In this study, we focus on results through 2050 only.

The main drivers of GCAM-USA are population growth, labor participation rates, and labor productivity along with representations of resources, technologies and policy. The energy system formulation in GCAM-USA consists of detailed representations of extractions of depletable primary resources such as coal, natural gas, oil, and uranium along with renewable sources such as bioenergy, hydro, solar, wind, and geothermal. GCAM-USA also includes representations of the processes that transform these resources to final energy carriers which are ultimately used to deliver goods and services demanded by end users in buildings, transportation, and industrial sectors. The version of GCAM-USA used in this study also includes detailed representation of natural gas resource production in the form of state-level supply curves for different types of gas resources (conventional gas, coalbed methane, shale gas, tight gas, offshore gas, and other unconventional gas) as well as natural gas trade (Appendix A5).

2.2. Overview of NANGAM

The North American Natural Gas Model (NANGAM) is a long-term partial-equilibrium model of the United States, Mexican, and Canadian gas markets [12]. NANGAM considers a total of 17 nodes, of which nine correspond to the U.S. census regions, one node to Alaska, two nodes to Canada (East and West), and five to Mexico (Northwest, Northeast, Interior-West, Interior, and South-Southeast) (see Appendix A6 for the mapping of the states to U.S. census regions). Of the above-mentioned nodes, there are 13 nodes with natural gas production capacity (census regions 2–9 for the lower-48 states, one for Alaska, two for Canada, and two for Mexico). The 17 nodes are currently connected through 51 representative pipeline links. The version of NANGAM used in this study incorporates all major and new pipeline projects in place as of May 2017 and verified through public media and sources. The model incorporates EIA pipeline data [30], which contains an aggregation of natural gas pipeline and expansion projects slated to commence operations in coming years as well as information on capacity of existing natural gas pipelines crossing between states, international borders, and offshore Gulf of Mexico (see Appendix A7 for NANGAM modeled pipelines). NANGAM also considers storage operators and infrastructure. The model allows for endogenous infrastructure development and expansion, and is built in five-year time-steps up to 2050, considering three seasons (low, high, and peak) for each time-step. The model in its current state can be used to analyze a range of existing or potential policy interventions. These include a host of energy and environmental policies such as tariffs for final demand, taxes or subsidies on production, taxes on emissions, and caps or quota constraints on emissions. All of these policy interventions can be set on a nodal (play or census region), regional, national, or continental level. In conjunction with other fuels, the model can implement different versions of a technology portfolio standard or of regulations regarding the fuel mix in power generation or final demand. NANGAM is written in GAMS and data be retrieved using Microsoft Access. NANGAM is also an outgrowth branch of the Multimod framework [31].

2.3. Coupling of GCAM-USA with NANGAM

We couple GCAM-USA with NANGAM to explore internally consistent scenarios of future natural gas infrastructure development in the U.S. This hybrid modeling approach attempts to close the gap between distinct approaches and perspectives employed in the two models: while NANGAM focuses on the North American natural gas sector supply chain (production, transportation, storage and consumption), GCAM-USA represents changes in the broader economy accounting for a large number of discrete energy technologies and captures the substitution of energy carriers on the primary, secondary and final energy level, process substitution, as well as efficiency improvements. In contrast, NANGAM focuses on the natural gas sector specific infrastructure. NANGAM considers all existing inter-state pipelines in the U.S., with detailed representations of the capacity of gas they can transport including investments costs of old and new projects. NANGAM also has detailed representations of pipelines in Canada and Mexico and considers natural gas trade across U.S., Mexico, and Canada. Hence, linking GCAM-USA and NANGAM provides a unique platform to model detailed natural gas infrastructure and flows under broad socioeconomic conditions.

Hybrid modeling approaches used in the literature broadly fall under three categories. The first approach comprises of coupling independently developed models via "soft-link" approaches [32,33]. The second method focuses on one model type and uses a "reduced form" representation of a second model [34–36]. The third approach provides completely integrated models by "hard – linking" different models, based on consistency of data and the interactions. The choice of hybrid approach is determined by the modeling objective. Soft-linking, to date, has been the most common approach of coupling models [33,37]. In

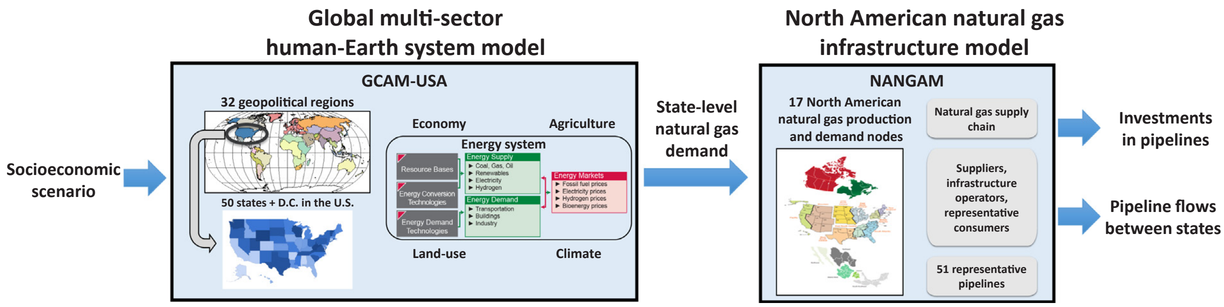

Fig. 1. Data flow in the model coupling.

this approach, modeling frameworks are executed separately and the exchange of data is controlled by the modelers. There are several advantages of soft-linking approaches, including practicality and clarity.

We adopt a soft-linking approach for simplicity and ease of reproducibility. Specifically, we employ a GCAM-USA-first-NANGAM-second coupling method (Fig. 1). We take this approach since GCAM-USA has a broader representation of the energy and economy. Hence, GCAM-USA is able to track changes in natural gas demand that are consistent with changes in other sectors of the broader economy (see [38–40,29] for details about the mathematical models used to calculate the demand in GCAM). For instance, transitions toward low-carbon technologies in the domestic power sector could potentially reduce natural gas demand to meet the finite demand for electricity in the end-use sectors. Likewise, changes in energy policies of importing countries such as Mexico and Canada could affect the demand for U.S. natural gas. In addition, immigration patterns and economic growth within the U.S. could affect the demand for U.S. natural gas both in final energy sectors (for example, buildings and industry) as well as transformation sectors (for example, electricity). We then harmonize the regional demand levels in NANGAM with those provided by GCAM-USA to analyze the development of infrastructure required to meet those demands. The harmonization relies on the different regional disaggregation of states in the U.S., Mexico, and Canada. GCAM-USA provides demand projections toward 2050 for each state while NANGAM considers 10 supply–demand regions in the U.S. (according to the Annual Energy Outlook 2016) and 5 regions in Mexico. Once state-level demand data is passed to NANGAM in the appropriate regional disaggregation, a demand constraint is imposed such that the demand level (provided by GCAM-USA) in each NANGAM region is met in every model period. This methodology allows NANGAM to find the investments and flows in the pipeline network that meet the demand requirements in each region.

2.4. Scenario design

We explore the natural gas infrastructure development in the U.S. under five socioeconomic scenarios that vary across future national and international natural gas demand. The first scenario (*Reference*) represents a counterfactual scenario to compare other scenarios against. This scenario is obtained by harmonizing key inputs and outputs of GCAM-USA (such as GDP and population, power sector technology costs, and investments and production tax credits) with the U.S. Energy Information Administration's Annual Energy Outlook-2016 [41]. The remaining scenarios are constructed as sensitivity cases off of the *Reference* scenario with different levels of domestic and international demands. The second scenario, labeled as *High domestic demand*, represents high natural gas demand across the U.S. driven by domestic constraints on the deployment of coal-fired power plants. This scenario is implemented by limiting the deployment of new coal-fired power plants (turning off the possibility of any new investment in coal-fired power plants in GCAM-USA) during the period of the study (2010–2050). This assumption is consistent with previous work focused on the U.S. [1,10,28,41,42]. The third scenario, labeled as *Low domestic demand* represents low demand for natural gas across the U.S. driven by a systemic transition to a low-carbon economy. This scenario is implemented by constraining economy-wide greenhouse gas emissions in the U.S. consistent with the U.S. mid-century strategy [28]. Specifically, we constrain economy-wide GHG emissions in the U.S. to 17%, 27%, and 80% below 2005 levels in 2020, 2025, and 2050 respectively. This scenario also considers constraints on GHG emissions for the rest of the world consistent with the Increased Ambition scenario in Ref. [43]. The fourth scenario (*Heterogeneous domestic demand*) represents heterogeneous natural gas demand within the U.S. This scenario is implemented by harmonizing regional population projections in GCAM-USA with the Socio-Economic Pathway 5 (SSP5) [44,45], which assumes higher population growth in the U.S. as a whole with heterogeneous growths patterns within the U.S.[5] Specifically, this scenario assumes heterogeneous population growths across the various census regions in the U.S. with states belonging to a census region assumed to grow at the same rate. The data to implement this scenario are obtained from the Environmental Protection Agency (EPA) ICLUS project [45]. The fifth scenario, labeled *High international demand*, represents increased international exports and is implemented by making U.S. LNG exports more economically competitive compared to the rest of the world. To model this scenario, we lower the price of U.S. LNG exports exogenously in GCAM-USA to make it more competitive in the international LNG trade market in GCAM-USA. Specifically, we lowered the price by US$ 0.45/GJ. This exogenous price reduction increases the share of U.S. LNG exports to the Mexican natural gas and other global markets. Although the magnitude of the price reduction is rather arbitrary, this scenario represents an increase in LNG exports of 75% in 2050 compared to the *Reference* scenario. For more context, Appendix A8 compares LNG export projections in this scenario with scenarios in the literature.

3. Results and discussions

3.1. Supply and demand of natural gas in the scenarios explored in this study

The *Reference* scenario is characterized by an increase in the supply of natural gas through 2050 (Fig. 2). Natural gas supply is generated principally in the southern (West South Central), mountains and northeastern (Middle Atlantic) regions (see SI section A5 for the mapping of the states into U.S. census regions) with the West South Central region being the main supplier through 2050. This result is consistent with projections made by the EIA's Annual Energy Outlook (AEO) [1,41].

Natural gas demand in the *Reference* scenario also increases, albeit at a slower pace than supply. In the *Reference* scenario, the U.S. is a net-exporter by 2020. Furthermore, the West South Central region accounts for the highest (and increasing) share of demand for natural gas, followed by South Atlantic and the Pacific regions. The high gas consumption in these regions is driven by an increasing demand from the

[5] This scenario assumes heterogeneous population growths across the various census regions in the U.S. States belonging to a census region are assumed to grow at the same rate.

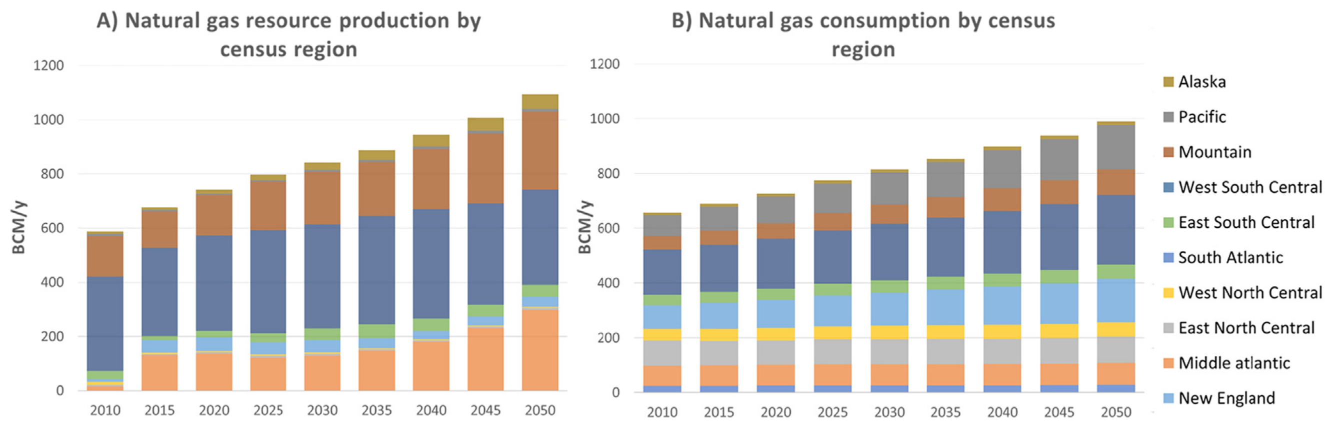

Fig. 2. Natural gas supply (left panel) and demand (right panel) by census region in the Reference scenario in billion cubic meters (BCM) per year.

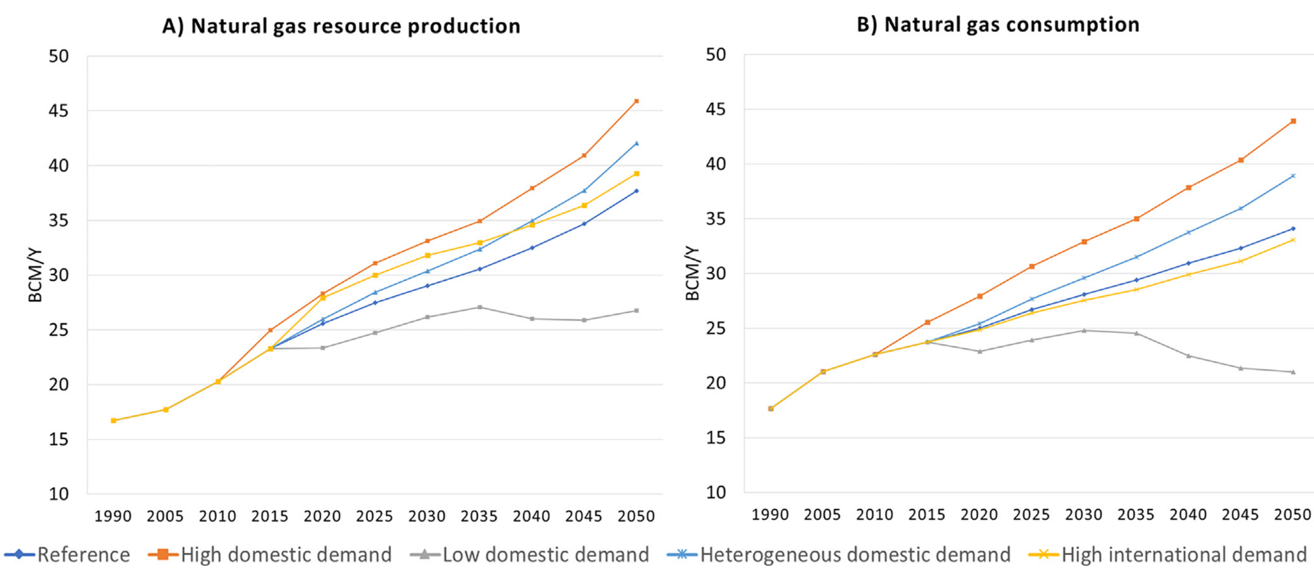

Fig. 3. U.S. natural gas production and consumption across scenarios in billion cubic meters (BCM) per year.

electric power and industrial end-use sectors.

The supply and demand in the remaining scenarios also increase over time; however, the rate of increase and the magnitudes of the supply and demand vary across scenarios, regions and time (Fig. 3). For example, the *Low domestic demand* scenario is characterized by slower increase in natural gas supply compared to the *Reference* scenario due to lower demand (which is by construction). In contrast, the *High domestic demand*, the *Heterogeneous domestic demand*, and the *High international demand* scenarios show an increase in supply compared to the *Reference* case to meet the higher natural gas demands in these scenarios. Interestingly, even though the natural gas supply in the *High international demand* scenario is higher than the *Reference* scenario to meet the increased international demand for gas, domestic consumption is lower. This is because the increase in exports imposes upward pressure on domestic prices and hence reduces domestic consumption. This finding is consistent with the literature [46–48].

The scenarios explored in this paper are also characterized by heterogeneous sub-national patterns of natural gas supply and demand (Fig. 4). For instance, natural gas demand increases in all regions in the *High domestic demand* scenario compared to the *Reference* scenario. This is driven in part by the assumption of no new deployment of coal-fired power plants, resulting in a shift to natural gas fired plants to meet more of the growth in demand for electricity. The increase in cumulative consumption is the highest in the West South Central (1955 bcm higher compared to the *Reference* scenario, corresponding to a 24% increase) and South Atlantic (950 bcm higher compared to the *Reference* scenario, corresponding to a 20% increase) regions. The increased consumption of natural gas in these regions is driven by the economic viability of natural gas in these regions relative to other sources of power generation [49]. In contrast, in the *Low domestic demand* scenario, cumulative consumption of natural gas decreases in all regions relative to the *Reference* scenario.

3.2. Natural gas infrastructure development and utilization in the scenarios explored in this study

Cost-effectively meeting the various levels of future natural gas demands represented in our scenarios requires three important changes, namely, rearrangement of flows across existing pipelines,[6] investments in pipeline capacity,[7] and changes in utilization rates[8] of existing pipelines.

3.2.1. Rearrangement of flows

All of our scenarios are characterized by a rearrangement of flows

[6] In this study, rearrangement of flows refers to the changes in volume (in bcm) across pipelines in a scenario. Flow is the actual volume of natural gas entering a pipeline.

[7] In this paper, investment in pipeline capacity refers to the increase in transportation capacity (natural gas volume in bcm) in each existing pipeline.

[8] In this paper, utilization rate refers to the total volume of natural gas in a pipeline (in bcm) divided by the total transportation capacity of the same pipeline. Hence it reflects the fraction of the total capacity being utilized.

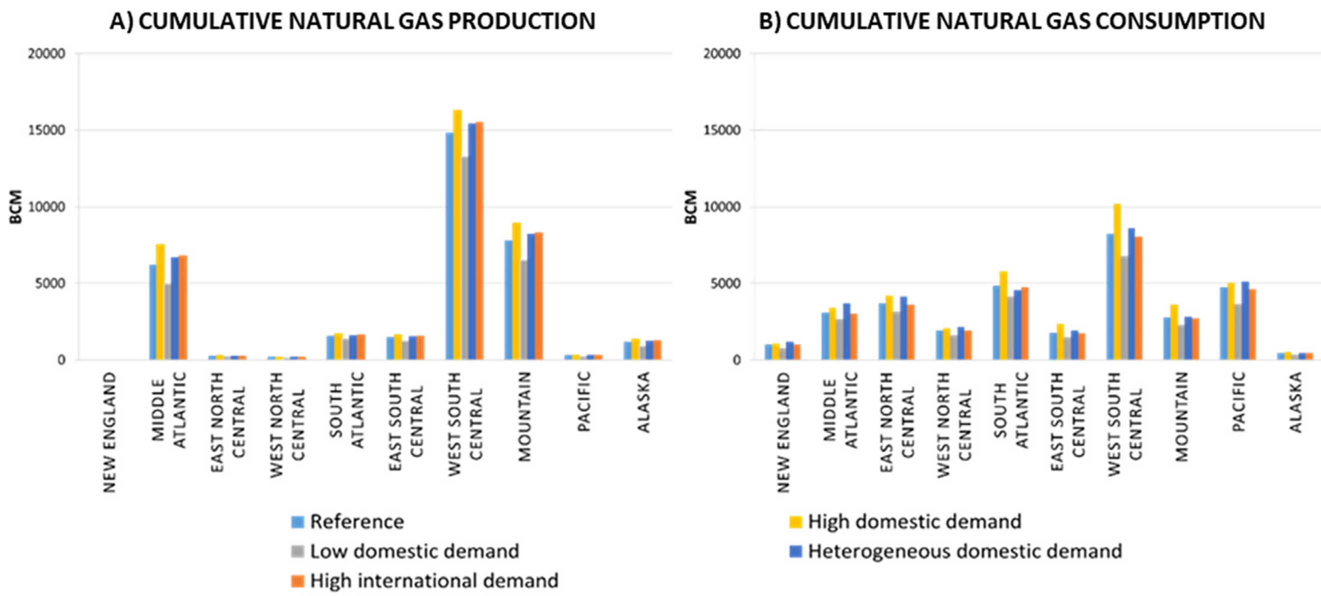

Fig. 4. Cumulative natural gas production and consumption across scenarios and regions in billion cubic meters (BCM).

across existing pipelines (Fig. 5). In all scenarios, the Middle Atlantic region emerges as a new natural gas supply hub (in addition to the West South Central region) due to the increased shale gas supply from the Marcellus and Utica basins. This region supplies demand in New England (replacing supply from Canada-east), East North Central (replacing gas imports from South Atlantic), and South Atlantic regions. This rearrangement of flows affords some leeway to southern regions such as West South Central to redirect flows and export natural gas to Mexico instead of supplying to regions within the U.S.[9] However, the magnitude of exports from the U.S. depend on the level of domestic demand within the U.S. For example, in the *High domestic demand* scenario, the total U.S. pipeline exports to Mexico are reduced by 3% relative to the *Reference* scenario. This is because, this scenario assumes no new deployment of coal power in the U.S. resulting in large increases in the demand for natural gas in the West South Central region. This in turn results in a reduction in the exports to Mexico to supply domestic demand.

3.2.2. Investments in pipeline capacity

In addition to a rearrangement of flows across pipelines, all the scenarios explored in this study are characterized by investments in pipeline capacity (Fig. 6). This investment occurs because existing pipeline infrastructure in the U.S. is not sufficient to meet the projected levels of natural gas demand in all of the scenarios. All scenarios are characterized by investments in the pipelines that connect the Middle Atlantic region to the East North Central region to facilitate the delivery of the increased natural gas supply from the shale-basins in Pennsylvania and West Virginia. As mentioned in Section 3.2.1, the natural gas export planning (pipeline and LNG) relies on capacity of natural gas extraction in Pennsylvania and West Virginia (Middle Atlantic) as well as the transportation via pipelines. This finding resonates with the recently approved Rover pipeline project by the Federal Energy Regulatory Commission.[10] Also, all scenarios show investments in pipelines that connect southern regions (e.g., west-south central) to Mexico, driven by increasing demand from the Mexican power sector. Additionally, in all scenarios except the *Low domestic demand* scenario, investments also occur in the pipeline that connects the Canada-west region to the Pacific region. Interestingly, existing natural gas infrastructure is insufficient even in the *Low domestic demand* scenario and investments in the pipeline that connects the Middle Atlantic region to the East North Central region are required even in this scenario. However, the magnitudes of the investments are lower than the *Reference* scenario.

Furthermore, the increasing demand for cheap natural gas produced in the U.S. results in increased exports to Mexico in all scenario which further results in investments in pipeline capacity in the West Central region to facilitate those exports. Our results also suggest investments in pipeline capacity in Mexico in addition to those within the U.S. to facilitate increased exports to Mexico. These investments are in line with the Mexican energy reform, which seeks to spur the development of the gas industry and improve its access by enhancing the natural gas infrastructure within Mexico and importing pipelines from the U.S. [12,50,51].

The magnitude of investments in pipeline capacity is the highest in the *Heterogeneous domestic demand* scenario even though this scenario does not have the highest levels of natural gas production and consumption at the total U.S. level (Fig. 3). This result is due to the different migration patterns within the U.S. this scenario assumes, resulting in significant increases in demand in key demand centers such as the Pacific and Mountain regions.

3.2.3. Utilization rate of existing pipeline capacity

Even though investments in pipeline capacity are required to meet the demand for natural gas in the U.S. and internationally in all the socioeconomic scenarios explored in this study, the utilization rate (defined as the fraction of that pipeline's capacity that is being utilized) of this infrastructure varies significantly across scenarios (Table 2).

In all scenarios, the utilization rate for the pipeline that connects the Middle Atlantic to the East North Central regions and the pipeline that connects Canada-west to the Pacific regions is 100% in 2050. This result occurs because these are the only pipelines in which investments occur and meeting natural gas demands cost-effectively requires that pipelines in which investments are made are used at the full capacity. However, all scenarios are also characterized by underutilization of the pipelines in which there is no investment. The underutilization of pipelines is even more severe in the *Low domestic demand* scenario. For instance, the utilization rate for pipelines that connect the East South Central to the South Atlantic regions in the *Reference* scenario is about 25% in 2050. In the *Low domestic demand* scenario, the utilization rate drops to about 7% (see Table 2). In this scenario, even though the

[9] This rearrangement of flows further results in pipeline capacity additions in export pipelines to Mexico.

[10] See http://www.roverpipelinefacts.com/. Last accessed on 11/14/2017.

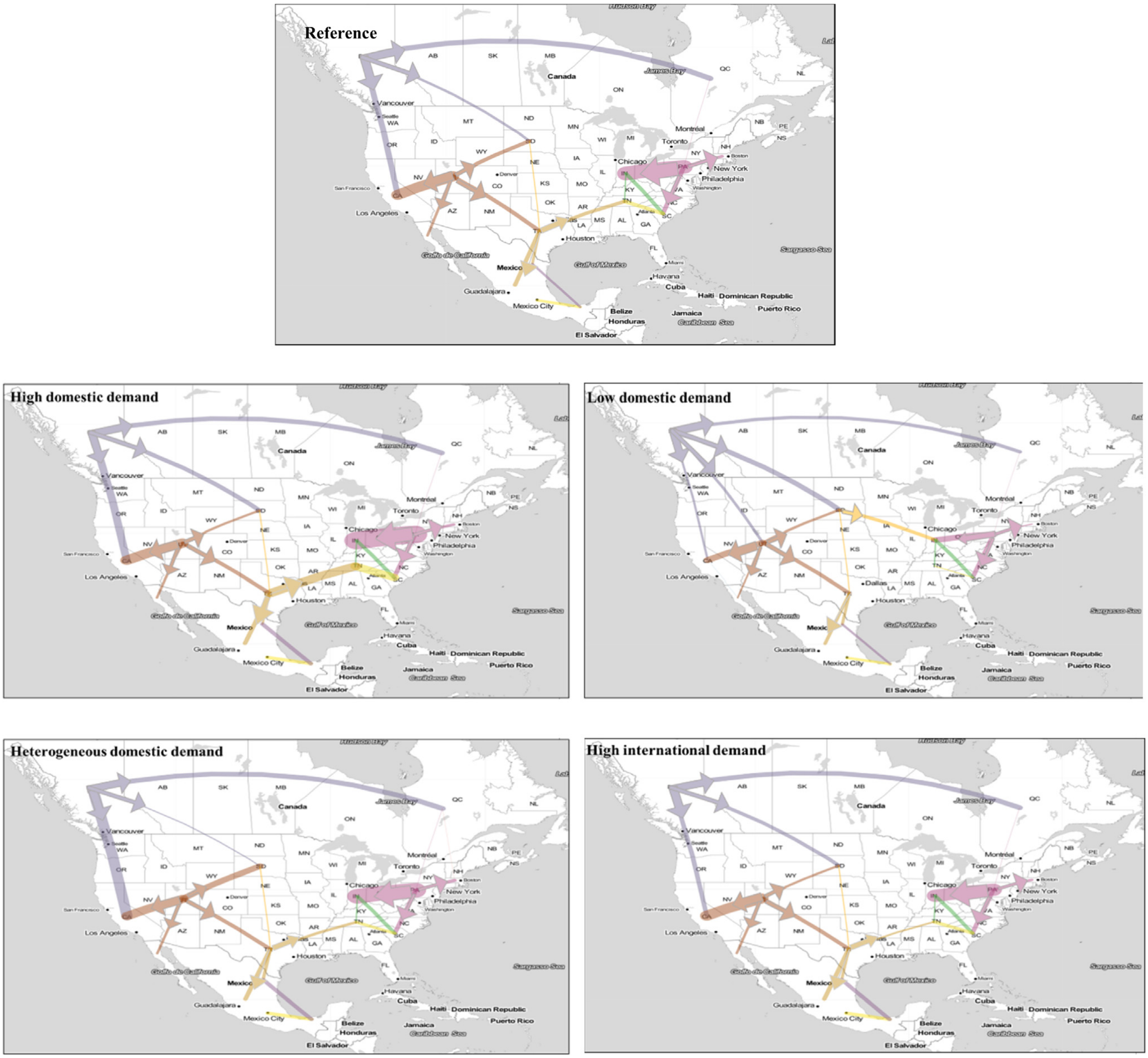

Fig. 5. Natural gas net flows (bcm) in 2050 for major gas pipelines across scenarios. Thickness of the bars indicate the magnitude of flows. Arrows indicate direction of flows. Note that this figure shows only those pipelines that have net flows in 2050, unutilized pipelines are not shown.

Middle Atlantic region emerges as a natural gas supply hub (similar to the other scenarios), the total outflows from this region reduces by 33% in 2050 compared to the *Reference* scenario (Table 3). The shifts in demand patterns within the U.S. in this scenario also results in the West South Central region lowering its supply to the domestic market and increasing exports to Mexico.

3.3. Discussion

The methodology and models utilized in this study allow the design and analysis of plausible future natural gas infrastructure scenarios. The methods developed in our study will be valuable to decision-makers as well as analysts. For example, our results indicate that new pipeline capacity will be required in the U.S. even in a low natural gas demand scenario. These results are critical to provide scientific decision-making support to plan and evaluate new investments by agencies such as the Federal Energy Regulatory Commission (FERC) to regulate inter-state transmission and to grant permission for constructions of pipelines. Likewise, understanding the rearrangement of flows and the role of Middle Atlantic emerging as a natural gas supply hub is critical for future energy planning. In particular, when the U.S. is expected to become a net energy exporter, the potential for future natural gas exports would depend greatly on the capacity of natural gas extraction in the Middle Atlantic and transportation to the demand regions. Furthermore, our study also highlights the need for adequate planning to minimize future risks of underutilization of pipeline capacity. The *Low domestic demand* scenario demonstrates the risks of underutilization of pipelines. Under-utilization of pipelines could create further risks for various stakeholders such as ratepayers, investors and land-owners [52]. Our results thus underline the need for decision-making to incorporate strategies to minimize such risks. For example, the *Low domestic demand* scenario represents a low-carbon future and is characterized by increased deployment of renewable technologies such as wind and solar (see Appendix A9). The risks of underutilization in this scenario could be reduced if, for instance, technological progress in carbon capture and storage (CCS) technologies results in an expansion of natural gas in combination with CCS technologies to supplant the deployment of renewables to meet the demand for electricity under

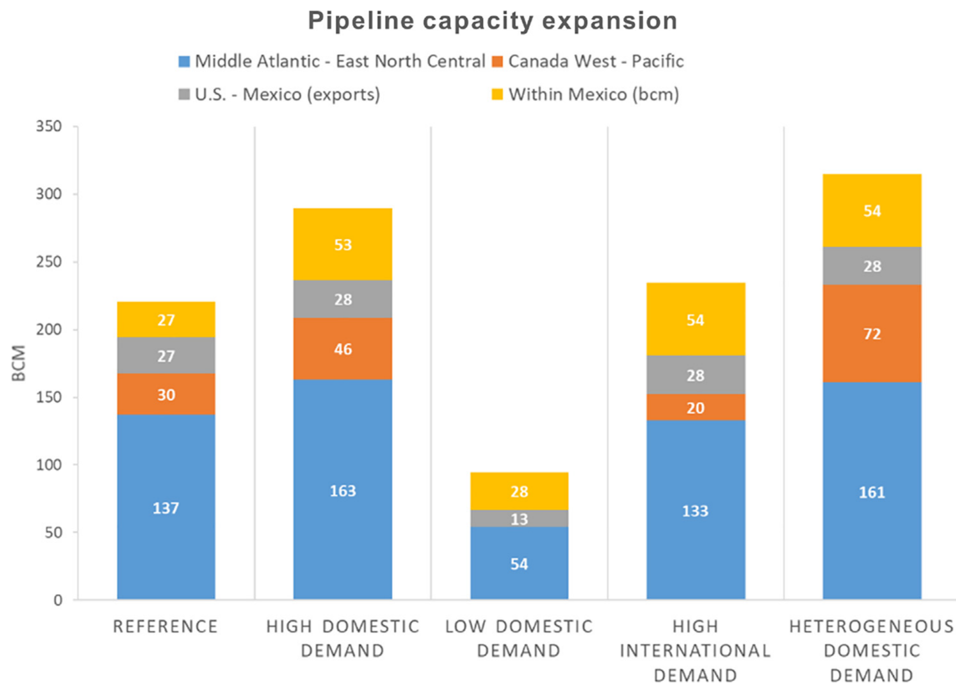

Fig. 6. Additions in pipeline capacity across scenario and regions.

Table 2
Pipeline utilization rate in 2050 across scenarios for a subset of pipelines modeled in NANGAM.

Pipeline	Scenario				
	Reference	High domestic demand	Low domestic demand	Heterogeneous domestic demand	High international demand
Middle Atlantic – East North Central	100%	100%	100%	100%	100%
CAW – Pacific	100%	100%	100%	100%	100%
Mountains – Pacific	85%	85%	53%	74%	88%
West South Central – East South Central	12%	28%	0%	10%	7%
East South Central – South Atlantic	25%	52%	7%	21%	24%
West South Central – Mexico	92%	75%	100%	100%	95%

Table 3
Total outflows by region and scenario over the period 2010–2050.

Region	Reference	High domestic demand	Low domestic demand	Heterogeneous domestic demand	High international demand
New England	0	0	0	0	0
Middle Atlantic	757	897	505	798	828
East North Central	58	60	58	58	69
West North Central	403	444	468	481	403
South Atlantic	197	197	200	197	175
East South Central	710	893	618	704	630
West South Central	1676	1784	1722	1662	1987
Mountain	1201	1170	1004	1307	1283
Pacific	0	0	2	0	0
Total	5002	5445	4577	5207	5374

stringent GHG emission constraints. A detailed examination of strategies to reduce the risks of underutilization is beyond the scope of this paper and is reserved for future work.

For analysts, our work highlights the value of integrated approaches and provides a framework to couple multi-sector human-Earth system models with detailed sector specific models and provide robust decision support. Although we focus on the U.S., the methods developed in this study can be applied to other geographical contexts.

4. Conclusions

This study couples a global multi-sector, multi-scale human Earth system model with state level detail in the U.S. (GCAM-USA) with a natural gas sector infrastructure investment model of North America (NANGAM) to investigate future natural gas infrastructure development in the U.S. under a range of plausible socioeconomic futures. This approach allows us to perform studies from a completely new modeling perspective that simultaneously considers not only the constraints imposed by global markets and sectors of the economy but also those constraints imposed by existing infrastructure access. Our analysis provides three main insights. First, existing pipeline infrastructure in the U.S. is insufficient to satisfy the increasing demand for natural gas and investments in pipeline capacity will be required. This finding is consistent across a broad range of socioeconomic scenarios explored in this paper. Our results suggest the emergence of new natural gas supply hubs – in particular in the Middle Atlantic region of the U.S. due to the availability of shale resources – and also a rearrangement of flows across pipelines in the country. In addition, satisfying future demand for natural gas cost-effectively also requires investments in pipeline capacity. Second, the magnitude of the investments is heterogeneous within the U.S. and depends on the capacity of existing infrastructure as well as the magnitude of demand increase. For example, in most of the scenarios explored in this study, investments occur in the Middle Atlantic, Pacific and West South Central regions. However, under a scenario with low domestic demand for natural gas, existing pipelines in the Pacific region are sufficient and investments in additional capacity are not required in the region. Finally, our results illustrate the risks of under-utilization of existing pipeline infrastructure in the long-term, in particular, under a scenario characterized by systemic transitions toward a low-carbon economy. For example, although the Middle Atlantic region emerges as a supply hub in all our scenarios, an economy-wide transition toward low-carbon technologies results in a reduction of flows from that hub by almost a third compared to a reference scenario that is agnostic to technology. More broadly, our study provides a decision-making framework to assess natural gas pipeline infrastructure development under future socioeconomic scenarios. Our framework and results can provide scientific decision-making support to agencies (e.g. the Federal Energy Regulatory Commission (FERC)) to appropriately plan for future investments while minimizing the risks of underutilization of capacity.

Our study also demonstrates the value of integrated approaches that combine higher-level modeling tools with process-level tools. Nevertheless, the study opens several avenues for future research. Foremost, the mechanism employed to couple the two models does not close the loop in terms of feeding infrastructure information from NANGAM back into GCAM-USA. Future work could investigate how constraints imposed by infrastructure development can influence the expansion of natural gas in key demand sectors such as the power sector. Second, while our study explores simple sensitivity scenarios that span a range of natural gas demand futures, future studies could explore the implications of various technological futures such as a low renewable or high electric car future for inter-state natural gas infrastructure development. Finally, further research is required to examine the natural gas infrastructure development under a broader suite of socioeconomic scenarios such as the ones represented in the Shared Socioeconomic Pathways literature [44].

Acknowledgements

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Appendix A

A.1. Major pipeline crossing multiple state borders (capacity in bcm)

Major pipelines in the U.S. Data per the U.S. EIA available at https://www.eia.gov/naturalgas/data.cfm#pipelines. Released on 5/11/2017. Data last update on 12/30/2016. Data for pipeline capacity was derived from the state to state capacity table for 13.000+ state and international border crossing points.

Pipeline	Segment capacity	2016	2015	2014	2013	2012
Algonquin Gas Trans Co	*Max Capacity*	*18*	*14*	*14*	*14*	*14*
Alliance Pipeline Co	*Max Capacity*	*19*	*19*	*19*	*19*	*19*
Columbia Gulf Trans Co	*Max Capacity*	*27*	*27*	*27*	*27*	*27*
Dominion Cove Point LNG LP	*Max Capacity (Eastward)*	*14*	*14*	*14*	*14*	*14*
Dominion Cove Point LNG LP	*Max Capacity (Westward)*	*12*	*11*	*11*	*11*	*11*
Dominion Transmission Co	*Max Capacity (West)*	*15*	*15*	*15*	*13*	*13*
Dominion Transmission Co	*Max Capacity (Eastward)*	*7*	*7*	*7*	*7*	*7*
East Tennessee Nat Gas Co	*Max Capacity (Eastward)*	*2*	*2*	*2*	*2*	*2*
East Tennessee Nat Gas Co	*Max Capacity (Westward)*	*2*	*2*	*2*	*2*	*2*
El Paso Nat Gas Co	*Max Capacity (West)*	*46*	*46*	*46*	*46*	*46*
Empire Pipeline Inc	*Max Capacity (West)*	*8*	*8*	*8*	*8*	*8*
Florida Gas Trans Co	*Max Capacity*	*31*	*31*	*31*	*31*	*31*
Gas Transmission Northwest	*Max Capacity*	*28*	*28*	*28*	*28*	*28*
Great Lakes Gas Trans Ltd	*Max Capacity*	*25*	*25*	*25*	*25*	*25*
Gulf Crossing Pipeline	*Max Capacity*	*18*	*18*	*18*	*18*	*18*
Gulfstream Natural Gas System (via the Gulf of Mexico)	*Max Capacity*	*13*	*13*	*13*	*13*	*13*
Iroquois Pipeline Co	*Max Capacity*	*12*	*12*	*12*	*12*	*12*
Kern River Gas Trans Co	*Max Capacity*	*25*	*25*	*25*	*25*	*25*
Maritimes/Northeast PL Co	*Max Capacity*	*9*	*9*	*9*	*9*	*9*
Midcontinent Express Pipeline LLC	*Max Capacity*	*19*	*19*	*19*	*19*	*19*
Midwestern Gas Trans Co	*Max Capacity (Northward)*	*7*	*7*	*7*	*7*	*7*
Midwestern Gas Trans Co	*Max Capacity (Southward)*	*7*	*7*	*7*	*7*	*7*

National Fuel Gas Supply Co	*Max Capacity (Northward)*	*8*	*8*	*8*	*8*	*8*
National Fuel Gas Supply Co	*Max Capacity (Southward)*	*5*	*5*	*5*	*5*	*5*
North Baja Pipeline Co	*Max Capacity (Southward)*	*5*	*5*	*5*	*5*	*5*
North Baja Pipeline Co	*Max Capacity (Northward)*	*7*	*7*	*7*	*7*	*7*
Northern Border Pipeline Co	*Max Capacity*	*25*	*25*	*25*	*25*	*25*
Northern Natural Gas Co	*Max Capacity*	*22*	*22*	*22*	*22*	*22*
Panhandle Eastern P L Co	*Max Capacity*	*16*	*16*	*16*	*16*	*16*
Portland Gas Trans Co	*Max Capacity (Southward)*	*2*	*2*	*2*	*2*	*2*
Portland Gas Trans Co	*Max Capacity (Northward)*	*2*	*2*	*2*	*2*	*2*
Questar P L Co	*Max Capacity*	*15*	*15*	*15*	*15*	*15*
Questar Southern Trails Pipeline Co	*Max Capacity*	*1*	*1*	*1*	*1*	*1*
Rockies Express Pipeline	*Max Capacity (Eastward)*	*19*	*19*	*19*	*19*	*19*
Rockies Express Pipeline	*Max Capacity (Westward)*	*21*	*25*	*0*	*0*	*0*
Ruby Pipeline LLC	*Max Capacity*	*16*	*16*	*16*	*16*	*16*
Southeast Supply Header Pipeline	*Max Capacity*	*16*	*16*	*16*	*16*	*16*
Southern Natural Gas Co	*Max Capacity*	*32*	*32*	*32*	*32*	*32*
Southern Star Central Gas PL Co	*Max Capacity*	*13*	*13*	*13*	*13*	*13*
Tallgrass Interstate Gas Transmission	*Max Capacity*	*3*	*3*	*3*	*5*	*5*
Texas Gas Transmission Co	*Max Capacity (Northward)*	*20*	*20*	*20*	*20*	*20*
Texas Gas Transmission Co	*Max Capacity (Southward)*	*8*	*0*	*0*	*0*	*0*
Trailblazer Pipeline Co	*Max Capacity*	*8*	*8*	*8*	*8*	*8*
Transcolorado Gas Trans Co	*Max Capacity*	*7*	*7*	*7*	*7*	*7*
Transcontinental Gas P L Co	*Max Capacity (Northward)*	*49*	*49*	*49*	*49*	*49*
Transcontinental Gas P L Co	*Max Capacity (Southward)*	*7*	*5*	*0*	*0*	*0*
Transwestern Pipeline Co	*Max Capacity*	*13*	*13*	*13*	*13*	*13*
Trunkline Gas Co	*Max Capacity*	*17*	*17*	*17*	*17*	*17*
Tuscarora Pipeline Co	*Max Capacity*	*2*	*2*	*2*	*2*	*2*
Vector Pipeline Co	*Max Capacity (Eastward)*	*14*	*14*	*14*	*14*	*14*
Vector Pipeline Co	*Max Capacity (Westward)*	*14*	*14*	*14*	*14*	*14*
Viking Gas Transmission Co	*Max Capacity*	*5*	*5*	*5*	*5*	*5*
WBI Energy Transmission	*Max Capacity*	*6*	*6*	*6*	*6*	*6*
Wyoming Interstate Co	*Max Capacity*	*23*	*23*	*23*	*23*	*23*

A.2. Approved major pipeline projects by FERC in 2017

Data as of October 31, 2017 available at https://www.ferc.gov/industries/gas/indus-act/pipelines/approved-projects.asp. Pipeline projects approved by FERC are available from 1997–Present.

Company/Project	Capacity (MMcf/d)	States	Filing Date	Issued Date
Atlantic Coast Pipeline, LLC (PF15-6) Atlantic Coast Pipeline Project	1500	NC, VA, WV	10/31/2014	10/13/2017
Texas Gas Transmission, LLC Abandonment of Compression	0	LA	4/26/2017	10/11/2017
Gulf South Pipeline Company, LP	23.5	TX	2/22/2017	5/24/2017
Valley Crossing Pipeline, LLC Border Crossing Project	2600	TX	11/21/2016	10/23/2017
Columbia Gas Transmission, LLC Central Virginia Connector Project	45	VA	8/12/2016	9/6/2017
EcoElectrica, L.P. LNG Terminal Sendout Capacity Increase Project	0	PR	8/11/2016	8/24/2017
Gulf South Pipeline Company, LP St. Charles Parish Expansion Project	133.33	LA	7/11/2016	10/6/2017
High Point Gas Transmission, LLC Abandonment by Sale		LA	7/1/2016	4/4/2017

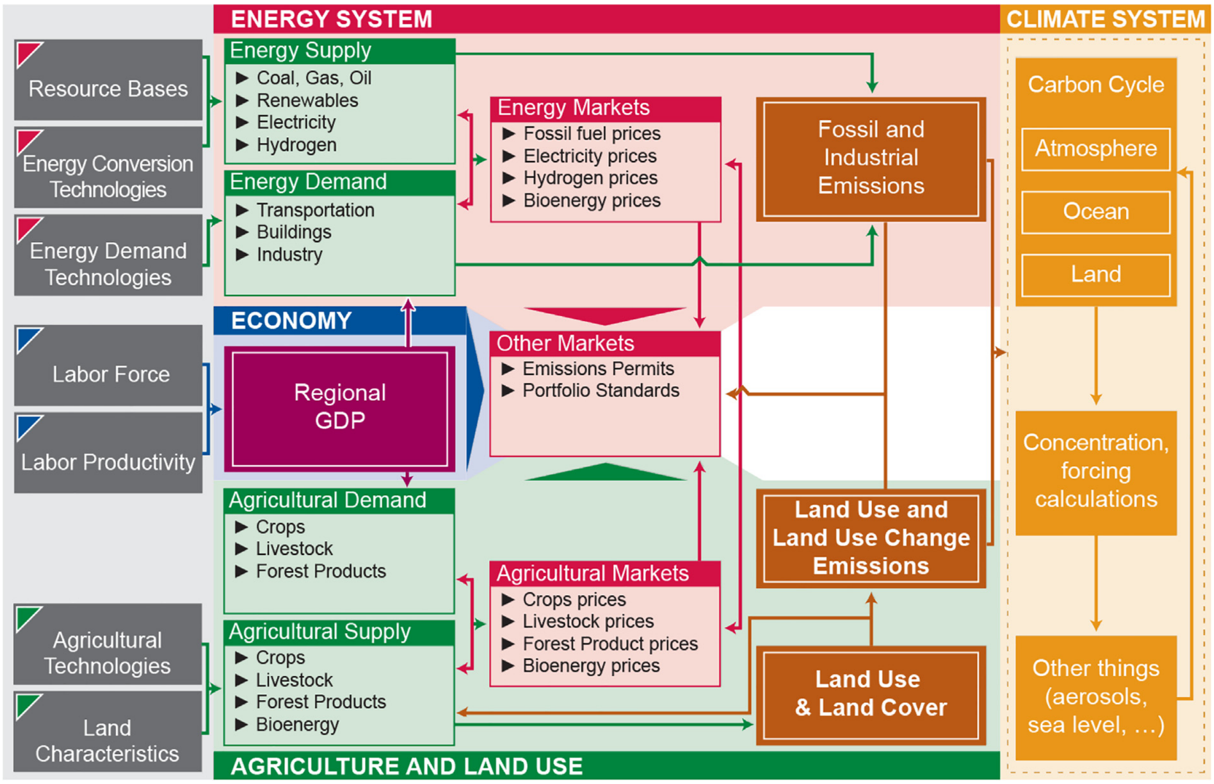
Texas Eastern Transmission, LP Bayway Lateral Project	300	NJ	6/29/2016	7/3/2017
Tres Palacios Gas Storage LLC Cavern Capacity Reclassification Project	0	TX	4/7/2016	9/21/2017
National Fuel Gas Supply Corporation Line Q Pipeline Replacement Project	0	PA	12/3/2015	9/6/2017
Tennessee Gas Pipeline Company, L.L.C The Orion Project.	135	PA	10/9/2015	2/2/2017
Tennessee Gas Pipeline Company, L.L.C. Abandonment and Capacity Restoration Project	0	AR, LA, MS, TN, KY, OH	2/13/2015	9/29/2017
National Fuel Gas Supply Corp/Empire Pipeline, Inc. (PF14-18) Northern Access 2016 Project	497	NY, PA	3/17/2015	2/3/2017
Transcontinental Gas Pipe Line Co., LLC (PF14-8) Atlantic Sunrise Project	1700	MD, NC, PA, SC, VA	3/31/2015	2/3/2017
Rover Pipeline LLC (PF14-14) Rover Pipeline Project (see Panhandle/CP15-94 and Trunkline/CP15-96)	3250	OH, PA, WV	2/20/2015	2/2/2017
Panhandle Eastern Pipe Line Company, LP Panhandle Backhaul Project (see Rover/CP15-93; Trunkline/CP15-96)	750	IN, IL, MI, OH	2/23/2015	2/2/2017
Trunkline Gas Company, LLC Trunkline Backhaul Project (see Rover/CP15-93; Panhandle/CP15-94)	750	IL, MS, TN	2/23/2015	2/2/2017
Tennessee Gas Pipeline Company, L.L.C. Orion Project	135	PA	10/9/2015	2/2/2017
Dominion Carolina Gas Transmission, LLC (PF15-29) Transco to Charleston Project	80	SC	3/9/2016	2/2/2017
Northern Natural Gas Company (PF15-33) Northern Lights 2017 Expansion	75.9	MN	6/24/2016	1/31/2017
Marshall County Mine Panel 17 W Project		WV	9/15/2016	1/26/2017
Algonquin Gas Transmission, LLC & Maritimes & Northeast Pipeline, L.L.C. (PF15-12) Atlantic Bridge Project	239	CT, MA, NY	10/22/2015	1/25/2017
Columbia Gas Transmission, LLC (PF14-23) Leach Xpress Project	1530	OH, PA, WV	6/8/2015	1/19/2017
Columbia Gulf Transmission, LLC Rayne Express Expansion	621	KY	7/29/2015	1/19/2017

A.3. Literature review on natural gas market modeling and infrastructure assessment

Research on natural gas markets and the associated infrastructure has been of global interest. For instance, the Chinese natural gas market, policies and its infrastructure deployment has been studied in [23,25–27]. These studies conclude that import prices are important to determine the infrastructure development and interregional flows within China. However, high import costs compared to the low natural gas capped prices set by the government are likely to exert great pressure on China's price reforms. Hence, pipeline capacity scarcity must be properly managed by the Chinese government. The European gas infrastructure has also been of interest [19–22,53]. Studies show that the European natural gas market presents high integration. However, network congestions and needs for new pipeline capacity in Germany, Denmark and eastern Europe have been identified. Authors have also found that Europe will depend on exports from Africa and Caspian region, leading to added import pipeline capacity [19–21,53]. However, in deep-decarbonization scenarios, Europe's import infrastructure and intra-European transit capacity currently in place or under construction are largely sufficient to accommodate the import needs of the decarbonization scenarios, despite the reduction of domestic production and the increase of import dependency [22]. Several studies have also focused on the U.S. and north American natural gas sector. The U.S. Department of Energy (DOE) analyzed the U.S. gas infrastructure under different demand scenarios from the power sector [9]. Increased demand for natural gas in the power sector will lead to pipeline capacity additions. However, these additions will occur at a slower pace than historical expansion of pipelines. Authors in [11,12] studied the effect of increased Mexican natural gas demand from the power sector. Results show higher U.S. pipeline exports to Mexico, which are possible under a shift of flows within the U.S. and pipeline capacity expansions in both the U.S. and Mexico. It has also been shown that lack of U.S. pipeline capacity has resulted in network congestion and increased transportation costs. The increased prices could be managed by increased storage or additional pipeline capacity [16–18]. Finally, Egging et al. [24] developed the World Gas Model (WGM), a Natural gas supply sector only with demand modeled by sector. In a global context, authors show that the share of LNG and pipeline flows changes over time and region. The European region will require new pipeline import capacity due to proximity to major gas suppliers while LNG will play a major role in the Asian market.

A.4. GCAM-USA model structure

Detail GCAM documentation and information can be accessed at http://jgcri.github.io/gcam-doc/toc.html.



A.5. Representation of fossil fuel resources and natural gas trade in the version of GCAM-USA used in this study

A.5.1. Representation of fossil fuel resources

The version of GCAM-USA used in this study includes updated representations of global fossil fuel resource supply curves. The supply curves are based on resources and cost curves, as represented in the Global Energy Assessment [54]. In addition, we use the BGR [55] country data to “downscale” the Rogner curves to countries, and then aggregate the country data back up to the 32 geopolitical regions in the model.

The version of GCAM-USA used in this study also includes detailed representations of natural gas resources in the U.S. Natural gas resources are represented by means of state-level supply curves (comprising of price and quantity points) for different types of gas resources (conventional gas, coalbed methane, shale gas, tight gas, offshore gas, and other unconventional gas). For on shore gas resources, the quantity points are obtained from the USGS National Assessment of Oil and Gas Resources Update (March 2013) (https://energy.usgs.gov/OilGas/AssessmentsData/NationalOilGasAssessment/Methodology.aspx). From the above data source, the quantity points are derived from information on conventional gas, coalbed gas, shale gas, and tight gas resources by resource basin and “probability of economic extraction” of 95%, 5%, and mean. We then map these resources to the states by using fixed ratios from basin to state across grades. Next, we obtain a low and high extraction cost estimate for each of the grades of natural gas types we model from the IEA ETSAP – Technology Brief P02 – May 2010 and map these to the 95% and 5% probability points respectively to obtain price points for the corresponding quantity points.

For offshore gas resources, we use supply curves from the Bureau of Ocean Energy Management 2010 Resource Assessment (https://www.boem.gov/Oil-and-Gas-Energy-Program/Resource-Evaluation/Resource-Assessment/Index.aspx). These curves are available in the form of price and quantity points, and maximum recoverable resource quantities.

To account for other resources not captured in the aforementioned data sets given that they were not developed for the mid-century time horizon consistent with this study, we also include a generic “unconventional gas other” resource. This resource is constructed by downscaling higher grades of unconventional gas resources for the whole of the U.S. from the Rogner data-set to the state level according to the state’s share of total unconventional USGS gas resources (coalbed methane, shale gas, tight gas).

We assume that the supply curves obtained above move downward in every time-step due to technical change.[11] Finally, to calibrate the model to historical production by state and resource type, we use a combination of EIA natural gas data sets from “AEO2014 Market Trends – Figure data – May 7, 2014” and EIA’s annual historical Natural Gas Gross Withdrawals and Production (https://www.eia.gov/dnav/ng/ng_prod_sum_a_EPG0_FGW_mmcf_a.htm). The historical quantities from the above data sources are scaled to match total natural gas production estimates for the U.S. from the International Energy Agency to ensure consistency with the rest of the model.

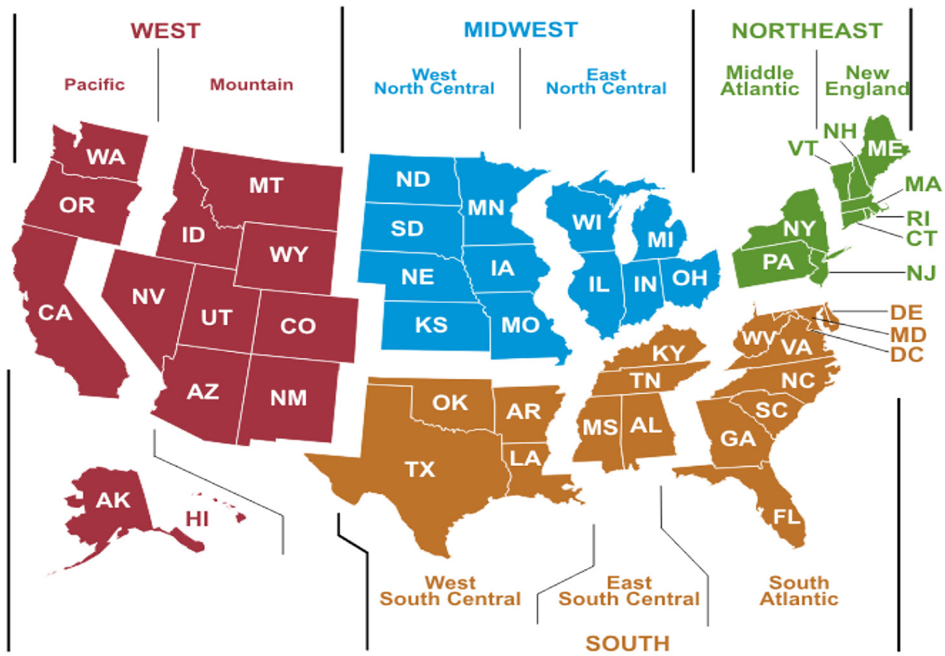
A.5.2. Representation of natural gas trade

In addition to detailed natural gas supply curves, the version of GCAM-USA used in this study also includes a representation of natural gas trade.

[11] Extraction costs for each natural gas resource type are assumed to improve at an annual rate of 1.7% from 2011 through 2050. Two resource types, shale gas and unconventional gas other, are assumed to experience improvement rates of 5% from 2011 to 2015 and 1.7% thereafter.

International trade in natural gas currently occurs among regionally interconnected pipeline markets as well as globally via shipped liquefied natural gas (LNG). Trade movements are sensitive to economic developments linked to energy supply and demand dynamics in gas origin and destination regions. In our representation, we assume that LNG is traded in a global market. In other words, all regions within GCAM-USA can supply natural gas to a global LNG market and can import LNG from this market. In contrast, pipeline gas is traded in six trade blocs defined by the geographic extent of exporting regions. The North American trade bloc comprises of USA, Mexico and Canada. Thus, the U.S., Mexico and Canada supply natural gas to a "traded North American pipeline gas" market from which the countries can import. Imports and exports of pipeline gas and LNG for each GCAM region are calibrated in the model base year (2010) using data from the BP Statistical Review of World Energy 2011 ("Natural gas: trade movements 2010," page 29).

A.6. Mapping of states to U.S. census regions [56]



Division 1
New England

Connecticut
Maine
Massachusetts
New Hampshire
Rhode Island
Vermont

Division 2
Middle Atlantic

New Jersey
New York
Pennsylvania

Division 3
East North Central

Illinois
Indiana
Michigan
Ohio
Wisconsin

Division 4
West North Central

Iowa
Kansas
Minnesota
Missouri
Nebraska
North Dakota
South Dakota

Division 5
South Atlantic

Delaware
District of Columbia
Florida
Georgia
Maryland
North Carolina
South Carolina
Virginia
West Virginia

Division 6
East South Central

Alabama
Kentucky
Mississippi
Tennessee

Division 7
West South Central

Arkansas
Louisiana
Oklahoma
Texas

Division 8
Mountain

Arizona
Colorado
Idaho
Montana
Nevada
New Mexico
Utah
Wyoming

Division 9
Pacific

Alaska
California
Hawaii
Oregon
Washington

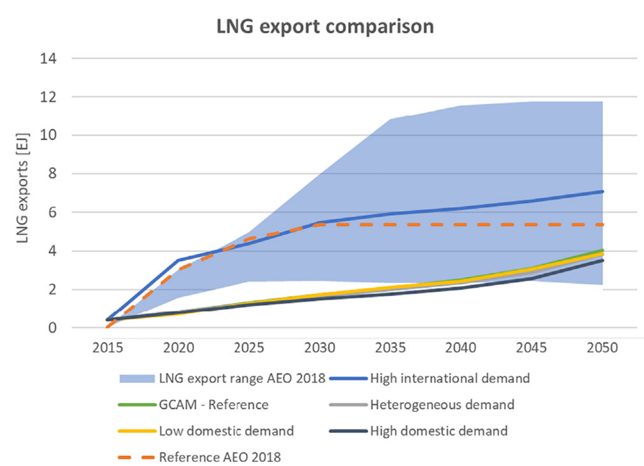
A.7. Pipeline projects modeled in NANGAM

Pipeline connecting NANGAM regions. Pipeline capacity was developed based on the U.S. state-to-state pipeline capacity data available at https://www.eia.gov/naturalgas/data.cfm#pipelines.

Region Out	Region In	Pipeline Capacity (bcm)
N_ALK	N_US8	6.0
N_CAE	N_US1	11.8
N_CAE	N_US2	33.3
N_CAE	N_US3	16.5
N_CAE	N_US4	0.3
N_CAW	N_US4	50.8
N_CAW	N_US8	56.8
N_CAW	N_US9	18.9
N_CAW	N_CAE	162.0
N_MEX1	N_US9	6.3
N_MEX2	N_US7	8.9
N_MEX2	N_MEX5	7.3
N_MEX4	N_MEX3	6.9
N_MEX5	N_MEX4	16.4
N_US1	N_CAE	2.2
N_US1	N_US2	5.4
N_US2	N_CAE	2.7
N_US2	N_US1	36.6
N_US2	N_US3	9.2
N_US2	N_US5	39.5
N_US3	N_CAE	42.0
N_US3	N_US2	22.1
N_US3	N_US4	10.0
N_US3	N_US5	34.7
N_US3	N_US6	11.6
N_US3	N_US1	0.001
N_US4	N_CAE	0.7
N_US4	N_US3	149.9
N_US4	N_US7	9.4
N_US4	N_US8	32.9
N_US5	N_US2	97.7
N_US5	N_US3	22.0
N_US5	N_US6	6.8
N_US5	LNG export	–

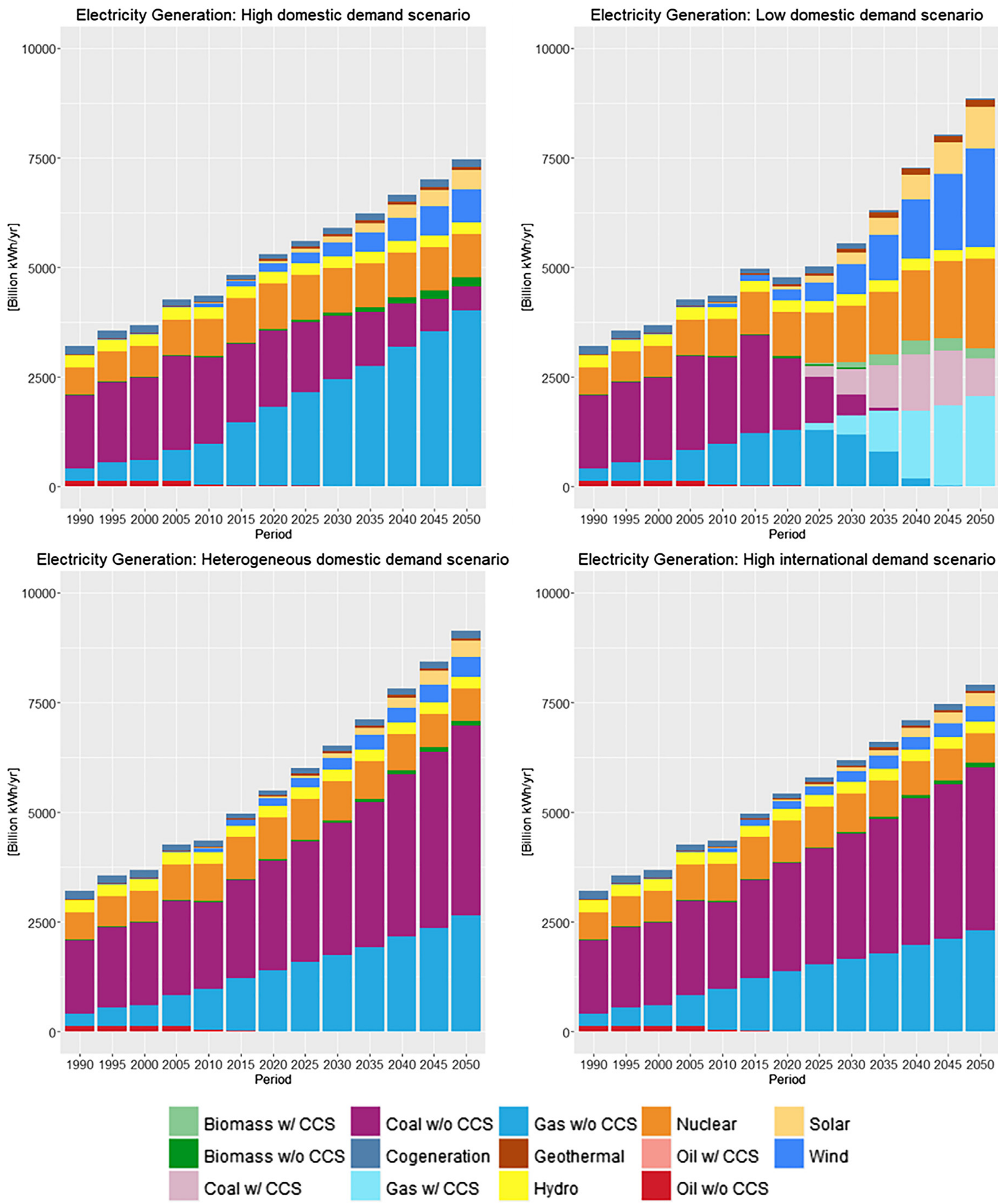
N_US6	N_US3	95.8
N_US6	N_US5	156.4
N_US6	N_US7	15.1
N_US7	N_MEX2	27.4
N_US7	N_MEX3	25.9
N_US7	N_US4	91.5
N_US7	N_US6	311.5
N_US7	N_US8	50.0
N_US7	LNG export	–
N_US8	N_CAW	0.8
N_US8	N_MEX1	7.3
N_US8	N_US4	99.4
N_US8	N_US7	39.6
N_US8	N_US9	127.2
N_US9	N_CAW	0.5
N_US9	N_MEX1	8.5
N_US9	N_US8	14.4

A.8. High international demand: U.S. LNG exports comparison



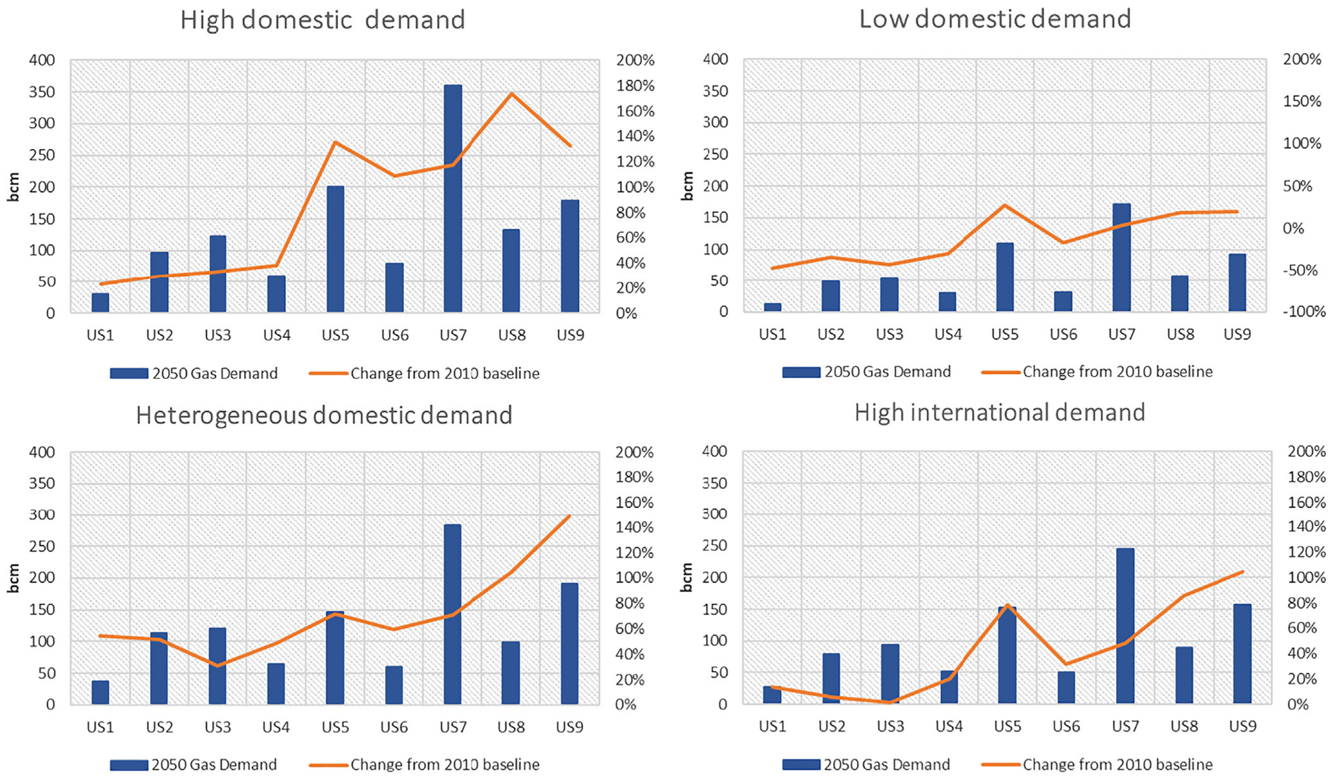
U.S. LNG exports are obtained endogenously in GCAM-USA as part of a global LNG market. To model the *High international demand* scenario in this paper, a price reduction to U.S. LNG exports was performed to make U.S. more competitive and therefore get a higher market share. The figure above shows a comparison of the U.S. LNG exports obtained in the *High international demand* scenario relative to LNG export projection in the literature. The U.S. LNG exports modeled in this scenario is within the range of projections by the Annual Energy Outlook. In 2050, LNG exports in the *High international demand* scenario is about 75% higher relative to the *Reference* scenario.

A.9. U.S. Electricity generation by fuel by scenario

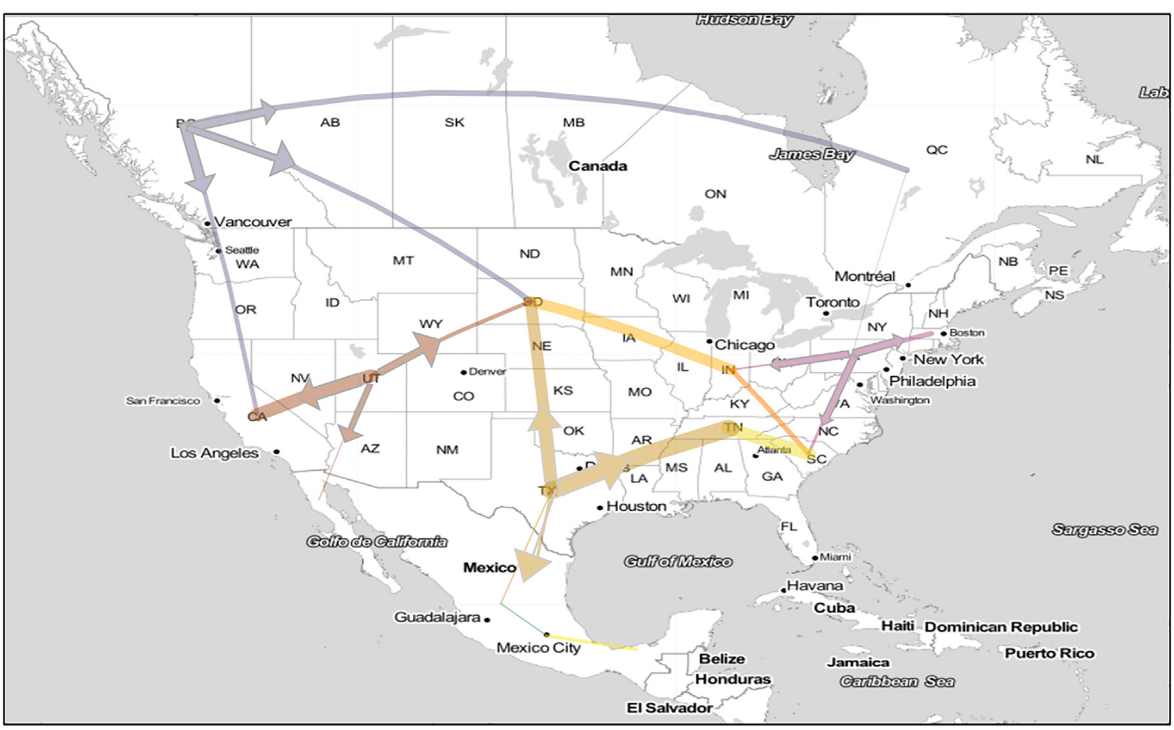


A.10. Natural gas demand changes by scenario

Natural gas demand changes from 2010 baseline level (line) and 2050 net demand level (bar plot)



A.11. 2015 Net natural gas flows in the Reference scenario



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