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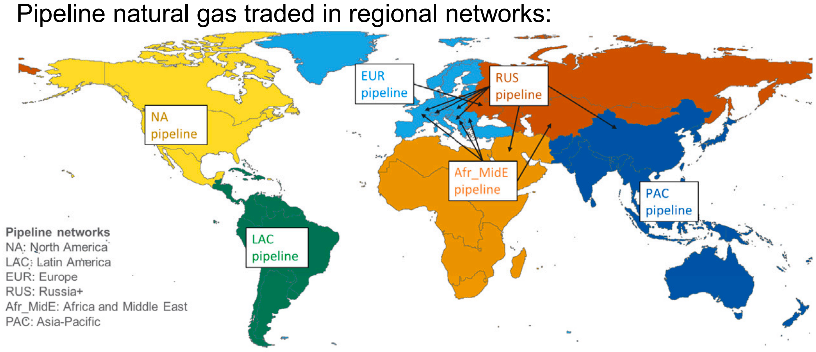
The future evolution of global natural gas trade

Global natural gas trade in this study:

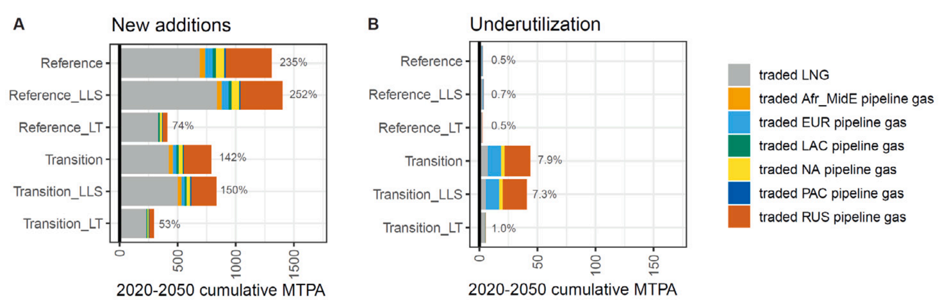
- Pipeline natural gas traded in regional networks:



- LNG traded in a single global pool

Scenario factors explored:

- Economy-wide energy system transitions
- LNG trade infrastructure costs
- Trade barriers



Brinda Yarlagadda, Gokul Iyer, Matthew Binsted, Pralit Patel, Marshall Wise, Jeff McLeod

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Highlights

Global gas trade through LNG and pipelines is expected to grow in the future

But LNG makes up a dominant share of gas trade

New LNG export infrastructure ranges from 230 to 840 MTPA by 2050 across scenarios

New pipeline export infrastructure ranges from 70 to 620 MTPA by 2050 across scenarios

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The future evolution of global natural gas trade

Brinda Yarlagadda,[1,3,*] Gokul Iyer,[1] Matthew Binsted,[1] Pralit Patel,[1] Marshall Wise,[1] and Jeff McLeod[2]

SUMMARY

Understanding the long-term evolution of natural gas is critical in the context of long-term energy system transitions. Here, we explicitly represent traded pipeline and liquefied natural gas (LNG) infrastructure in the Global Change Analysis Model (GCAM). We find LNG to make up a dominant share of gas trade, as it can be flexibly shipped across regions. New global investments in LNG and pipeline export infrastructure respectively range from 230 to 840 and 70–620 million tons per annum (MTPA) by 2050 across scenarios; the lower end of this range is achieved through transitioning to low-carbon energy systems along with limited trade. Our results also highlight diverging implications for regions based on their gas trade profiles. For example, Russia, which produces gas largely for pipeline exports may experience greater production losses due to liquefaction and shipping improvements and geopolitical shifts than regions oriented more toward domestic and LNG markets, such as USA and Middle East.

INTRODUCTION

Natural gas is an important source of energy with widespread use in the electricity, industry, and buildings sectors.[1] Natural gas combustion results in low emissions compared to the combustion of other fossil fuel sources of coal and refined petroleum products.[2] Natural gas-fired power plants serve as a source of firm electricity capacity which can be particularly important as countries transition their grids to utilize higher levels of variable renewable electricity sources.[3] Natural gas trade is a key contributor to GDP in several exporting economies, e.g., contributing to 12% of GDP in Qatar and 6% of GDP in Russia,[4] and it has been important for meeting energy demands in many importing countries, particularly in Asia and Europe.[1] However, dependence on natural gas imports, particularly pipeline gas imports, also poses energy security risks for importing countries due to the fact that pipeline gas trade entails a fixed source and destination. For example, recent geopolitical events have highlighted energy security risks in Europe, which is heavily reliant on natural gas imports via pipeline.[5,6] The desire to reduce import dependency has resulted in increased gas prices and concerns about meeting energy demands in Europe.[7–9]

Across energy commodities, there is a wide range in the physical distances across which trade occurs. Commodities such as oil and coal, which can be readily shipped, are more easily traded globally, while commodities such as electricity, which requires a network of transmission lines, have much more localized trade. Natural gas falls in the middle. Historically, most natural gas trade occurred through pipeline networks, which are physically limited to a regional scale.[10] However, the trade of liquefied natural gas (LNG), which is first cooled to liquid form for transport and then re-gasified at its destination, has been growing rapidly. LNG exports have more than tripled since 2000 and made up just over half of international gas trade in 2018.[11,12] Emerging LNG infrastructure, such as floating storage and regasification units offer further potential for LNG to be supplied to more regions globally, beyond those regions with onshore gas terminals in place. Natural gas trade capacity is set to increase further in the coming decades; gas trade infrastructure under construction and proposed corresponds to an increase of 85% and 28% in LNG terminal (liquefaction, storage, and regasification) and pipeline capacity, respectively.[13] Natural gas trade is unique among energy commodities in that the two dominant means of trade have very different physical and market characteristics, and as a result, have different future growth expectations (see Table S1 for further details).

Several factors could affect the future evolution of natural gas trade. On the supply side, increases in resource availability could shift regional production, trade, and consumption patterns around the word. For example, in the United States, the shale gas revolution enabled the US to switch from being a net importer of LNG to a major net LNG exporter.[14] On the demand-side, reduced trade, and transportation service demands due to the COVID-19 pandemic temporarily lowered gas demands.[15] Regional transitions to a low-carbon economy and the availability of renewable energy and electricity storage technologies could also lower demand for natural gas. On the other hand, regions transitioning away from higher-emission fuels such as coal could have higher demands for natural gas in the near-term.[16] Trade-related factors, such as the availability and cost of different trade infrastructure or geopolitical barriers to trade, could affect the trajectory of overall natural gas production, consumption, and trade, as well as the relative growth of LNG versus traded pipeline gas across different regions. It is therefore important to consider the interactions between multiple factors affecting natural gas trade, as well as the evolution of the natural gas trade sector within the context of other sectors of the energy system and the economy.

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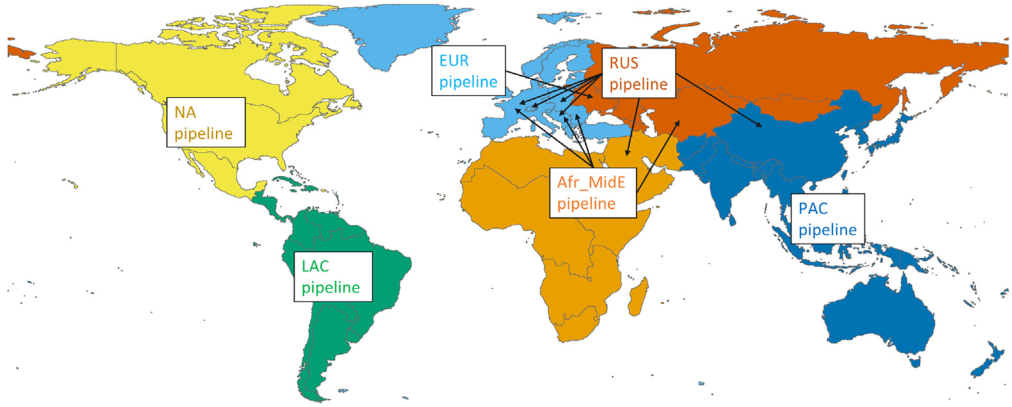

Figure 1. Pipeline network blocs

Regions shown with the same color form a "pipeline network bloc", and trade pipeline gas among themselves. In addition, some regions may also import gas from additional bloc(s), as shown with arrows. These trade patterns are consistent with current trade flows.[35,36] A full table of which regions can import from/export to each pipeline network bloc is shown in Table S4.

Several studies have evaluated the future dynamics of fossil fuel markets. Studies have considered the dynamics of specific fuels with detailed sectoral models, e.g., Auger et al.[17] for coal and Madhavi & Nuttall[18] for oil. Other studies have looked broadly across the energy system to understand how fossil fuels will compete with other technologies under a range of scenarios varying economic growth, deployment of transitions to low carbon energy systems, and fossil fuel availability.[19–22]

Similarly, models analyzing the future evolution of natural gas trade can be generally grouped into two classes: 1) detailed natural gas sectoral models and 2) multi-sectoral models that include some representation of natural gas supply and demand (see Table S2 for previous studies of each class). Detailed natural gas sectoral models generally represent pipeline gas and LNG as distinct trade pathways, and many of them represent detailed supply chain agents within each trade pathway.[14,23,24] However, these models generally do not consider the interactions and competition across natural gas and other energy supply technologies, nor do they consider the interactions across multi-sectoral demands for natural gas. On the other hand, multi-sectoral models aim to provide more holistic representation of the energy system with a full suite of supply technologies to meet endogenous, multi-sectoral demands.[9,25–29] However, these models have historically not explicitly included the representation of pipeline gas and LNG trade pathways and investments required for each.

Recently, a few multi-sectoral modeling studies have included explicit representation of pipeline gas and/or LNG trade pathways.[30–32] IEA's World Energy Outlook 2022[31] provides global-level pipeline gas and LNG trade projections for scenarios representing different levels of climate policy achievement (comparison plots with our results shown in Figures S9–S13), and qualitatively describes regional trends. However, regional-level pipeline gas and LNG trade flows are not quantified. Moreover, broader factors affecting the evolution of natural gas trade are not explored. Shepard et al.[32] use the MESSAGEix-GLOBIOM integrated assessment model (IAM), with pipeline and LNG trade pathways (see Table S3 for comparison of gas trade across IAMs). They explore the effects of energy trade tariff policies and a global carbon tax on overall global energy trade network characteristics (e.g., size and diversity of supply). Trade flows of coal, oil and LNG are included, but pipeline gas trade is not assessed. The models used in Feijoo et al.[30] explicitly represent global LNG and regional pipeline trade, in competition with other energy technologies to meet multi-sectoral energy demands. However, their study focuses on North America, looking specifically at future US gas trade investments, and therefore does not analyze the evolution of LNG and pipeline gas trade flows globally. Similarly, many natural gas trade studies have largely focused on within-country or within-continental region trade.[8,9,29,30,33,34] As a result, the global trade dynamics of LNG and pipeline gas, under a wide range of scenarios remains underexplored.

Our work aims to contribute to recent advances in the representation of natural gas trade in the multi-sectoral modeling literature space. We explicitly represent LNG and pipeline gas as separate trade pathways in the Global Change Analysis Model (GCAM) version 5.4, and further quantify future investment levels in both. GCAM is a long-term, global, multi-sector model representing the interactions of natural gas with other energy sectors and the broader economy. Each region's natural gas demand is met by either domestically produced or imported gas, enabling the tracking of gross imports and exports of natural gas across regions. LNG is traded in a single, global market, similar to other fossil fuel or agricultural commodities. Pipeline gas is traded in six regional pipeline blocs (Figure 1). — North America (NA), Latin America (LAC), Europe (EUR), Russia+ (RUS), Africa and Middle East (Afr_MidE), and Asia-Pacific (PAC)— consistent with current trade flows.[35,36]

Using GCAM with this new natural gas trade infrastructure capability, we explore a range of scenarios to understand how economy-wide energy system transitions, trade infrastructure costs, and trade barriers might affect the future evolution of natural gas trade (Table 1). Although a wide range of factors could affect the evolution of natural gas, we focus on the above factors since they are expected to result in different dynamics or competition between traded pipeline gas and traded LNG. We explore two alternative economy-wide energy system pathways. The *Reference* pathway reflects GCAM's default assumptions about the evolution of the energy system and is the counterfactual against which to compare the other scenarios. For more context, population in the *Reference* scenario grows from 7.4 billion to 9.3 billion,

Table 1. Scenario design

Scenario	Economy-wide transition	Trade infrastructure	Trade barriers
Reference	Reference evolution of the energy system	Reference assumptions about Liquefaction and Shipping Costs	Reference assumptions involving low barriers to trade
Reference_LLS	Reference evolution of the energy system	Low Liquefaction and Shipping Costs (LLS)	Reference assumptions involving low barriers to trade
Reference_LT	Reference evolution of the energy system	Reference assumptions about Liquefaction and Shipping Costs	High trade barriers resulting in limited trade (LT)
Transition	Transition to low-carbon energy	Reference assumptions about Liquefaction and Shipping Costs	Reference assumptions involving low barriers to trade
Transition_LLS	Transition to low-carbon energy	Low Liquefaction and Shipping Costs (LLS)	Reference assumptions involving low barriers to trade
Transition_LT	Transition to low-carbon energy	Reference assumptions about Liquefaction and Shipping Costs	High trade barriers resulting in limited trade (LT)

GDP from $89 trillion to $206 trillion (2020$), primary energy consumption from 550 EJ to 870 EJ, electricity generation from 24,000 TWh to 59,000 TWh, and final energy consumption from 430 EJ to 650 EJ globally between 2015 and 2050. The *Transition* pathway entails a shift from growing fossil fuel use toward low- and no-carbon energy technologies, with a linear decline to zero energy system CO_2 emissions in 2050 globally. Note that our *Transition* pathway does not account explicitly for countries' policy commitments. Under each of these economy-wide energy system pathways, we explore alternative assumptions about trade infrastructure costs and trade barriers. The *Low Liquefaction and Shipping Cost (LLS)* assumption is intended to represent the potential for more rapid advances in LNG liquefaction and shipping technology. *LLS* is modeled by linearly reducing the costs of liquefaction and shipping on traded LNG to half from their 2015 levels by 2050 globally (see Table S5 for details). The *Limited Trade (LT)* assumption is intended to represent the potential for geopolitical or energy security concerns to limit the growth of natural gas trade. *LT* is modeled by imposing constraints on gas imports of both traded LNG and traded pipeline gas. In gas exporting regions and developed regions that are gas importers with sufficient resources, the constraint phases out gross gas imports by 2030. In developed regions that have low natural gas resources and developing regions that are gas importers, the constraint maintains the same share of net imports in the region's total natural gas consumption throughout the century. A detailed description of the regional groupings in the *LT* scenarios is provided in Table S7.

RESULTS

Global traded natural gas grows over the coming decades

In most of our scenarios, globally traded gas increases by 2050 (Figure 2). In 2015, 92 EJ of natural gas was domestically produced and consumed, while 28 EJ of natural gas was traded, out of which 16 EJ was traded through pipelines and 12 EJ was traded as LNG. By 2050, under the *Reference* scenario, the quantity of traded LNG is larger than that of traded pipeline gas globally (37 EJ and 34 EJ, respectively). The faster growth of LNG over the coming decades reflects increasing preferences for it over pipeline gas, in line with expectations of LNG's increased dominance due to improvements in LNG infrastructure technology, allowing LNG to be shipped more widely around the world.[6]

In the *Transition* scenario, traded gas is 41% lower in 2050 than in the *Reference* scenario, due to global energy system transitions toward lower-carbon fuels. The *Low Liquefaction and Shipping Cost (LLS)* assumptions result in 21% and 18% increases in LNG and 9% and 9% decreases in pipeline gas in 2050 relative to *Reference* and *Transition*, respectively. On balance, *Reference_LLS* and *Transition_LLS* increase traded gas by 7% and 6% in 2050 relative to *Reference* and *Transition* and decrease the consumption of domestically produced gas by 1% and 2%, respectively.

In contrast to all other scenarios, the *Limited Trade (LT)* scenarios result in decreased traded natural gas by 2050, due to the import constraints in these scenarios. Under the *Reference_LT* and *Transition_LT* scenarios, traded LNG in 2050 is 67% and 58% lower than the *Reference* and Transition scenarios, respectively. In addition, pipeline gas in 2050 is 85% and 76% lower. In order to meet the demand for gas, *Reference_LT* and *Transition_LT* result in 28% and 27% higher domestically produced gas consumption compared to *Reference* and *Transition*, respectively.

Regional natural gas trade varies widely

Gas production, trade, and consumption patterns are widely different across regions and scenarios (Figure 3). Under the *Reference* and *Transition* scenarios, the USA, Middle East, and Russia are the largest natural gas producers in 2050, which is consistent with historical patterns. While the USA, Middle East, and Europe were the largest natural gas consumers in 2015, and remain so in 2050 under the *Reference* scenario, China becomes the largest gas consumer by 2050 under the *Transition* scenario. In 2050, Europe, USA and Middle East have substantial decreases in gas consumption under *Transition* relative to *Reference* (59%, 56%, and 48%, respectively). These regions have relatively lower shares of coal in their energy mix under *Reference*. In contrast, China and India, regions with high shares of coal in *Reference*, experience

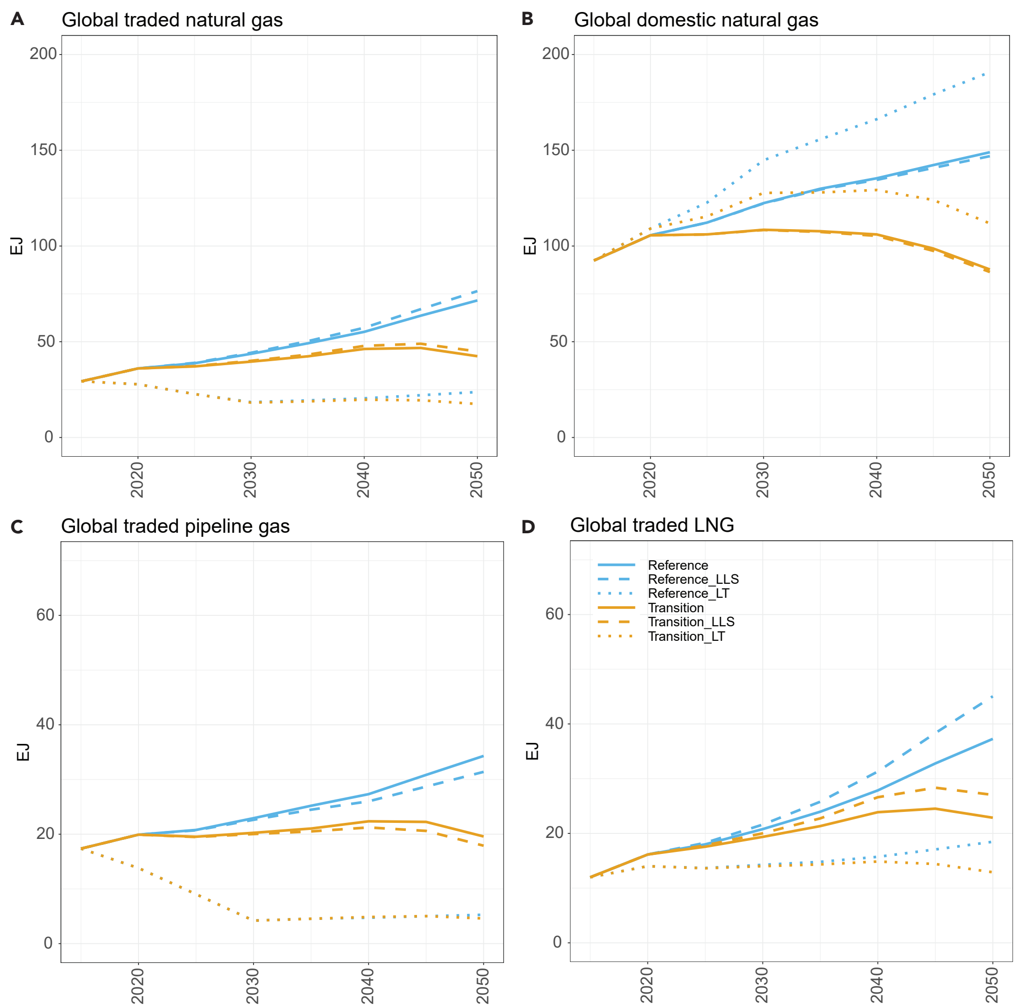

Figure 2. Global natural gas projections

(A) traded natural gas, (B) domestic natural gas (produced and consumed within the same region), (C) traded pipeline natural gas, and (D) traded LNG through 2050.

only 10% and 17% decreases in gas consumption, respectively. In the *Transition* scenario, it is more economical to reduce coal consumption and continue the use of natural gas, including in combination with carbon capture and storage (CCS) in these regions (Figures S6–S8). Such transitions are consistent with previous studies.[5,37] See Text S1 and Figures S9–S13 for detailed comparison of our results with results from the IEA World Energy Outlook[5,31] and IPCC AR6 database.[38]

While many regions focus most of their gas production on meeting domestic demand, a few regions export more than half of their total gas production, including Russia (55%), Central Asia + Eastern Europe (61%), and Europe (62%) in the *Reference* scenario in 2050. Meanwhile, even though many regions are able to meet most of their demand with domestic production, a few regions are much more reliant on imports, importing close to or more than half of their natural gas consumption, including China (48%), Europe (78%) and East Asia (97%) in the *Reference* scenario in 2050. Major gas exporters differ in their reliance on pipelines versus LNG to export gas. For example, Russia exports 85% of its total gas exports through pipelines in 2050 *Reference,* while USA exports only 21% of its gas exports and the Middle East only 3% through pipelines, with the remaining share exported as LNG. Among major importers, there is also diversity in import pathways. For example, 75% of Europe's gas imports flow through pipelines, in contrast with 59% in China and 0% in E. Asia in 2050 *Reference,* with the balance of imports transported as LNG. Overall, regional trade patterns are similar, though smaller in magnitude, under *Transition* compared to *Reference.* Note that the Reference and *Transition* scenarios do not explicitly include recent geopolitical trends. Those are implicitly modeled in the *Limited* Trade scenarios, which are discussed subsequently.

Across regions, *Low Liquefaction and Shipping costs (LLS)* increase traded LNG production and consumption, while decreasing domestic and traded pipeline gas (Figures 4A and 4B). In many regions, the increase in exported LNG results in increased net natural gas production, but a few regions have small decreases in gas production. For example, in Russia, a decrease of 1.4 EJ of pipeline exports outweighs an

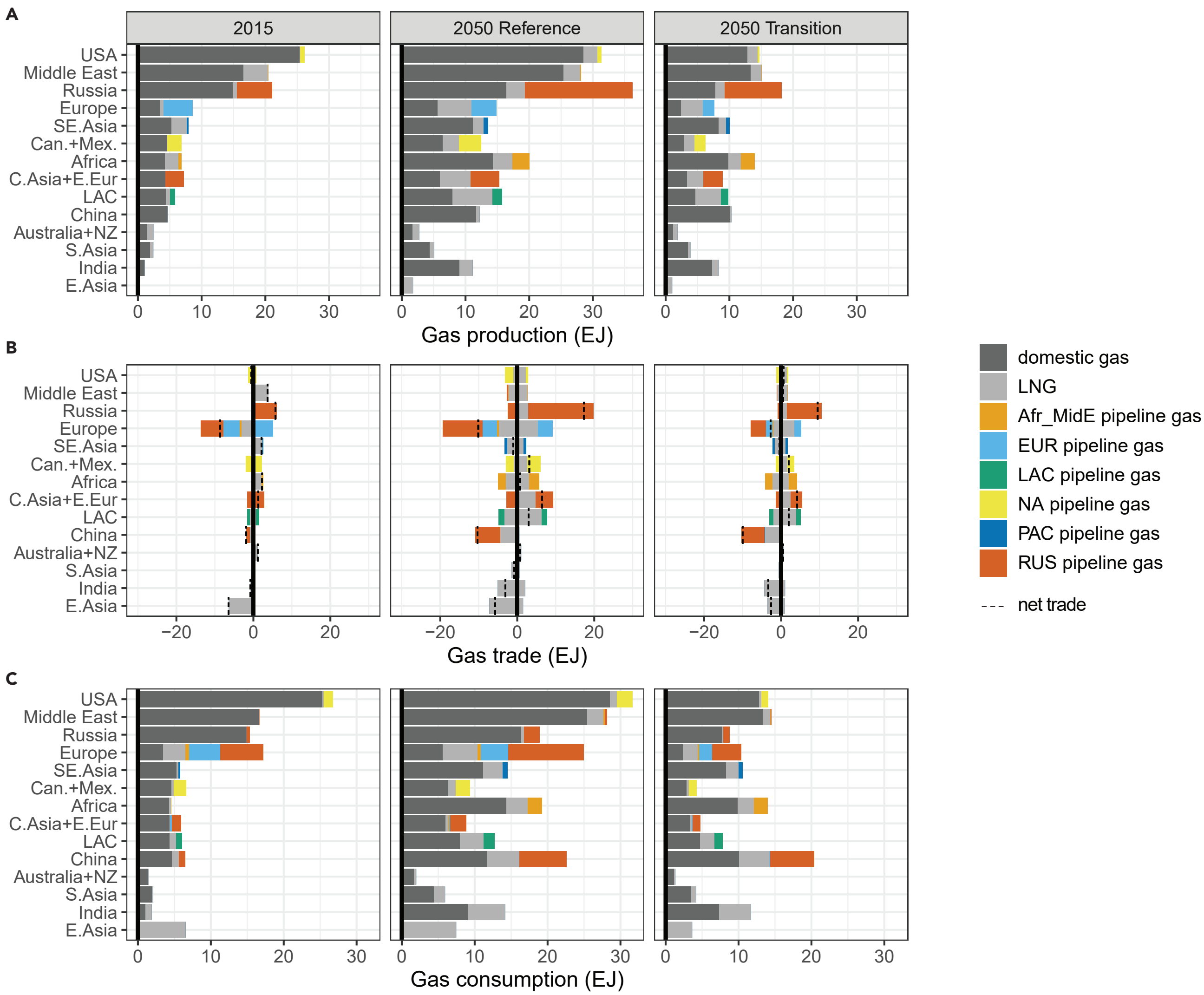

Figure 3. Regional natural gas projections under Reference and Transition scenarios

(A) gas production, (B) gas trade, and (C) gas consumption across aggregated regions in 2015 and 2050 Reference and Transition. In the gas trade figure (B), gross exports are shown to the right of the y axis, gross imports are shown to the left of the y axis, and net trade is shown with a dashed line. For simplicity, some regions have been aggregated from multiple GCAM regions. Note that Europe includes GCAM regions: EU-12, EU-15, Europe_Non_EU, and EFTA. C. Asia + E. Eur includes GCAM regions Central Asia and Eastern Europe. See Table S10 for full aggregated region groupings.

increase of 1.1 EJ of LNG exports under *Reference_LLS* compared to *Reference* in 2050. In most regions, the increase in imported LNG results in increased net natural gas consumption, which substitutes for other fuels (Figure 4C). However, a few regions have negligible changes in gas consumption. For example, in the USA and Middle East, cheap domestic gas supplies are already amply available, and LNG cost breakthroughs do not significantly change regional gas prices, therefore they do not induce much additional demand for gas.

Limited Trade (LT) decreases both traded LNG and pipeline gas across regions, resulting in increased consumption of domestically produced gas (Figures 4D and 4E). In some major gas exporting regions, such as Russia and Central Asia + Eastern Europe, lack of trade results in less overall natural gas production. These regions are net exporters that export more than half of their gas production in the *Reference* scenario. Under *Reference_LT* in 2050, although Russia shifts 3.9 EJ of its gas production to domestic markets, it is outweighed by 16 EJ of reduced gas exports (93% of which are pipeline exports). On the other hand, gas producing regions which predominantly produce for their domestic market, such as the USA and Middle East, increase overall gas production under the *Reference_LT* scenario. In both cases, net gas exporting regions increase their gas consumption, switching away from other fuels (Figure 4F), because they have ample domestic gas resources available that they cannot export. Importing regions, particularly China and Europe, decrease their gas consumption when trade is limited, switching mainly to bioenergy and other fossil fuels. Under *Reference_LT*, China decreases gas consumption by 3.6 EJ (14%) relative to *Reference* in 2050. In Europe, gas imports are fully phased out by 2050 (a reduction of 19 EJ) and gas consumption decreases by 6.5 EJ (26%)

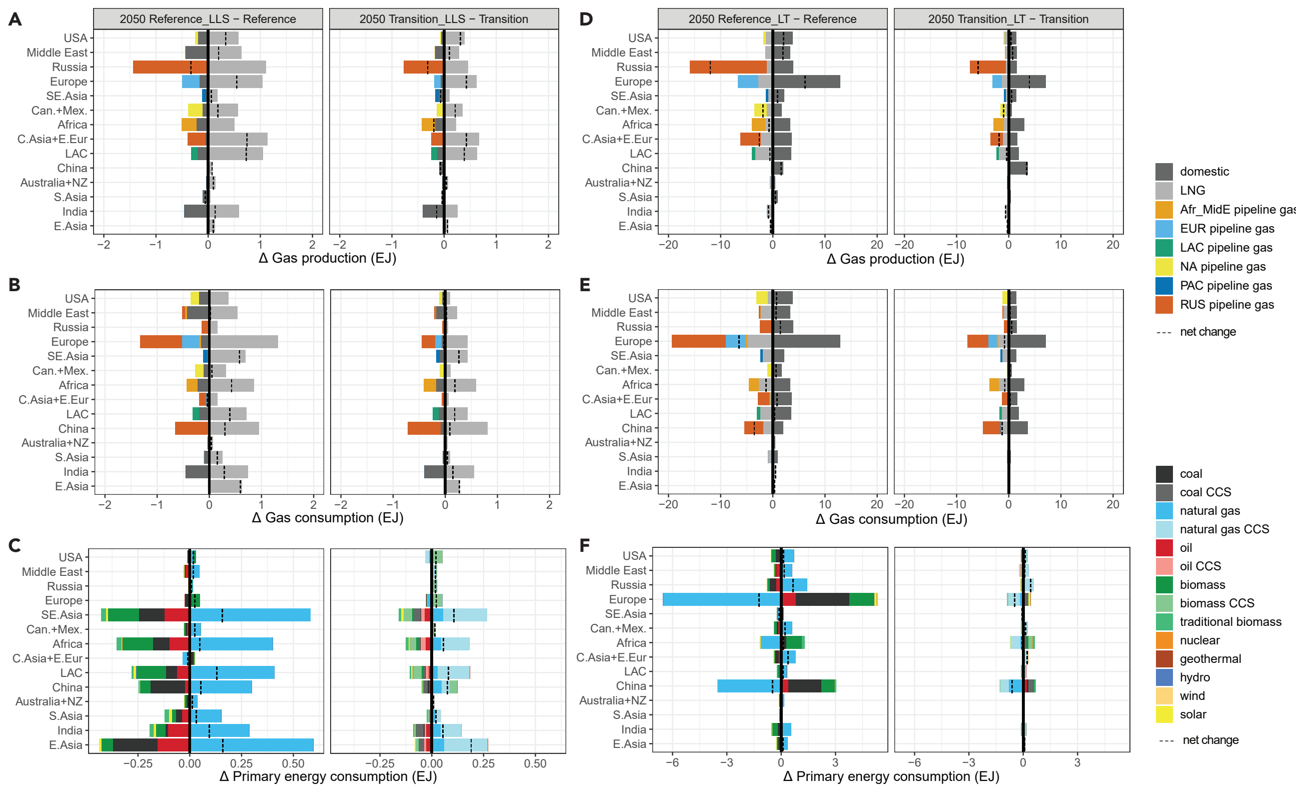

Figure 4. Regional projections under alternative trade patterns

(A) change in gas production, (B) change in gas consumption, and (C) change in primary energy consumption in 2050 *Low Liquefaction and Shipping Cost (LLS)* scenarios.

(D) change in gas production, (E) change in gas consumption, and (F) change in primary energy consumption in 2050 *Limited Trade (LT)* scenarios, relative to base *Reference* or *Transition* scenarios. Net changes are shown with a dashed line. For simplicity, some regions have been aggregated from multiple GCAM regions. Note that Europe includes GCAM regions: EU-12, EU-15, Europe_Non_EU, and EFTA. C. Asia + E. Eur includes GCAM regions Central Asia and Eastern Europe. See Table S10 for full aggregated region groupings.

relative to *Reference*. Domestic gas production increases by 13 EJ (230%) and 2.0 EJ (17%) respectively in Europe and China relative to *Reference*.

Assumptions about trade infrastructure costs and trade barriers under the *Transition* scenarios (*Transition_LLS* and *Transition_LT*) result in similar trends as their corresponding *Reference* counterparts (*Reference_LLS* and *Reference_LT*, respectively). However, changes in gas production and consumption are lower in magnitude, since less natural gas is used in the overall energy system. Additionally, under *Transition* scenarios, many regions switch between gas with CCS and other low-emission technologies (Figures 4C and 4F). For example, in regions that increase gas consumption under *Transition_LT*, such as the USA, Middle East and Russia, there is a shift from bioenergy with CCS or oil with CCS toward gas with CCS. On the other hand, in much of Europe and China, there is a decrease in gas CCS resulting in a shift toward coal with CCS, renewables and other technologies.

Investments in natural gas trade infrastructure are needed

Across scenarios, investments in new pipeline and LNG trade infrastructure are needed globally to meet increased demands (Figure 5). Between 2020 and 2050, 1310 million tons per annum (MTPA) of traded natural gas export capacity, including both pipeline and LNG infrastructure, are added in the *Reference* scenario. Out of the new added export capacity, 52% is new LNG infrastructure, 30% is new pipeline infrastructure in the Russia+ network, and the remaining new pipeline infrastructure comes from other pipeline networks around the world. *Low Liquefaction and Shipping costs (LLS)* result in additional LNG infrastructure being built over the coming decades. The *Reference_LLS* scenario has 148 MTPA of additional LNG export capacity added between 2020 and 2050 compared to *Reference*, with less new additions needed in each of the pipeline networks. The *Transition* and *Limited Trade (LT)* scenarios result in less new additions relative to *Reference*. The *Transition and Reference_LT* scenarios have 40% and 52% less additions by 2050 compared to *Reference*, respectively. In combination, under the *Transition_LT* scenario, there is 230 MTPA of new gas export capacity added between 2020 and 2050, 72% less than under the *Reference* scenario. For context, current global liquefaction capacity stands at 478 MTPA, while proposed aspirational liquefaction capacity (pre-decisional) is estimated at 997 MTPA.[6]

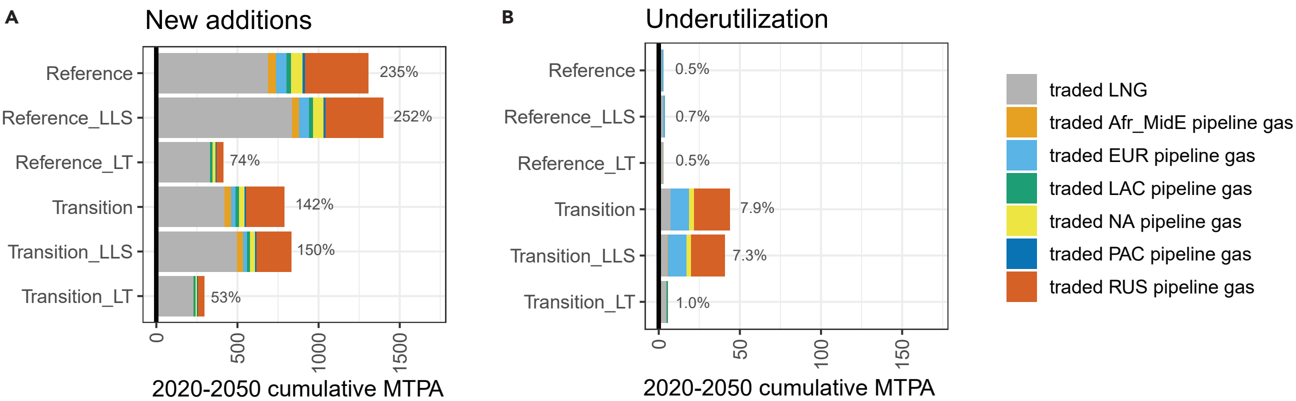

Figure 5. Pipeline and LNG export capacity additions and underutilization

(A) 2020–2050 cumulative new export capacity additions, (B) 2020–2050 cumulative export capacity underutilization. Underutilization is capacity that has already been built but is not operated at full capacity. MTPA = million tons per annum. Percentages beside each bar represent the percentage relative to 2015 capacity that the cumulative new additions or underutilization represent for each scenario. See Figure S3 for import capacity additions and underutilization. See Figures S2 and S4 for 2050 cumulative capacity additions and underutilizations by region.

Risks of underutilized capacity exist in the *Transition* cases exist as energy systems transition to low-carbon fuels, although they represent a small percentage of total capacity. The *Transition* and *Transition_LLS* cases have 44 and 41 MTPA of cumulative underutilized capacity by 2050, respectively. In the *Transition* scenario, 26% and 50% of this underutilized capacity is in the Europe and Russia+ pipeline networks, respectively.

DISCUSSION

This study explicitly represents LNG and pipeline gas as separate trade pathways in a state-of-the-art multi-sectoral model, quantifying the future evolution of and investment levels in each. Across our scenarios, global traded natural gas ranges between 60% and 260% of 2015 levels, with traded LNG ranging between 110 and 380% and traded pipeline gas ranging between 27 and 200% of their 2015 levels. Our scenarios project 230–1460 MTPA of new gas export infrastructure needed between 2020 and 2050, 53–81% of which is new LNG export infrastructure. The increased growth of traded LNG over pipeline gas reflects expectations of its increasing dominance as it can be shipped more widely around the world.

Increased natural gas trade opens opportunities to use natural gas to meet increasing demands for electricity, energy in industry and buildings, and fertilizers. However, increased natural gas trade also presents costs and potential risks in a world of shifting geopolitics and broader economy-wide transitions. Our results highlight how costs and potential risks diverge across regions based on each region's natural gas trade status and overall energy system profile.

For importing regions, increased reliance on traded gas—particularly traded pipeline gas—and its associated trade infrastructure could represent a potential risk for economies in maintaining secure supplies of energy. Thus, many importing regions are looking at different strategies to enhance energy security.[39] Advances in LNG technology, such as the reduction of liquefaction and shipping costs, could help reduce dependence on pipeline gas imports from a limited set of trade partners, allowing regions to import natural gas more flexibly from a wider set of regions. For example, Europe imports 62% of its total gas consumption—75% of which through pipeline— under a reference scenario in 2050 and reduces its pipeline import dependency to 69% under a scenario with lower liquefaction and shipping costs. As is consistent with recent strategies in Europe aiming to meet gas shortages due to ongoing geopolitical events, increased LNG trade can serve as a way to hedge against the risk of potential sudden loss of gas supply due to geopolitical events impacting pipeline trade.[34,40] However, this strategy could require significant investment in new LNG trade infrastructure (Figures 5 and S3).

Importing regions may also meet increased energy demands with a combination of domestic gas production (in regions that have domestic resources, such as Europe) and shifts to other fossil and renewable resources, as seen in our scenarios with limited trade. Alternatively, transitioning to a low-carbon energy system facilitates less demand for natural gas within each region's energy system, as regions instead switch to renewable and low-carbon fuels.[40] However, it is important to note that importers experience different levels of gas consumption reduction. For example, under a scenario with an economy-wide transition to low-carbon fuels, China only reduces gas consumption by 10% relative to a reference scenario by 2050. However, Europe reduces gas consumption by 59%. This finding is consistent with regional differences in gas consumption reduction in the literature, e.g., between IEA's STEPS and APS scenarios[31] (Figure S11).

Overall, transitions to low-carbon energy systems globally result in less gas trade and less need for gas trade infrastructure. For example, our *Transition* scenario results in 40% less cumulative new additions in natural gas export capacity globally by 2050. These transitions could thus also reduce dependence on gas imports, which in some cases, could improve energy security.[27] In our study, the combination of transitioning to a low carbon energy system and limited trade results in the lowest level of new natural gas trade capacity additions across scenarios explored in this study. While risks of underutilized capacity might increase under transitions to low-carbon energy systems, natural gas with CCS technologies can potentially mitigate this risk, by maintaining some demand for natural gas.[30]

For net exporting regions, the implications of shifting trade patterns— due to technological advancements in LNG or geopolitical shifts—depend on whether the region largely produces gas for exports versus for the domestic market, and whether the region largely exports via pipeline or LNG. For example, Russia, which exports 55% of its gas production (85% of which through pipelines) in 2050 under a reference scenario, experiences 1% and 33% declines in production respectively under low liquefaction and shipping cost and limited trade assumptions. Thus, regions which largely produce gas for exports, and largely export through pipelines, may experience larger production losses as a result of advances in LNG liquefaction and shipping technology, or due to geopolitical shifts that disrupt trade. While not directly comparable with our limited trade scenarios, recent geopolitical events resulting in Russia's diminished trade position highlight the risks of its historical dependence on pipeline exports.[27]

On the other hand, regions such as the USA or Middle East, which largely produce for the domestic market with a relatively smaller share of exports and have a larger share of exported LNG as compared to exported pipeline gas do not experience loss of production due to shifts in trade patterns explored here. Nevertheless, all exporters also face particular risks associated with increasing trade infrastructure. For LNG exporters, new capital infrastructure can pose a significant cost, as the liquefaction plants required at export terminals are much more capital intensive and take much longer to build than the required infrastructure (storage and regasification plants) on the import side.[10]

Our work opens several avenues of future research. Foremost, future work might explore the uncertainty around the costs of pipeline and LNG infrastructure, and the costs of natural gas transport. Further research could look into the regional economic implications of natural gas trade expansion or limitation, taking into account recent regional investments in natural gas trade infrastructure. Finally, the modeling capability developed in this study also lends itself to research on implications of alternative energy futures for investments, underutilization, and premature retirements of natural gas trade infrastructure, as has been done in the power sector.[41,42]

Limitations of the study

This study has focused on a few initial exploratory factors. Several other factors, in addition to and in combination with the factors we have chosen here could yield different future pathways for pipeline gas and LNG. Our study does not include infrastructure requirements for the internal transportation of gas within GCAM regions. Our study does not include energy penalties associated with liquefaction, regasification and shipping, which would be helpful in further comparing the trade of natural gas with the trade of other energy commodities. These limitations can be considered for future work.

STAR★METHODS

Detailed methods are provided in the online version of this paper and include the following:

- KEY RESOURCES TABLE
- RESOURCE AVAILABILITY
  - Lead contact
  - Materials availability
  - Data and code availability
- METHOD DETAILS

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.isci.2024.108902.

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AUTHOR CONTRIBUTIONS

Conceptualization: G.I., M.W.; methodology: B.Y., M.B., J.M., and G.I.; software: B.Y., M.B., and J.M.; formal analysis: B.Y., data curation: B.Y., M.B., and J.M., writing – original draft: B.Y., writing – review and editing: G.I., M.B., P.P., and M.W.; visualization: B.Y.; supervision: G.I., M.B.; project administration: G.I. and M.W.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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STAR★METHODS

KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Deposited data		
Model input data	This study	https://doi.org/10.5281/zenodo.7689562
Model output data	This study	https://doi.org/10.5281/zenodo.8392736
Software and algorithms		
GCAM	Joint Global Change Research Institute	https://github.com/JGCRI/gcam-core

RESOURCE AVAILABILITY

Lead contact

Further information and requests for resources should be directed to and will be fulfilled by the Lead Contact, Brinda Yarlagadda (brinda.yarlagadda@pnnl.gov)

Materials availability

This study did not generate any new physical materials.

Data and code availability

- The Global Change Analysis Model (GCAM) is an open-source model, available at https://github.com/JGCRI/gcam-core. Documentation detailing the natural gas trade structure used in this study is available at https://jgcri.github.io/gcam-doc/cmp/350-Detailed_Natural_Trade.pdf.
- Data and code needed to reproduce the research and figures presented in this study are fully documented and accessible in the meta-repository at https://github.com/brinday/gas-trade. The GCAM model code and input data associated with this study are available at https://doi.org/10.5281/zenodo.7689562. Model output data is available at https://doi.org/10.5281/zenodo.8392736.
- Any additional information required to reanalyze the data reported in this paper is available from the lead contact upon request.

METHOD DETAILS

The Global Change Analysis Model (GCAM) is a global, multi-sector model that links together socioeconomic, energy, land, water, and climate sectors.[43] The version of the model used here is based on GCAM v5.4, which is calibrated to a 2015 base year. GCAM solves for commodity prices in each five-year time step through 2100 such that supply and demand are in equilibrium in all energy, agriculture, and water markets.

Natural gas production potentials and costs are derived from Rogner (1997) graded resource supply cost curves.[44] Production is modeled using a resource-reserve model.[45] Reserves are a subset of resources that can be extracted at current prices with currently available technologies. Reserves are taken out of the resource pool and production occurs from these reserves alone over their lifetime as long as prices remain above production costs. Additional reserves are converted from resources when prices are sufficiently high.

Global fossil fuel trade (including coal, oil, and natural gas) is modeled with the Armington approach,[46] in which each region consumes fossil energy supplies from a mix of domestic and imported supplies (which are imported from a single, global market). In this study, each region's imported natural gas is further divided into imported LNG and imported pipeline gas (see Figure S1 as example). Imported LNG comes from the global market for traded LNG, which can in turn be exported from any GCAM region. On the other hand, imported pipeline gas may only be supplied by the regional pipeline network bloc(s) that a given region belongs to (see Figure 1). Some regions may import from multiple pipeline network blocs, based on historically observed trade flows (see description of Comtrade data below). For simplicity, each region only exports to one pipeline network bloc.

Historical natural gas trade is calibrated to UN Comtrade data for the 2015 base year.[36] The Comtrade dataset used contains volumetric data on bi-lateral trade of natural gas, via pipeline and LNG, for exporter/importer country pairs. This data is aggregated to GCAM's 32 energy-economic regions, with intra-regional trade (i.e., trade between countries within a GCAM region) excluded. Due to a known gap in Comtrade data in not including natural gas imports from Russia to Germany (when in fact, this trade flow has been significant), we have added supplementary data from Eurostat,[47] which includes natural gas imports for Germany and Poland. Total gas trade is adjusted to maintain GCAM's global energy balances (calibrated based on the International Energy Agency (IEA)'s Energy Balances dataset); in other words, gross Comtrade flows are adjusted to realize net trade consistent with natural gas production and consumption (and implicit net trade) data from the IEA.[12] Further adjustments are made to ensure that annual energy flows are balanced for (1) total natural gas imports and exports (across pipeline and LNG carriers) in each region; (2) pipeline exports and imports for each of the six regional pipeline network blocs shown in Figure 1; and (3) LNG imports and exports globally. By assumption, all exports from a region go into its primary regional pipeline network bloc, but regions are allowed to import from multiple regional pipeline network blocs if such trade flows are present in the historical data. In the future, pipeline trade relationships are limited to those established historically – the model structure does not allow new pipeline export/import relationships to develop. All regions are allowed to trade natural gas via LNG in the future. We make additional adjustments in the USA region to account for the fact that the USA has become a net gas exporter since 2015, our calibrated base year. We additionally reduce the future growth expectations in the USA for imported natural gas.

GCAM uses a logit choice formulation to determine the shares between domestic versus international natural gas consumption, as well as between pipeline and LNG trade. Preference parameters determine how the competition between domestic versus imported natural gas, as well as between pipeline gas versus LNG trade will evolve from historical patterns. We have set parameters to decrease the preference bias for domestic gas over time, in line with expectations of increasing global market integration. We further parametrize LNG to increase more rapidly in line with recent pipeline and LNG capacity trends showing that LNG capacity is likely to become increasingly dominant in the coming decades.

Trade infrastructure (both pipeline and LNG) are represented as vintaged capacities. Liquefaction, shipping, and regasification costs for LNG capacity and pipeline costs for pipeline gas capacity are shown in Tables S5–S6 in the supplemental information.

All scenarios in this paper use default GCAM socioeconomic assumptions, based on SSP2 pathways (Tables S8–S9). Within each GCAM region, natural gas is demanded in several energy transformation and end-use sectors. Energy transformation sectors include electricity, gas-to-liquids refining, hydrogen production, and district heating (in some regions). End-use sectors include buildings (including commercial and residential buildings), industry (including cement, fertilizer, and aggregate industrial sectors), and transportation (including passenger and freight road transportation). Gas is also used as a feedstock in producing fertilizer and in the aggregate industrial production sector.