Research in International Business and Finance 58 (2021) 101460

Contents lists available at ScienceDirect

Research in International Business and Finance

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

Freedom gas to Europe: Scenarios analyzed using the Global Gas Model

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A R T I C L E I N F O

JEL classification:
C61
L13
L95
Q34
Q37
Q48

Keywords:
Numerical modeling
Natural gas
Liquefied natural gas
Energy policy
USA
Europe

A B S T R A C T

State-of-the-art, open access numerical modeling of imperfectly competitive energy markets offers a sound and transparent way to address topical research questions in energy and commodity markets. We use an open access equilibrium model, the Global Gas Model (GGM), and sector-specific, politically motivated scenarios to investigate the prospects for sales of liquefied natural gas (LNG) from the U.S. into the European energy market. We discuss the risks and opportunities for U.S. LNG and derive implications for policy, business, and finance in the energy sector. We find that Europe is not an attractive market for US LNG in the base case and in scenarios of moderate support of U.S. LNG flows into Europe. In these scenarios, Asia offers higher prices for US LNG and draws substantially higher import volumes. Our modeling results show that the interconnectedness of global gas markets due to an abundance of LNG import capacity in Europe and other regions—particularly Asia—allows for adjustments to global trade patterns that mitigate the consequences of regional disturbances.

1. Introduction

Numerical modeling has been one of the pillars of research on energy and commodity markets for many decades. While robust tools for conducting research in energy and commodity markets are available, they need to be continuously reexamined and updated. Numerical modeling of markets, which allows for imperfectly competitive behavior, competes with optimization-based, techno-economic modeling that implicitly assumes perfectly competitive markets in many sectors. Equilibrium modeling takes into account imperfect market structures (Gabriel et al., 2013). Owing to their complexity, the application of equilibrium market models has been largely limited to academic research. However, there have been recent methodological advances that simplify the application of equilibrium models, which we put into practice in this study.

In addition, we argue that contemporary research should be open source and, more broadly, findable, accessible, inter-operable, and reproducible (FAIR) (Wilkinson et al., 2016). We present a first application of the Global Gas Model[1] (GGM), which was recently made openly available, to natural gas market modeling. Open source modeling can contribute to keeping data and research questions topical and relevant. In combination with FAIR principles, equilibrium market models are as suitable for addressing policy questions as

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[1] https://www.ntnu.edu/iot/energy/energy-models-hub/ggm

https://doi.org/10.1016/j.ribaf.2021.101460
Received 1 June 2020; Received in revised form 23 May 2021; Accepted 24 May 2021
Available online 28 May 2021
0275-5319/

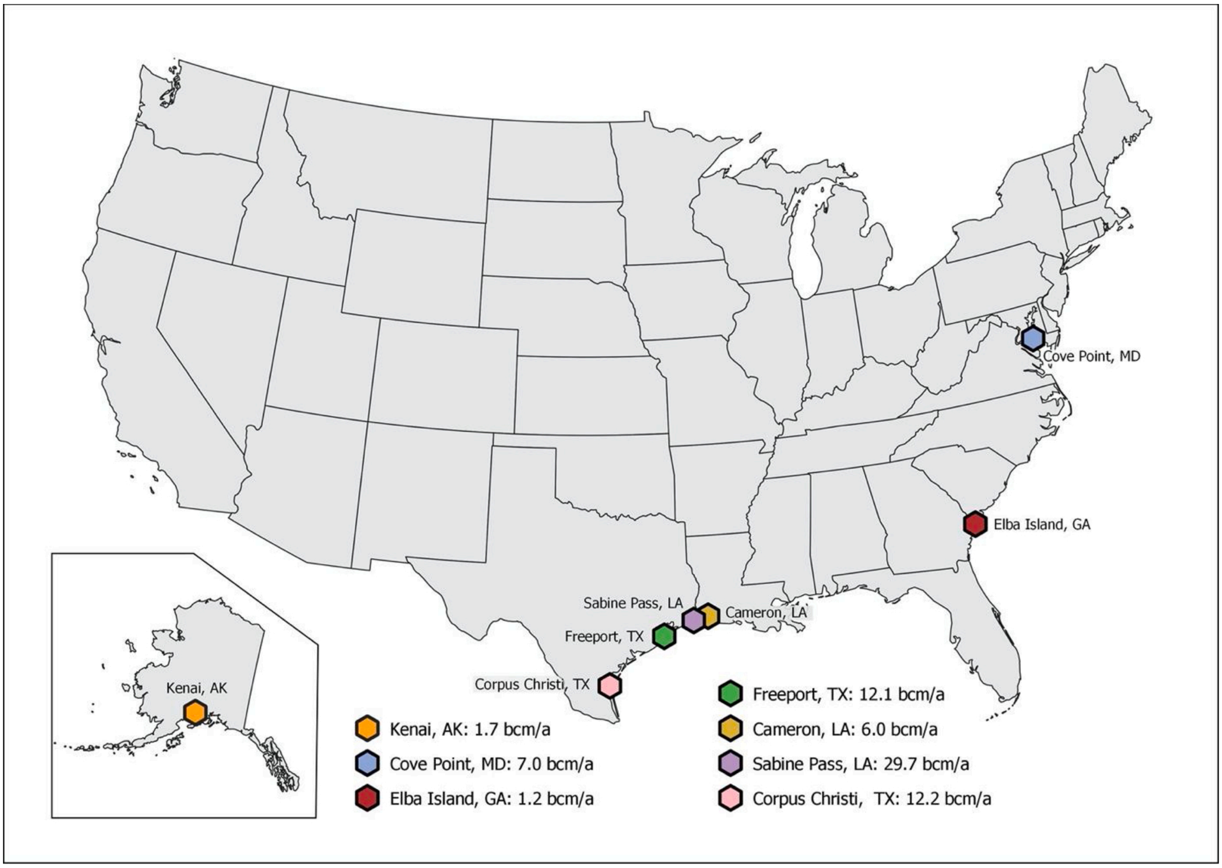

Fig. 1. Existing U.S. LNG export terminals and their capacities in bcm/year.
Note: There are currently no exports from the Alaska (AK) terminal, but the capacity exists.
Source: Author's figure based on FERC North American LNG Export Terminals (Released November 21, 2019, https://www.ferc.gov/industries/gas/indus-act/lng.asp)

simpler modeling methods. Finally, we believe that market-specific scenarios are required to answer relevant, topical research questions. While Shared Socioeconomic Pathways are relevant for climate policy analysis (Riahi et al., 2017), we develop market-specific scenarios to address questions regarding supply and supply security in a specific market, the natural gas market.

In this study, we investigate the future potential outcomes of a recent phenomenon in global natural gas markets, namely the enormous shale gas production levels that have allowed the U.S. to become a net exporter of natural gas, most notably of liquefied natural gas (LNG), in recent years. U.S. LNG export capacity has grown rapidly since the first LNG exports from the lower 48 states (i.e., the U.S. excluding Alaska and Hawaii) began in 2016. This supply of LNG needs to find its markets, and the U.S. under the Trump administration pushed hard to promote U.S. LNG exports in Europe. At the same time, the U.S. government imposed sanctions on the construction of the Russian Nord Stream 2 pipeline project in the wake of the Ukrainian-Russian conflict and the Russian intervention in the U.S. elections in 2016. Yet, these sanctions would potentially also improve market opportunities for U.S. LNG exports. Moreover, there has been debate of financially supporting U.S. LNG exports with measures like tax breaks, which would effectively be subsidies.[2]

LNG exports to Europe had been stable at low levels for several years, even in the face of dramatic market developments, such as the Dutch production collapse (Holz et al., 2017). At the same time, demand for LNG in Asian markets continues to grow strongly, which will necessarily require a large increase in imports given the little availability of long-distance pipelines (Holz et al., 2015). Given these circumstances, one could expect that U.S. LNG exports will show a preference for Asian markets and that the substantial imports of U.S. LNG into Europe that occurred in 2019 will be a temporary exception to the long-run equilibrium.

In this study, we investigate the effects of several policies supporting U.S. LNG exports to Europe. We use the Global Gas Model, an open access equilibrium model, reformulated as optimization problem that simulates global natural gas market outcomes to 2050 based on production, cost, and demand function assumptions (Egging and Holz, 2019). Using our *Base Case* equilibrium scenario as the benchmark, we compare the results of several other scenarios to investigate the potential effects of various support schemes for U.S.

[2] For example, https://www.offshore-energy.biz/annova-lng-gets-373-million-tax-abatement/ and https://www.desmogblog.com/2018/12/20/louisiana-calcasieu-driftwood-lng-export-tellurian-tax-break (last accessed June 1, 2020)

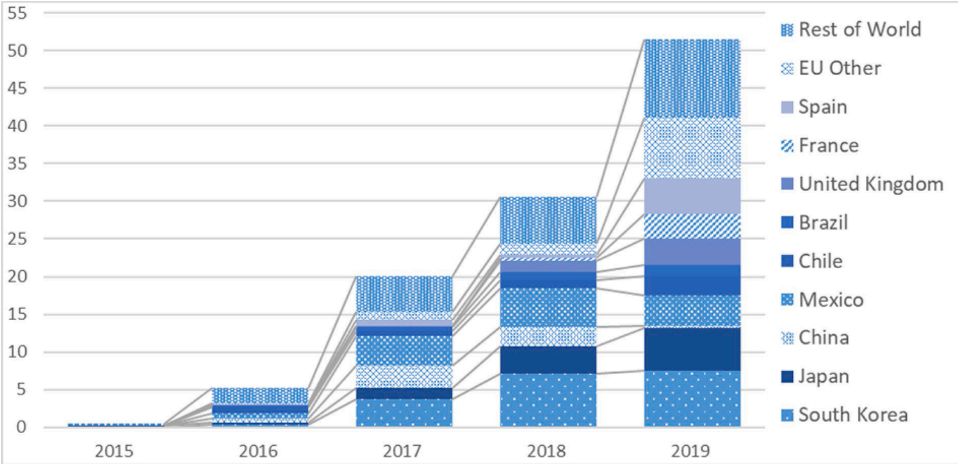

Fig. 2. U.S. LNG exports 2015–2019, in bcm/year.
Note: Countries receiving the largest percentage of U.S. LNG exports are indicated in the chart.
Source: Author's figure based on EIA U.S. Natural Gas Exports by Country (released May 29, 2020) www.eia.gov

LNG exports to Europe. Thus, we extend our earlier analysis on the possibilities of U.S. LNG exports to Eastern Europe (Stähr et al., 2015) to cover a larger regional context and additional support policies. We compare LNG transport subsidies and sanctions against the Nord Stream 2, as well as Chinese support for LNG imports and a Russian boycott of the European market. Across these scenarios, we find that it would require strong support for U.S. LNG exports to Europe rise above the *Base Case* level.

The rest of this study is organized as follows. In the next section, we discuss the background of U.S. LNG exports (from the lower 48 states) that began in 2016, as well as the long-term trend and current conditions for European LNG imports. In Section 3, we describe the GGM equilibrium model and our scenarios. In Section 4, we present and interpret our modeling results. Section 5 concludes with a discussion of the benefits and limits of long-term equilibrium modeling in investigating the effects of energy policy.

2. Background

2.1. U.S. LNG exports: from imports to massive exports

Before the shale gas boom led to a massive increase in domestic production, the U.S. had been a net importer of LNG for many decades (Ruester and Neumann, 2009). It began importing in the 1970s, relying primarily on three LNG regasification terminals on the East coast (Everett, Cove Point, and Elba Island) as well as one on the Gulf coast (Lake Charles). Just before the shale gas boom began, two more regasification terminals were planned and built on the U.S. Gulf coast, in addition to terminals in Mexico. While one of these regasification terminals is still in operation (the Everett terminal, located in Boston, Massachusetts), some of the others were converted to liquefaction terminals (e.g., Cove Point and a later project Sabine Pass). In addition, a large number of new liquefaction projects were developed (see Table B1 in the Appendix for a complete list of LNG projects in the U.S.).

Since the U.S. started exporting LNG in February 2016 from the Sabine Pass terminal in Louisiana, the number of terminals and LNG volumes increased steadily. As of early 2020, six LNG export terminals are in operation, representing a capacity of approximately 70 billion cubic meters (bcm) per year (see Fig. 1).[3] These terminals exported approximately 50 bcm in 2019.[4] In addition, various projects have been approved that would increase liquefaction capacity in the U.S. by more than 300 bcm per year, not counting those projects that have yet to be approved, which would add another 120 bcm per year.

While some of these projects may not be developed, it is still likely that LNG exports from the U.S. will continue to increase. The new U.S. government under President Biden is expected to keep an export-friendly policy, given that the Democratic administration under President Obama and then Vice-President Biden oversaw the largest natural gas expansion in U.S. history, lifting the crude oil and LNG export ban for the first time in 40 years.

There is a broad political consensus in the U.S. in favor of reducing European dependency on Russian natural gas, potentially in order to promote U.S. LNG but also for political reasons. These efforts increased when construction of the Nord Stream 2 began; for example, Congress voted a law in 2019 that imposes sanctions on any firm that helps Russia's Gazprom complete the construction of the pipeline into the EU.[5] These sanctions include revoking previously issued visas and asset freezes. These measures were effective in

[3] https://www.eia.gov/todayinenergy/detail.php?id=37732 (last accessed May 29, 2020)
[4] https://www.eia.gov/dnav/ng/ng_move_expc_s1_a.htm (last accessed May 26, 2020)
[5] "Protecting Europe's Energy Security Act of 2019:" https://www.congress.gov/bill/116th-congress/house-bill/3206 (last accessed February 16, 2021))

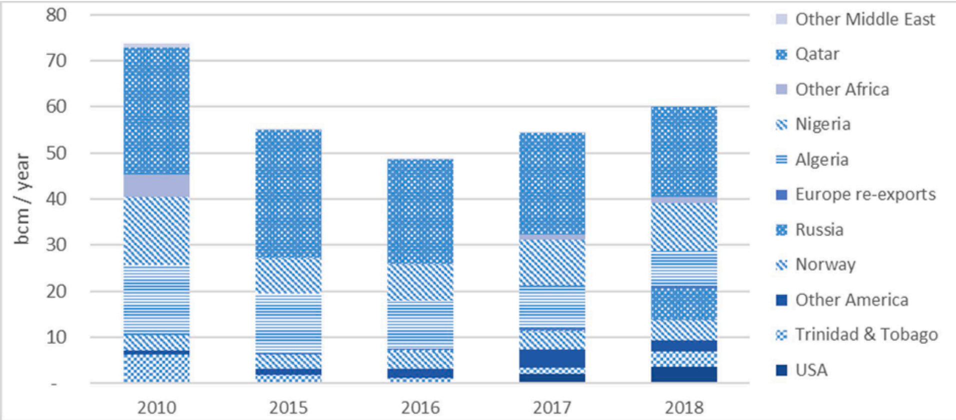

Fig. 3. LNG exports to the EU 2010–2018, in bcm per year.
Source: Author's figure based on BP Statistical Review of World Energy (2011, 2016–2019).

halting construction work on the Nord Stream 2 project for several months in 2019 and almost the entire year 2020.

The term "freedom gas" was coined in May 2019 by then U.S. Energy Secretary Rick Perry, who drew a parallel between energy diversification and the American efforts to liberate occupied Europe in World War II. Secretary Perry stated that the U.S. was once again delivering a form of freedom to Europe, only that instead of soldiers this freedom takes the form of LNG.

As latecomers to the global LNG market, backed by ample shale gas supplies, U.S. LNG suppliers differ from their international competitors in terms of their business strategies. Laing et al. (2020) show that most U.S. natural gas (and oil) firms are U.S.-focused in their operational strategies, with a few exceptions of entities that are part of multinational companies. Moreover, U.S. natural gas suppliers, and in particular, U.S. LNG operators pursue operational strategies that are distinct from those of their international competitors, that is, they do not export LNG under long-term contracts; rather, they act as flexible suppliers to the world's spot markets. Most other LNG and natural gas trade still occurs in the framework of long-term contracts, which explains the typically inefficient pricing of natural gas in most parts of the world noted by Chen and Lin (2014).

The flexibility of U.S. LNG supplies is shown by its diverse destinations (see Fig. 2). Geographically, the U.S. is relatively well-positioned in terms of transport distances to serve both the Atlantic and Pacific markets and is closer than any other LNG supplier to Latin America. Moryadee et al. (2014) emphasize that low North American natural gas prices make U.S. LNG attractive to importers across the globe. Asia, with its almost insatiable hunger for energy, received half of U.S. LNG exports in 2018 and more than a third in 2019; South Korea alone accounted for almost half of these exports and Japan another third. North America (Mexico) and Latin America absorbed approximately one-fourth of U.S. LNG exports. Europe imported a relatively small volume of U.S. LNG in 2018 (12 %) for region-specific reasons, including ample supplies from incumbent suppliers, but significantly increased imports in 2019 to 38 % (see also Section 2.2).

2.2. *LNG imports in Europe: small but decisive*

LNG imports play a small yet decisive role in the European market because they allow for a substantial diversification of natural gas supplies to the region. LNG imports made up only about 15 % of the total European supply of natural gas in 2018 (BP Statistical Review 2019). However, the number of suppliers to the EU almost tripled if LNG suppliers are considered in addition to pipeline suppliers (IEA, 2019). This heightened competition is particular visible in Eastern Europe where LNG terminals have modified the market structure from a monopoly to an oligopoly, thereby greatly reducing prices. This was particularly notable in Lithuania and somewhat less so in Poland, which has also benefited from reverse pipeline flows from Germany. More LNG regasification terminals are planned in Europe, particularly in Germany where there currently are no such terminals. Moreover, some Eastern European countries, such as Croatia, that are currently supplied exclusively by Russia have also been considering constructing LNG terminals.

There are currently 21 LNG import terminals operating in Europe (ENTSO-G., 2019). However, they have seen relatively low capacity utilization rates over the past decade, averaging less than 25 % between 2012 and early 2019 (FWE, 2019). This is due to a mixture of stable to decreasing demand and ample pipeline capacity. Even dramatic changes, such as the sharp drop in domestic production in the Netherlands, did not lead to a strong increase in European LNG imports (Holz et al., 2017). Since 2017, the situation in the Netherlands has been somewhat similar to that of the UK about 15 years ago, where domestic production declined rapidly in the early 2000s and four LNG terminals were built to satisfy demands for natural gas from power plants and households. However, the Netherlands has continued to operate only one LNG terminal, which also delivers LNG to consumers in other countries including Germany, because it also has access to the continent's ample pipeline supplies, in particular from Norway, but also from Russia.

Sources of LNG imports in Europe have become increasingly diversified in recent years, in the wake of increasing global LNG supplies (see Fig. 3). Over the period from 2010 to 2018, the EU's LNG imports from Africa and countries in the Middle East declined, both in absolute value (63 bcm to 39 bcm) and as a share of total LNG imports (86 % to 66 %). While Norwegian LNG supplies have

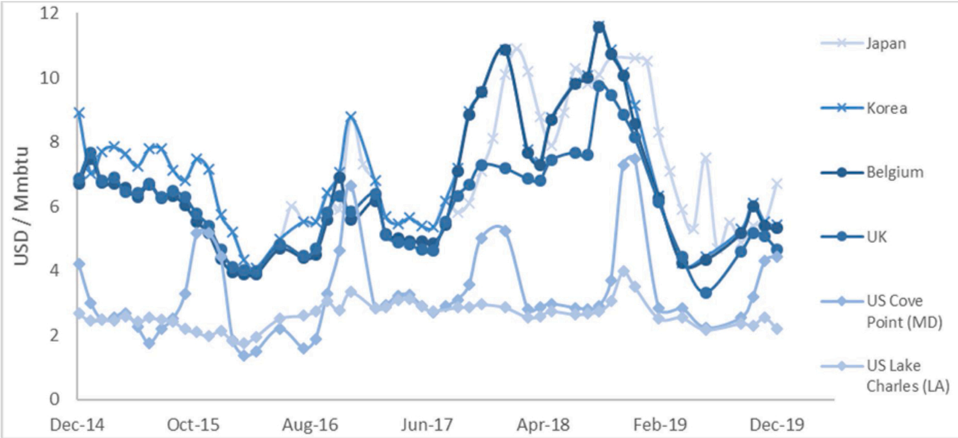

Fig. 4. World LNG prices 2015–2019 in USD per Mmbtu.
Note: only the marked points are observed (published) prices; the lines are interpolated.
Source: Author's figure based on FERC Market Oversight and METI Japan.

been relatively constant, Russia and the Americas have made up the difference, with a combined share of 27 % in 2018. From the Americas, supplies to the EU from the U.S. grew almost tenfold (from 0.4 to 3.5 bcm), comprising the largest share, with Trinidad and Tobago as a close second (3.3 bcm).

Moreover, flexible LNG imports indicate a trend away from long-term contracts that contain a destination clause.[6] This trend is less noticeable in other major gas importing regions of the world, particularly Asia. The substantial growth in global LNG supplies led to a notable decline in global prices in 2019 (Fig. 4). As mentioned previously, U.S. LNG exports are usually not tied to long-term contracts but are flexibly directed to markets where spot hub prices are most attractive or at least cover supply costs (production and all transportation costs).

Due to the strong link between LNG prices and oil prices and milder than average winters (the main season for natural gas demand) in 2018 and 2019, natural gas prices in Asia decreased compared to prices in Europe over the period from 2015 through 2019 (see Fig. 4). With a narrower price spread between Asia and Europe, more LNG was directed to Europe since the end of 2018. Since October 2018, LNG imports to Europe rose by more than 80 % compared to the average of the previous years (2012–2017). Europe was able to accommodate these higher than equilibrium volumes thanks to its liquid spot market and large underground gas storage capacity.[7] European demand in 2019 was also higher than the long-run equilibrium because of the fear that the Ukrainian transit of Russian gas deliveries to Central Europe would be interrupted (Mitrova et al., 2019). While a new Ukraine transit contract was being negotiated in late 2019 that would cover the next five years, tensions between the U.S. and Russia over natural gas supplies to Europe continue.

3. Material and Method: Model, data, and scenarios

GGM, as documented in Egging and Holz (2019), is a multi-period partial equilibrium model that represents the entire natural gas value chain, including its diverse agents, and covers approximately 98 % of global gas production and consumption. Most importantly, the model distinguishes the various entities that are active in the natural gas sector and includes them with their respective profit maximization problems, including their technical constraints and market clearing conditions along the value chain. These entities are producers, traders, pipeline owners and operators, LNG liquefaction owners and operators, LNG regasification owners and operators, and storage owners and operators and are characterized as rational, profit maximizing economic agents. This setting matches the U.S. natural gas and LNG sector where market-based exchanges prevail. It fits less well with those parts of the market where long-term contracts dominate (e.g., in East Asia). However, inputs are calibrated such that the long-term equilibrium obtained from the model fits with the observed data.

GGM considers natural gas production, continental pipeline networks, liquefaction, regasification, LNG shipping, and different types of storage at the individual country level with further disaggregation within large countries (the U.S., Canada, Russia, China, and India). The model focuses on infrastructure investment and trade, taking into account market power exerted by some of the dominant

[6] Destination clauses were a major element of natural gas long-term contracts in the past, prohibiting importers from re-exporting natural gas to other countries. Therefore, suppliers were the only players that could exploit arbitrage opportunities from price differences between countries. The European Commission confirmed the prohibition of a destination clause in natural gas sales to Europe in 2018 with the case of Gazprom sales to Central and Eastern Europe. (https://ec.europa.eu/competition/elojade/isef/case_details.cfm?proc_code=1_39816).

[7] Aggregated European storage capacity utilization in 2019 was, on average, 15% higher than on the same dates in 2011–2018 and was up to 28% higher in April and May 2019 than in the same months in 2011–2018. In 2020, between January and April, storage utilization was, on average, 45% higher than in January-April 2011–2018 and more than 60% higher in April.

Table 1
Assumptions of the policy scenarios.

Scenario	Scenario description	Scenario implementation
"Trump"	Financial support to U.S. LNG exports to Europe and sanctions on finishing Nord Stream 2 pipeline	Shipping costs U.S. to Europe decreased by 0–100 %; Nord Stream 2 delayed by ten years
"Putin"	Disruption of all Russian exports to Europe	Russian trader not allowed to sell any gas to EU and Switzerland
"Altmaier"	Support to LNG import terminals in Germany	Capital costs and/or operational costs of regasification terminals in Germany decreased by 0–100 %
"Jinping"	Support to LNG import terminals in China	Capital costs and/or operational costs of regasification terminals in China decreased by 0–100 %

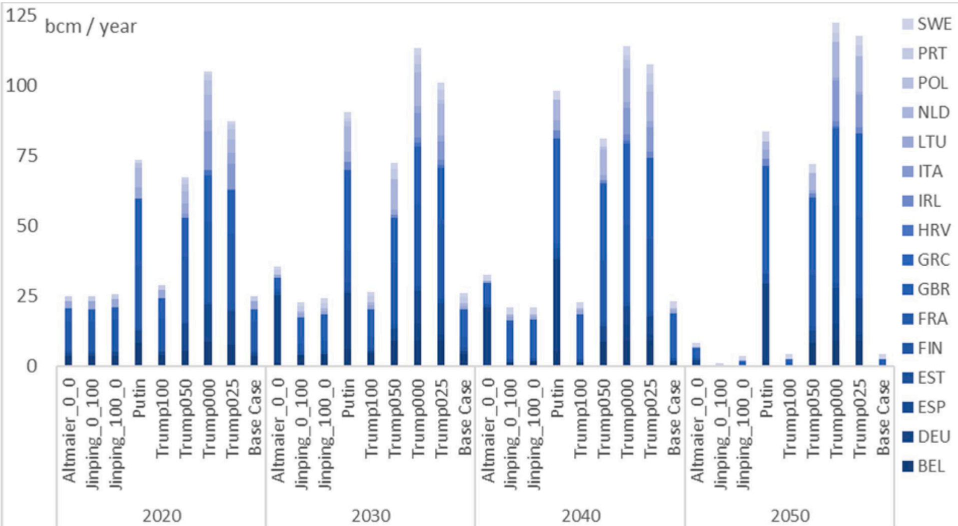

Fig. 5. LNG exports from the U.S. to various destinations in Europe in the Base Case and selected scenarios in bcm/year.
*Note: The numbers following the scenario name indicate the percentage of the*Base Case *cost data applied (i.e., the opposite of the subsidy rate). In the* Altmaier *and* Jinping *scenarios, the first number refers to operational costs; the second number refers to the investment costs in regasification capacity. In the* Trump *scenarios, the number is the share of* Base Case *LNG transportation costs between U.S. liquefaction and European regasification nodes. For example, "100" means* 100 % *of the* Base Case *cost, hence, a 0% subsidy.*

suppliers. An earlier version of the model was programmed as a mixed complementarity model (Egging, 2013). The version of the model used in this study is formulated as an optimization problem, following the method outlined in Egging-Bratseth et al. (2020). It is implemented as a quadratic program in GAMS and solved using CPLEX. The model is set up for a time horizon out to the year 2050, with five-year increments starting in 2015.

We include a "business-as-usual"-style *Base Case*. The *Base Case* in this study is an updated version of the *Base Case* scenario used in earlier Global Gas Model versions, such as Holz et al. (2015); Richter and Holz (2015), and Richter (2015). The production and demand data for the *Base Case* and all other scenarios in this study was obtained from the (IEA, 2018) and, for Europe, from the Reference Scenario in PRIMES (PRIMES European Reference Scenario, 2016).[8] Data were calibrated to match the consumption and production growth rates from 2020 onward as provided in these two sources.

We investigate the effect on U.S. LNG flows to Europe, and to Asia, of several support schemes with varying strength. We do so by adjusting (decreasing) the costs of investments or operations along the LNG value chain, which consists of liquefaction, transportation, and regasification, thereby modeling policies that support (subsidize) these elements of the value chain.

For example, in Germany, there has been discussion about supporting the construction of regasification terminals with subsidies during the investment stage and tax breaks once they are operational. We model such a policy as a decrease in regasification investment costs and a separate decrease in operational regasification costs. For simplicity and for identifying the order of magnitude of support that makes a difference in LNG flows, we use arbitrary levels of support of 0% (no subsidy), 25 %, 50 %, 75 %, and 100 % (no costs, fully subsidized). While the highest subsidy levels may be unrealistic, analyzing them gives an indication of the maximum potential of any support scheme.

To illustrate the political "slant" of the policies analyzed, the scenarios are named after their most prominent promoters (see Table 1). The above-mentioned German regasification policy is named for the German minister of economics, Altmaier, while the

[8] Notably, the production outlook for the Netherlands was adjusted downward compared to the PRIMES Reference Scenario 2016.

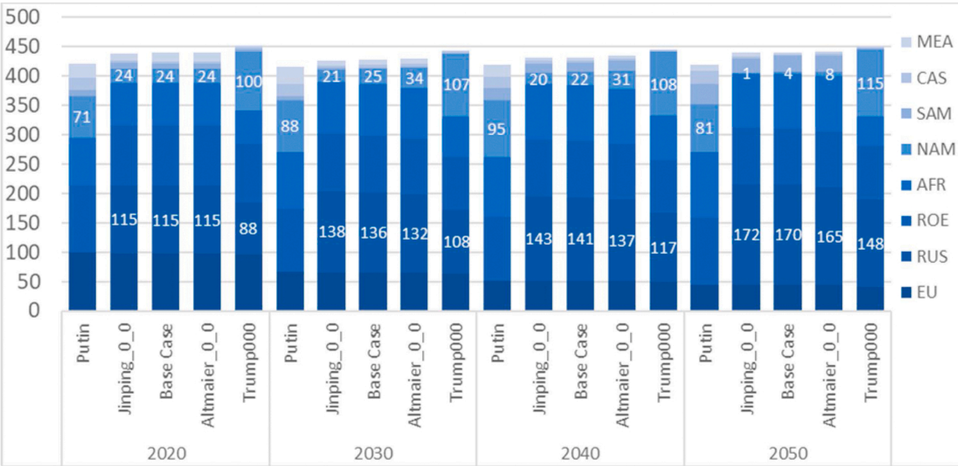

Fig. 6. EU supply mix by supplying region, Base Case and selected scenarios 2020–2050, in bcm per year.

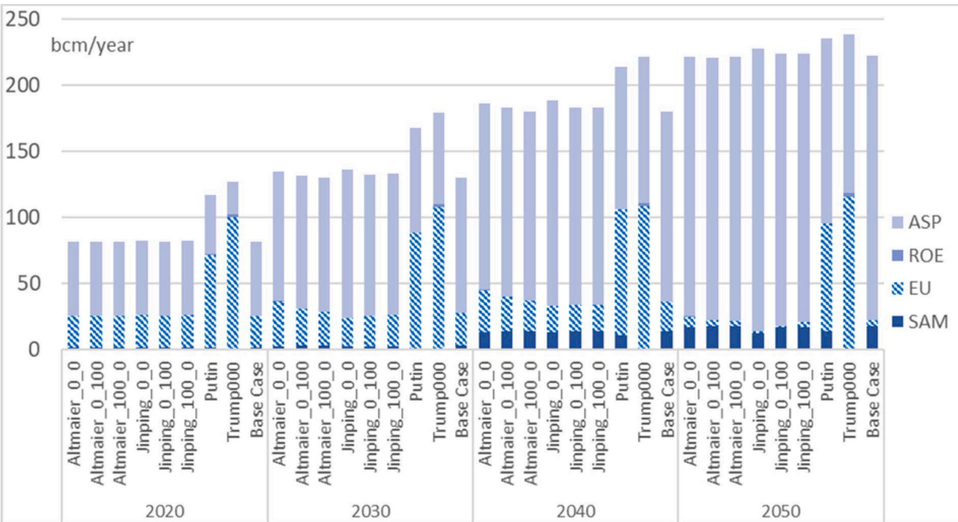

Fig. 7. North American exports and their destination regions in selected scenarios 2020–2050, in bcm per year.

same-style policy in China is named for Chinese President Xi Jinping. The *Trump* scenario includes support for LNG exports from the U. S. to Europe along with sanctions against finalizing the Nord Stream 2 pipeline so that the start of operations for this pipeline between Russia and Germany is delayed to 2030 (instead of the early 2020s).

We also include a scenario of Russian disruption of LNG supplies to Europe, named after Russian President Putin, following a similar analysis of Gazprom's market power in Europe in Richter and Holz (2015). Indeed, if natural gas from Russia— the largest single supplier to Europe—were eliminated, there would likely be a need for alternative supplies, such as U.S. LNG. The likelihood of a Russian boycott of the European market has increased in recent years given the deterioration in political relations and, more importantly, the growth of natural gas export infrastructure in other import markets, in particular, China, which are now available at large scale.

4. Results

In this section, we investigate the results obtained using the Global Gas Model in the scenarios described above. Figs. 5, 6 and 7 present an overview and a comparison of the results under the various scenarios. The following sub-sections then discuss each policy scheme separately.

In the *Base Case*, U.S. LNG exports to the EU are between 23 and 26 bcm in the period 2020–2040, then collapse to only 4 bcm by 2050. The late decline in the *Base Case* and the low support scenarios are due to a combination of factors, most importantly a strong rise in demand in Asian markets that attract most of the U.S. LNG and a simultaneous increase in LNG imports in Europe from South

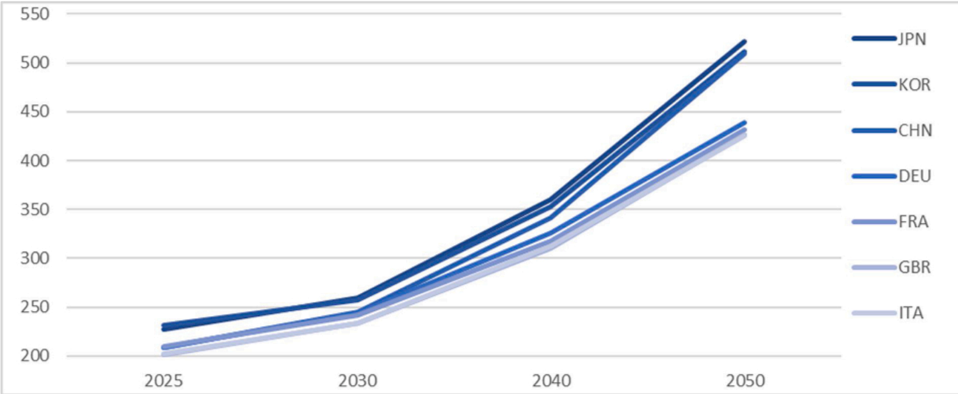

Fig. 8. Price trends for selected countries in the Base Case (€/ 1000 cm).
Note: The vertical axis is truncated at the lower end at 200 € / 1000 cubic meters.

America and Africa.

U.S. LNG is a rather small contributor to diversifying European supplies (see Fig. 6). Only in the *Putin* scenario does U.S. LNG represent an essential component of European supplies. In general, the largest share of European supplies is provided by Russia, thanks to its vast production capacities, favorable pipeline transport conditions, and proximity to Eastern and Central Europe (via Ukraine and Belarus) and Central Western Europe (via the Baltic Sea). Russia provides more than a quarter and, in later periods, more than a third of European consumption. In the early periods, it is slightly surpassed by Norway, which supplies about 22 % of European consumption. Norwegian export levels and market share in Europe stabilize over time, while Russian supplies increase.

Among all scenarios, the *Trump* scenarios that include the highest subsidy levels achieve the highest levels of U.S. LNG exports to Europe (see Fig. 5). In all model periods, the scenarios with full (100 %) and 75 % subsidies of shipment costs lead to U.S. LNG shipments to Europe being well above 100 bcm per year. They are succeeded by the *Putin* scenario, which also leads to U.S. LNG exports several times higher than the *Base Case* levels, but below 100 bcm in all years. In comparison, the *Altmaier* and *Jinping* scenarios have only small effects on U.S. LNG deliveries to Europe. Fig. 5 shows only the most extreme variants of these two scenarios (i.e., the variants with the highest subsidy levels). As expected, the *Altmaier* scenario leads to higher imports of U.S. LNG, compared to the *Base Case*, while the *Jinping* scenario leads to lower European LNG imports because imports in China are subsidized.

U.S. LNG exports serve a variety of destinations in Europe, with France and the UK as the largest importers. Deliveries of U.S. LNG extend as far as Lithuania in the east and Sweden in the north. Potential new LNG regasification import capacities in Germany and Croatia are only used in some scenarios, namely the *Altmaier* and *Putin* scenarios (Germany) and the high subsidy *Trump* scenario (Croatia).

Fig. 7 reveals that Europe imports a much smaller share of U.S. LNG than Asia. In the *Base Case*, Europe absorbs less than 20 % of U. S. LNG exports across all time periods. Only when policy support is very high, namely when Russia boycotts Europe or when LNG shipment subsidies are 75 % or 100 % of transport costs is a higher share of U.S. LNG directed to Europe. In the *Putin* scenario, Europe can attract up to 60 % of U.S. LNG exports and up to 80 % in the full subsidy *Trump* scenario. In all other scenarios, Asia largely dominates exports of LNG from the U.S. (and from all other sources), absorbing two-thirds or more.

4.1. Base Case: Europe no more than the last resort for U.S. LNG supplies

Figs. 5, 6 and 7 show that in the long-run equilibrium, Europe is not a major market for global LNG exporters, including LNG supplies from the U.S. Instead, Asia, where the price of LNG is typically higher, strong growth is expected over the coming decades, will be the primary market for LNG (Holz et al., 2015). Europe's share of the global LNG trade is rather small, starting at about 17.5 % in 2020, and gradually decreasing to just under 14 % in 2050. Note that although this share declines, LNG import volumes increase by 33 % over these three decades.

LNG is also a relatively small share of European supplies in the *Base Case* (Table 2). Only around 50 bcm per year, or 10 % of total gas supplies in Europe, are covered by LNG, with the remaining 90 % covered by domestic production and pipeline imports. Remarkably, the U.S. contributes about half of total LNG imports in Europe in the modeled scenarios (see Table B1). This remains fairly constant throughout the 2040s and even to 2050 due to the stable demand assumption in the *Base Case*. By 2050, LNG from South America and Africa somewhat displaces U.S. LNG exports to Europe, as U.S. production is directed to the high demand markets in Asia instead.

In equilibrium, a balance between plentiful, cheap pipeline gas and higher cost LNG is seen in the European market. Europe is the only world region with a dense pipeline network that is connected to a large number of suppliers. In the long-run equilibrium depicted by the *Base Case* in our fundamental model, European demand can, to a large extent, be satisfied by regional pipeline gas mostly from Russia (meeting a third of European demand, on average, between 2020–2050), Norway (covering 22 %, on average, between 2020 and 2050), and Algeria (18 %). LNG plays only a complementary role mostly in European countries that cannot satisfy all of their needs

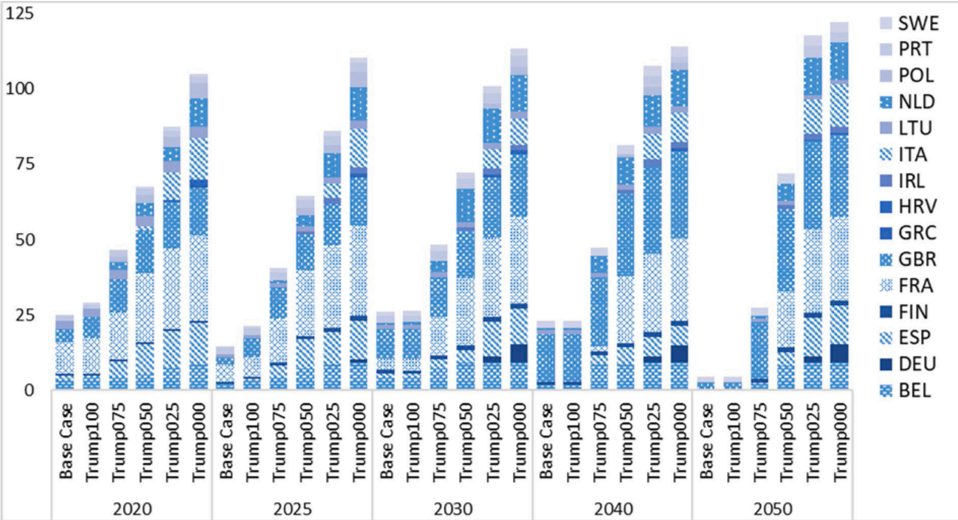

Fig. 9. LNG exports U.S. to Europe in the Trump cases, in bcm per year.

with pipeline gas (e.g., Spain) or where it helps to reduce the market power of incumbent monopolists (e.g., in Lithuania).

In a global market equilibrium, Europe receives only those "leftover volumes" that—for whatever reason—cannot find a market in Asia. Thus, some analysts have referred to the European market as "the last resort" for U.S. LNG suppliers.[9] The developments in 2019 showed that Europe—thanks to its liquid spot markets and ample storage supplies—can indeed fulfill this role and import high volumes of (U.S.) LNG at times when other markets experience low demand (Section 2.2). However, 2019 was a deviation from the long-run equilibrium depicted in the *Base Case,* indicated by a considerably smaller price differential between Europe and Asia (see Fig. 4) than was warranted by market fundamentals.

The situation in 2019 underlined the arbitrage function of relative prices in the global market. Fig. 8 shows nodal prices in Europe and Asia in future model years. Early in the scenario, wholesale prices in Japan and South Korea are about 10 % higher than in large EU countries and China, and that price difference increases to 20 % by 2050. Around 2040, to secure its growing natural gas needs, prices in China converge to the level of prices in Japan and South Korea. In other words, Asia becomes more attractive over time relative to Europe for natural gas suppliers who are acting globally. This is reflected in the low LNG import volumes in Europe in the later years of the *Base Case*.

4.2. *Trump scenario: subsidizing LNG transport to Europe*

To analyze the effects of a U.S. support scheme that favors EU destinations, we look at the impact of LNG shipping cost reductions from east coast terminals in the U.S. to European receiving terminals. Additionally, we assume U.S. sanctions postpone the completion of the Nord Stream 2 pipeline from Russia to Germany through the Baltic Sea, thereby causing a decade-long delay, which means that only 55 bcm capacity is available in 2020 and 2025 (Nord Stream pipeline) and 110 bcm from 2030 onwards (instead of late in 2020 as in the *Base Case*).

We investigate different intensities for the support scheme. The *Trump100* scenario considers only the effect of the Nord Stream 2 delay, that is, with no support for LNG shipments to Europe. Trump075 to Trump000 consider increasingly larger subsidies on shipping routes, where *Trump075* means shipment costs of 75 % of the *Base Case* (i.e., 25 % of shipment costs are subsidized), and *Trump000* is the full subsidy case (with 0% of transport costs).

The impact on U.S. LNG exports to Europe of U.S. sanctions that hamper the completion of Nord Stream 2 is very small (see Fig. 9); only 4.4 and 6.5 bcm of additional U.S. LNG are consumed in Europe in 2020 and 2025, respectively. This calls into question the effectiveness of the U.S. policy of imposing sanctions in the absence of any support policy.

Indeed, an accompanying reduction in shipping costs has more dramatic consequences in the scenarios. In 2020 and 2025, every additional reduction (in 25 % increments) causes an increase in U.S. exports to Europe of about 20 bcm. From 2030, when Nord Stream 2 is on stream regardless of the subsidy level, the effects are similar or even larger in magnitude. With shipment cost subsidies of 100 % or 75 %, U.S. LNG exports to Europe can reach levels well above 100 bcm, approaching 120 bcm per year. These are the highest levels for U.S. LNG exports to Europe across all scenarios considered in the study.

Supplying Europe with 120 bcm versus 4.5 bcm (*Base Case*) in 2050 implies a market share of 30 % compared to 1%. In the most extreme *Trump* scenarios, we see a clear ripple effect through global markets. Higher exports to Europe reduce exports to other markets to some extent and reduce domestic consumption in the U.S. Exporting becomes relatively more profitable for U.S. natural gas

[9] For example, Argus Media webinar on May 7, 2020 (www.argusmedia.com).

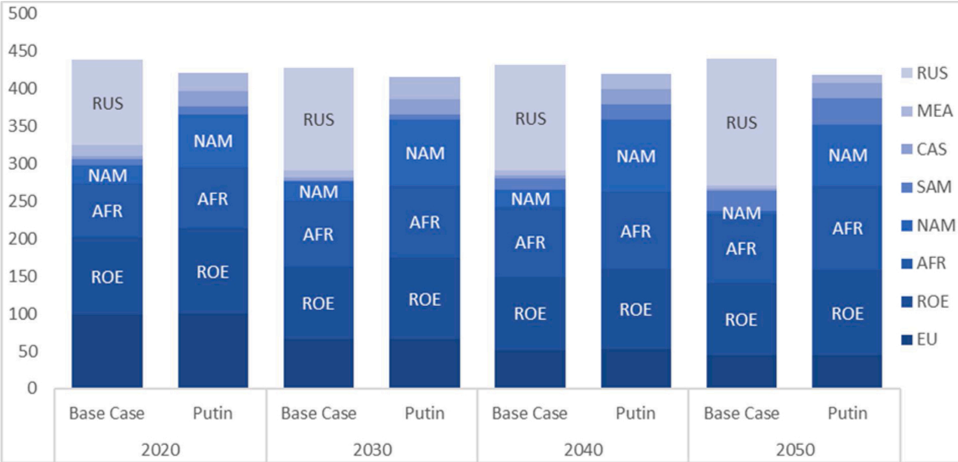

Fig. 10. EU supply breakdown over time in Base Case and Putin scenarios, in bcm/year.

suppliers, and U.S. domestic prices somewhat increase. By contrast, prices in Europe are lower than in the *Base Case* due to the abundant supply. Lower prices drive out some Russian supplies, which are redirected to other markets, mostly Asia. The same happens to LNG supplied by some African and Middle Eastern suppliers. Overall, U.S. export subsidies aimed at Europe cause a global price decrease, with the notable exception of U.S. domestic prices. Prices in Europe decline the most, and European consumers benefit the most because of U.S. policy, American consumers, and taxpayers.

4.3. Putin scenario: opening the door for U.S. LNG?

In this hypothetical, exaggerated scenario, we evaluate the impact and importance of competition between Russia and the U.S. in exporting LNG to Europe. Clearly, we do not anticipate a full-blown Russian boycott of European markets over an extended period. Although political relations between Russia and western European countries have been cooler recently than in the past, the double-digit multi-billion dollar investment in Nord Stream 2 indicates Russia's desire to participate in the European gas market. Still, since Russia's dominance in the market increases over time in our *Base Case* (26 % market share in 2020, 39 % in 2050), it is valid to analyze Europe's vulnerability with respect to Russian natural gas exports, and the potential for LNG exports from the U.S. to mitigate Europe's dependency on Russia. The *Putin* scenario analyzes the consequences of an immediate and total disruption of Russian supplies to the EU and Switzerland.

As Fig. 10 shows, if Russia were to halt natural gas exports to Europe, those shipments would be replaced to a large extent (at least 85 % in any given year) by other suppliers. Notably, North America (primarily the U.S.) would gain a much larger market share in this situation. Here the abundance of LNG import capacity in Europe provides a backup option. EU consumption would drop by at most 5%, and prices would increase by approximately 10 % at most.

Again, we see a ripple effect across global markets. Russia stops exporting to Western Europe and redirects its natural gas flows mostly to Asia in addition to other parts of Europe and for increased domestic consumption. This simultaneously opens up the EU market to other exporters and pulls them out of the Asian markets. For all LNG exporters in all regions—the Americas, Africa, and the Middle East—the result is that a large part of their exports is redirected from Asia to Europe.

In all years, a Russian boycott leads to much greater supplies flowing from other regions to Europe. Notably North America provides the lion's share of that supply. Although Russian supplies are dominant in the *Base Case,* increasing from 115 bcm in 2020 to 170 bcm in 2050, the decline in EU consumption resulting from the Russian boycott is no more than 12–18 bcm (3%–5%) until 2040. This increases slightly in 2050, to 22 bcm (5%), which can be attributable to the demand-side dominance of Asia and to the general willingness of Asian countries to pay relatively high prices.

In this scenario, U.S. LNG exports to Europe rise as high as 95 bcm per year (Fig. 5) without any subsidy. Hence, a "Putin" boycott would do the U.S. a favor, opening the door for more U.S. LNG in Europe.

4.4. Subsidizing LNG imports: a game-changer for Germany?

Germany does currently not have regasification capacities. Several projects have been proposed over the past four decades, but no investment decision has ever been finalized. In the *Base Case*, there is no investment in German regasification capacity until 2050; therefore, there are no direct LNG exports to Germany.

Recently, there has been discussion of promoting the use of LNG in Germany and, to that end, of supporting construction of regasification terminals with investment subsidies, or tax breaks when they are operational. We operationalize these support schemes with combinations of reductions in investment and/or operational regasification costs, ranging from 0% to 100 %, in 25 %-increments.

Fig. 11 shows that the impact of scenarios with low cost reductions is very small. Although several more combinations of

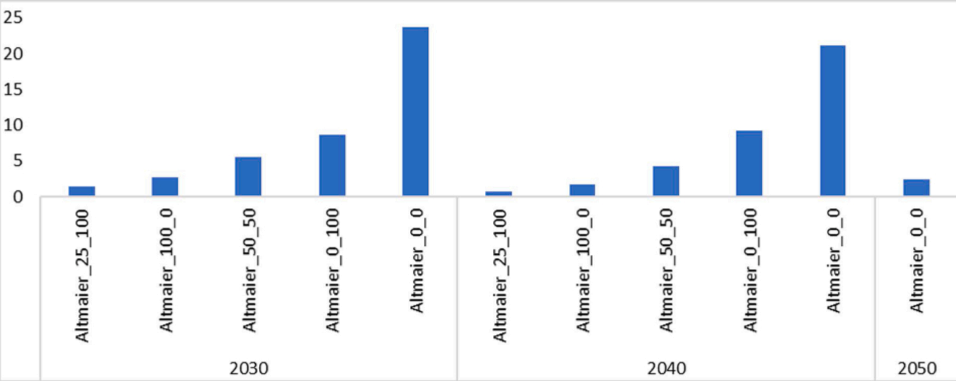

Fig. 11. German LNG imports from the U.S. in different scenarios in bcm per year.
Note: In these Altmaier *scenarios, the numbers following the scenario name indicate the percentages of the* Base Case *costs applied (the opposite of subsidies). The first number refers to operational costs; the second number refers to investment costs to construct regasification capacity.*

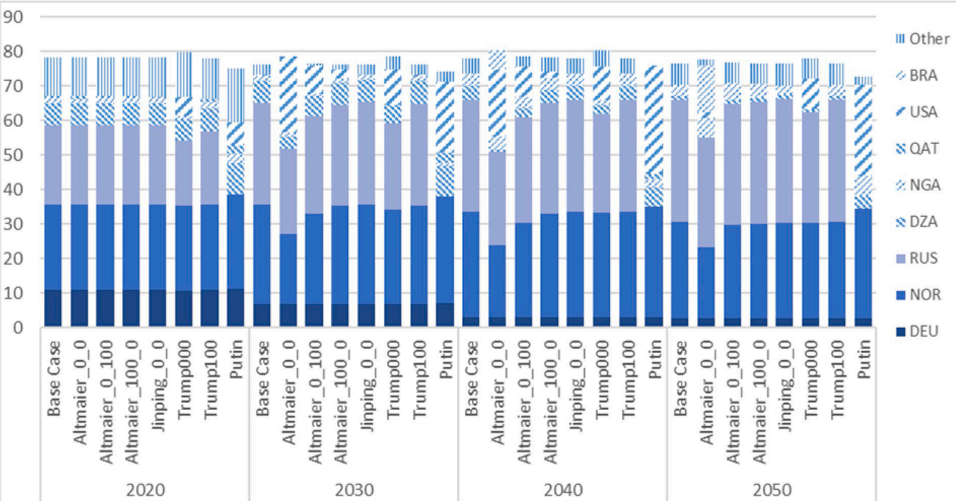

Fig. 12. Germany Supply Breakdown in the Base Case and selected scenarios in bcm/year.

investment and/or operations support were analyzed, only a few result in Germany importing LNG from the U.S. In scenarios with low investment support and no operations support (Altmaier_75_100 and _50_100, equivalent to a 25 % or 50 % investment cost subsidy, respectively), U.S. LNG exports to Germany remain at zero. High levels of investment support (e.g., 75 % investment support as in "_25_100″) result in only modest levels of LNG imports. Only by entirely eliminating investment costs or operational costs, or very large percentages of both, do we see a significant volume of U.S. LNG exports to Germany in 2030 and 2040. LNG imports begin only in later years, not in 2020, because there is a lead-time of one model period (five years) before investments are available as usable capacity.

Throughout the period of the analysis, all the way to 2050, Germany continues to rely mainly on natural gas supplied via pipelines from Norway and Russia (see Fig. 12). They are supplemented by generally modest LNG imports from South America, North and West Africa, and the Middle East, which reach Germany indirectly (e.g., via Belgian or Dutch LNG terminals) in scenarios without support for building German regasification capacities.

We focus on Germany in scenarios that include support for building regasification capabilities but do not present similar scenarios for Europe as a whole because Europe has substantial unused regasification capacity (FWE, 2019). It is therefore unlikely that further support for regasification would lead to more (U.S.) LNG imports. Indeed, as discussed in Holz et al. (2016), the problem is the lack of interconnections within Europe, which hinders efficient trading of natural gas between European countries. The problem is particularly apparent around Spain, which has very limited interconnections to its neighbors, Portugal and France. Reducing pipeline bottlenecks between European countries is primarily a regulatory and political challenge; if the U.S. wants to export more LNG to the EU, addressing this challenge might be a fruitful avenue to pursue.

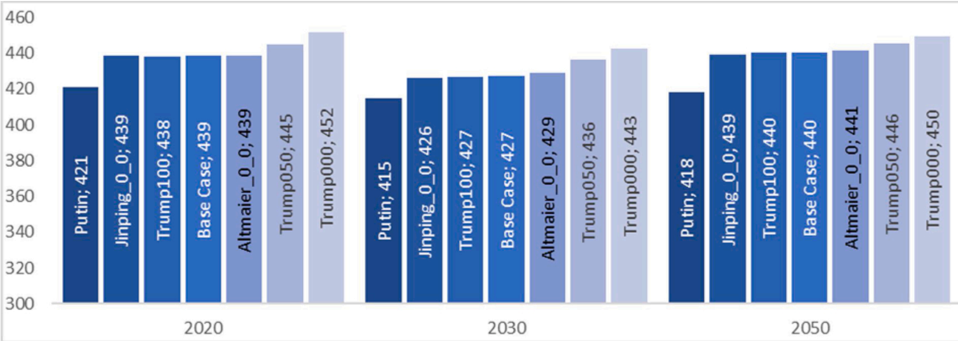

Fig. 13. Total EU consumption Base Case and selected scenarios in bcm/year.
Note: The vertical axis is truncated at the lower end at 300 bcm per year.

4.5. Summing up the effects for Europe

Fig. 13 presents EU consumption in different periods under selected scenarios. The columns are ordered according to the level of consumption. The *Base Case* results are in the middle, results for *Putin* scenarios are to the left, with the lowest consumption level in all years, and *Trump* scenarios that entail full shipping cost subsidies produce the highest consumption. Clearly, neither Chinese nor German subsidies for regasification terminals affect aggregate EU consumption levels in a significant way. Only the *Putin* and extreme *Trump* scenarios have a noticeable, albeit still rather modest, effect. Compared to the *Base Case*, EU consumption in any year, varies by no more than −5% to +3%, and average prices vary by no more than −5% to +10 %.

5. Conclusions

In this study, we investigate the role of U.S. LNG exports to Europe and, in particular, the effect of several policies on these trade flows and on natural gas consumption in Europe. We use a state-of-the-art, open access numerical model to analyze scenarios out to 2050 and analyze the long-term equilibrium results. Open access numerical modeling has the benefit of quantifying insights for use in energy policy decisions and informing decision-makers in government and business in a way that is transparent and easy to comprehend. In this spirit, we opted to use a deterministic model to keep the complexity of the analysis manageable and because the value of stochastic information produced by stochastic numerical models of natural gas markets has proved to be small (Egging and Holz, 2016). Moreover, our model is an equilibrium model, which allows us to take into account simultaneous actions by all types of participants along the value chain in the natural gas sector and to incorporate imperfect competition, a feature that is still relevant in global natural gas markets.

We find that only scenarios with aggressive policy actions have noticeable effects on the European natural gas sector. These effects are mostly seen in the supply mix; the impact on consumption is very small across the scenarios. In other words, neither Chinese nor German subsidies to encourage construction of regasification terminals, nor subsidies to promote U.S. LNG exports affect aggregate EU consumption levels in a significant way. Only a Russian boycott or large tax breaks on U.S. LNG exports have a discernable effect. Altogether, compared to the *Base Case*, EU consumption varies by no more than −5% to +3% in any year, and average prices vary by no more than −5 % to +10 %. The reason for this resilience in European consumption lies in the strong diversification of European supplies: when one supplier fails—even one as large as Russia—its volumes can be replaced by other suppliers, at least to a very large extent.

U.S. LNG trade flow patterns are of course, affected by the various scenarios but here again, the effect is noticeable only when the policies are extreme, that is, they include very large subsidies or a complete Russian boycott of the European market that leads to higher imports of U.S. LNG in Europe. The impact on the market share for U.S. LNG of a delay in the Nord Stream 2 pipeline construction due to U.S. sanctions is minimal.

We find that the interconnectedness of global gas markets, due to an abundance of LNG import capacity in Europe and in other regions, has allowed global trade patterns to adjust and has mitigated the consequences of regional disturbances. In other words, local and regional policy changes have ripple effects around the world. The two main importing regions that are the focus of these effects are Europe and Asia. Depending on the policy settings, LNG and Russian pipeline supplies are balanced between these two world regions. Thanks to this balance, consumption levels in these regions are barely affected by a change in policies across our scenarios.

Asian demand shows strong growth in the coming decades. In our *Base Case*, Asian demand surpasses demand in North America (currently the largest gas consuming region) and Europe in the second half of the 2020s. The Covid-19 pandemic is unlikely to reverse this trend; at most, it may cause a delay. By 2050, Asia alone will account for almost 30 % of global demand for natural gas, up from 20 % today. Given this growing demand, Asia is the preferred market for (U.S.) LNG. Europe only occupies that place when its (relative) willingness to pay is high, which is the case when large supplies (e.g., from Russia) are disrupted or when the willingness to pay is low in competing regions, particularly in Asia.

While we did not analyze a scenario involving low willingness to pay in Asia, events in 2019 and early 2020 illustrate this condition.

Table B1
U.S. LNG export terminal projects and their status.

Terminal	Status
Cameron, LA	Operating
Corpus Christi, TX	Operating
Cove Point, MD	Operating
Elba Island, GA	Operating
Freeport, TX	Operating
Kenai, AK	Existing, mothballed
Sabine Pass, LA	Operating
Calcasieu Parish, LA	Approved, under construction
Cameron, LA (expansion)	Approved, under construction
Corpus Christi, TX (expansion)	Approved, under construction
Elba Island, GA (expansion)	Approved, under construction
Freeport, TX (expansion)	Approved, under construction
Sabine Pass, LA (expansion)	Approved, under construction
Brownsville, TX	Approved, not under construction
Cameron, LA (expansion)	Approved, not under construction
Corpus Christi, TX (expansion)	Approved, not under construction
Freeport, TX (expansion)	Approved, not under construction
Gulf of Mexico	Approved, not under construction
Jacksonville, FL	Approved, not under construction
Lake Charles, LA	Approved, not under construction
Pascagoula, MS	Approved, not under construction
Plaquemines Parish, LA	Approved, not under construction
Port Arthur, TX	Approved, not under construction
Cameron, LA (expansion)	Pending application
Coos Bay, OR	Pending application
Nikiski, AK	Pending application
Sabine Pass, LA (expansion)	Pending application
Galveston Bay, TX	Project in pre-filing
LaFourche Parish, LA	Project in pre-filing
Plaquemines Parish, LA (expansion)	Project in pre-filing
Port Arthur, TX (expansion)	Project in pre-filing

Table C1
Country abbreviations.

Node	Country
AUT	Austria
BEL	Belgium
BGR	Bulgaria
CHN	China
CYP	Cyprus
CZE	Czech Republic
DEU	Germany
DNK	Denmark
ESP	Spain
EST	Estonia
EU	EU28 (i.e., EU27 + UK)
FIN	Finland
FRA	France
GBR	United Kingdom
GRC	Greece
HRV	Croatia
HUN	Hungary
IRL	Ireland
ITA	Italy
LTU	Lithuania
LUX	Luxembourg
LVA	Latvia
MLT	Malta
NLD	Netherlands
POL	Poland
PRT	Portugal
ROM	Romania
RUS	Russia
SVK	Slovakia
SVN	Slovenia
SWE	Sweden

Table C2
Region abbreviations.

EU	EU28 (EU27 + United Kingdom)
ROE	Rest of Europe, including Turkey, Ukraine and Belarus
AFR	Africa
NAM	North America (USA, Canada, and Mexico)
SAM	South America
CAS	Caspian region and Central Asia
MEA	Middle East
ASP	Asia Pacific

During this period, low prices in Asia due to mild winters, the link between oil and gas prices, and little flexibility among importers in Asia to shift to suppliers other than those who deliver under long-term contracts contributed to high levels of U.S. LNG exports to Europe. Moreover, Europe's demand for imports was temporarily boosted due to higher-than-average increases in inventories in preparation for a potential disruption of Russian natural gas supplies through Ukraine at the end of the transit contract at the end of 2019.

However, in the long run, we conclude that overall conditions for U.S. LNG exports are less favorable in Europe than in Asia. This is even truer now than in the past, as the EU aims to become climate neutral by 2050. Therefore, it would be more rational for the U.S. administration to direct its political support of LNG exports toward Asia rather than Europe. An LNG trade war with China is counterintuitive and would probably be counter-productive in this respect.

The globalization of natural gas markets that has been fueled by declining costs in LNG value chains has increased connections across regional markets. This connectedness means that effects from regional shocks are felt more broadly, but it also dampens the magnitude of those effects in specific regions. Therefore, globalization should affect considerations of risk in matters, such as contracts, portfolio management, and investment in the natural gas value chain.

To extend this research, it would be helpful to incorporate pressures from climate policies. The 2015 Paris Agreement implicitly provides a push for decarbonization for all countries across the globe, not just in Europe. In a next step, potential stranded assets in the natural gas value chain could be quantified using the open Global Gas Model, complementing the reserves perspective of McGlade and Ekins (2015) and Chevallier et al. (2021).

Author contributions

Ruud Egging-Bratseth: Data curation, Formal analysis, Methodology, Software, Visualization, Writing – Review & Editing.
Franziska Holz: Conceptualization, Writing original draft, Project administration, Funding acquisition, Supervision.
Victoria Czempinski: Writing original draft, Formal analysis, Validation.

Declaration of Competing Interest

Ruud Egging-Bratseth and Franziska Holz are involved with the NTNU Energy Transition Initiative which is co-sponsored by Equinor, the Norwegian energy company. However, their contracts are with NTNU.

Acknowledgements

We would like to thank Reinhard Madlener for inspiring us to this research. We also thank Akira Schroth for research assistance.

Franziska Holz and Victoria Czempinski acknowledge funding from the German Ministry for Education and Research (BMBF) under grant number 01LA1811B ('FoReSee' project). Ruud Egging-Bratseth and Franziska Holz acknowledge funding from the NTNU Energy Transition Initiative. Ruud Egging-Bratseth acknowledges funding from the Norwegian Research Council, grant 296205Norwegian Centre for Energy Transition Strategies (FME NTRANS).

Appendix A. Glossary

Table A.1 Definitions of technical terms.

Term	Definition
LNG	Liquefied Natural Gas (natural gas cooled to −167 °C). LNG is approximately 600 times less voluminous than in its gaseous state and can therefore be transported in ships over long distances and can be used as liquid fuel. It needs to be cooled continuously to stay in its liquid state.
Liquefaction	Process of cooling down the natural gas to −167 °C so that it becomes liquid.
Long-Term Contract (LTC)	The typical contract structure used in the natural gas industry, both for pipeline and LNG sales, for both international and national deliveries. LTCs guaranteed revenues to project developers and they guaranteed supplies to customers at a time when there were no

(continued on next page)

(*continued*)

Term	Definition
	liquid natural gas markets. The importance of LTCs has always been smaller in North America than in other regions, and their dominance has faded in Europe over the last decade or so. In Europe, some of the standard characteristics of LTCs had to be removed under regulatory pressure in the last decade, notably oil-price indexation and destination clauses.
Regasification	Process of warming up liquefied natural gas, typically to ambient temperature. This process is, of course, much less energy-intensive and therefore less costly than liquefaction.
Shale Gas	Natural gas produced (extracted) from shale rocks. The product has the same properties as natural gas from other geological sources, in particular the same methane content of approximately 95 %.

Appendix B. LNG terminals in the U.S

Appendix C. Global Gas Model regional node abbreviations

See Tables C1 and C2

Appendix D. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.ribaf.2021.101460.

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