Modeling Europe's role in the global LNG market 2040: balancing decarbonization goals, energy security, and geopolitical tensions

Sebastian Zwickl-Bernhard*[1,2] and Anne Neumann[2,3]

[1] *Energy Economics Group (EEG), Technische Universität Wien, Gusshausstrasse 25-29/E370-3, 1040 Wien, Austria*
[2] *Department of Industrial Economics and Technology Management, The Norwegian University of Science and Technology, Trondheim, Norway*
[3] *Center for Energy and Environmental Policy Research, Massachusetts Institute of Technology, 400 Main Street, Cambridge, MA 02142, USA*

Abstract

This paper examines the LNG trade in 2040, focusing on the role of Europe as an LNG importer. The analysis exemplifies the complexities of Europe's strategy of simultaneously achieving decarbonization objectives and resolving energy security concerns regarding LNG. We propose an optimization model to find the optimal global LNG trade between exporters and importers. As an alternative for Europe to rely solely on imports, the potential substitution of imports with domestic natural gas production equipped with carbon capture and storage is considered. Two scenarios (low and high LNG demand) scenarios are examined. Findings indicate a noteworthy role of Europe in the global LNG market solely in the ambitious sustainable scenario, whereas its significance diminishes in the high-demand scenario. Examining the volumes of LNG sent toward Europe, African exporters appear as notably significant. However, as global LNG demand rises, the discernibility of genuinely stable trends or patterns in trade declines. The value of long-term contracts may experience a resurgence in the future. Future work should include long-term contracts, allowing for fixed LNG volumes traded. Furthermore, we see our obtained LNG supply costs for Europe as valuable inputs for large-scale energy system models aiming to optimize the sustainable transition of Europe's energy infrastructure.

Keywords— LNG; 2040; Europe; decarbonization; political tension; supply cost; demand, carbon capture and storage

* *Corresponding author:* zwickl@eeg.tuwien.ac.at; *Address:* Energy Economics Group (EEG), Technische Universität Wien, Gusshausstrasse 25-29/E370-3, 1040 Wien, Austria

1 Introduction

With the Paris Agreement 2015, the world is committed to achieving carbon neutrality by mid-century [1]. Towards carbon neutrality, indisputably renewable energy resources will play a key role in reducing the use of fossil fuels such as oil and coal [2]. To what extent natural gas, also a key fossil fuel, will play a role in future energy systems during their transition to carbon neutrality is still debated controversially. Despite ambitious climate targets of some countries and regions, substantial demand for natural gas globally must still be assumed until mid-century (and possibly even later).

Historically, natural gas demand has been highly concentrated geographically near natural gas production as it has been mainly transported through gas pipelines, which limited the transport distance to a few thousand kilometers. As liquefied natural gas (LNG) became technically and economically available at scale in the last decades, the number of countries with access to natural gas through LNG imports via cargo transport has increased rapidly. In those countries that traditionally had a high share of oil and coal in their primary energy consumption, LNG has become - alongside renewable energy sources - the fuel of choice to reduce carbon emissions. One example is China [3], but other countries, such as India [4], Nigeria [5], and Ghana [6], could also be mentioned. Traditionally, the Asian energy market, particularly the Japanese one, firmly focused on LNG. Other countries in the Asian Pacific, for example, South Korea and as mentioned China, have shifted to LNG and increased their demand significantly in the past decades [7]. Notably, China has become the largest LNG importer worldwide, with more than half of its total natural gas imports via LNG [8]. In developing countries, increasing demand for natural gas not only replaces coal and oil but is expected to enable energy accessibility [9].

In contrast to developing countries, the situation and expectations for Europe regarding LNG demand are different and primarily a question of energy security. The European natural gas import landscape was historically shaped around supplies via pipelines with some LNG tankers providing imports mainly to the Iberian Peninsula. About one-third of Europe's total natural gas imports were covered by Russian piped gas. This varied across European countries and could be as high as 65% (Germany) or 100% (Bulgaria) [10, 11]. The geographical proximity, the generally low price of Russian pipeline imports, and the low level of active short-term gas trading in Europe were key factors for making Europe unattractive for LNG imports. However, this situation has changed fundamentally as a result of the invasion of Ukraine by Russia in February 2022. In response to Russian aggression and the resulting war in Ukraine, Europe has imposed sanctions on Russia which have also led to the collapse of Russian piped gas imports to Europe and, consequently, a rethinking of natural gas policies in Europe (see for example in Wiertz et al. [12]). On the one hand, measures were taken to reduce energy and, especially natural gas, demand. On the other hand, Europe had to find alternatives to replace the imports from Russia.

A recent paper studying in detail the question of how Europe could replace Russian natural gas imports is given by Nikas et al. [13]. The authors explore three different "corner" strategies: (a) replacing with other gas imports, such as LNG, (b) boosting European domestic energy production, and (c) reducing demand and accelerating energy efficiency. In addition to (limited) increased piped gas imports such as from Norway and other regions, the main consequence is also that LNG is (back) on Europe's agenda. The scrutiny of the second corner, about the acceleration of European energy production, is essential, particularly when it comes to the consideration of applying it for a revival of European fossil fuel production. In other words, it is probably necessary to be critical in order to adopt a discerning perspective, especially with regard to the potential impact on European natural gas production (e.g. in Groningen, the Netherlands). While we generally admit the inclusion of reactivated natural gas fields in Europe within our analysis, we claim that carbon capture and storage (CCS) emerges thereby as an integral component. A revival of European natural gas production without CCS would not only significantly jeopardize the achievement of European decarbonization targets, it would also seriously undermine irreparably the credibility of the measures of the European energy transition.

In the short term, LNG is essential for the supply security of Europe's energy systems. That is why Europe was willing to pay high prices in 2022, facing the risk of not being able to meet all the natural gas demands otherwise. In order to bring the procured quantities of LNG to Europe and individual countries, new LNG terminals (such as floating LNG terminals) were built across Europe. For example, Germany, Poland, but also Italy, and Greece have already built or are currently in the process of building LNG terminals [14]. In view of the above, it is expected that LNG will play an important role in Europe's energy supply not only in the years of the current crisis mode but also in the medium term. Although European countries have attempted to negotiate short-term supply contracts for LNG, the investments made in LNG terminals and related transport infrastructure point to longer-term planning[1]. The potential contribution of LNG to European and global climate goals and regional demand projections is uncertain.

Against this background, this paper aims to answer the following research questions:

- How, in terms of import volumes from regions and associated supply costs, will Europe meet its expected LNG demand in 2040 given increased global LNG demand driven primarily by developing countries?
- Which impact will geopolitical tensions between importing and exporting regions have on the European LNG supply if global LNG trade is prone to be used as a political weapon? Against this background and with a view to a possible cultural change regarding carbon capture and storage (CCS) in Europe, the question arises as to whether European domestic natural gas production equipped with CCS can be part of the solution for covering the demand in a decarbonized European energy system.

Consequently, the core objective of this work is to investigate the dynamics of the global LNG market equilibrium until 2040. For this, we focus our analysis on the traded LNG quantities among the most relevant import and export countries to meet expected demands and resulting regional LNG costs. We specifically look at the European market and the most relevant export countries covering Europe's demand until 2040. The analysis also allows estimating LNG price developments until 2040, which is not only a main novelty of the paper, but also a relevant contribution to the literature. LNG costs are often required for modeling energy systems and are, in those predominantly, an exogenous input parameter. Providing present values for LNG price trends, especially for those in Europe considering the absence of Russian pipeline gas, may therefore be of great relevance for future work of the scientific community analyzing the trajectory of the European energy system toward carbon neutrality.

The method applied is the development of a linear optimization model. The objective is to minimize total LNG import costs (i.e., the sum of costs from all import countries) while fulfilling all importers' exogenously predefined LNG demands. The LNG demands are taken from existing studies for a scenario with high ambitions to decarbonize the global energy system (the so-called *Net Zero* scenario) and a scenario with a further increase in LNG due to growing global energy demand (the so-called *Persisting Fossil Demand* scenario). Import and export countries are represented by nodes in the model. Optimality of the model finds, among others, optimal LNG flows from each export to each import country. For the European importers, optimality also includes the amount of LNG imports substituted by domestic natural gas production with CCS. Input parameters encompass LNG import volumes (i.e., demands) with a monthly or yearly resolution, LNG export capacities, and LNG break-even prices. Additionally, spatial and further techno-economic data are used to calculate LNG transportation costs between each export and each import region.

The paper is organized as follows. Section 2 provides relevant background information from the scientific literature and outlines the novelties of this work beyond existing research. Section 3 presents

[1] For example, the LNG terminal in Poland will not start operations until 2025.

the materials and methods developed in this work, including the mathematical formulation of the model, input data, and scenarios. Section 4 presents the results of this work, including the impact of political tensions on the European LNG imports and supply costs. Section 5 discusses the results, concludes the work, and outlines possible future research.

2 Background

This section contains background literature on the broad topic of LNG in sustainable energy systems, which is the focus of this paper. It is divided into three subsections. The first subsection 2.1 deals with the role of LNG in future energy systems and decarbonization pathways. Among other things, the aspect that LNG is, for many, a promising so-called bridge technology in the transition toward decarbonized energy systems (including also an option for tackling energy crises) is discussed in detail. At the same time, literature is highlighted that critically questions the feasibility of the fossil fuel LNG when aiming for zero-emission future energy systems. In addition, this complex discussion attempts to consider the different perspectives of developed and developing countries. Therefore, it is expressly pointed out that no claim to completeness is made for this subsection, not the other subsections. The second subsection 2.2 is dedicated to the literature dealing specifically with the modeling of LNG and, in particular, the modeling of global LNG trade. The focus is primarily on the different techno-economic modeling approaches for determining LNG trading volumes between exporters and importers and LNG supply costs. Then, the third 2.3 elaborates on LNG and other energy carriers as a political weapon. Selected works that examine the relationship between geopolitical tensions and energy systems are listed. The most important aspects of this relationship's historical context are also subject to this discussion. Finally, the novelties and own contributions of this paper are outlined in 2.4.

2.1 The role of LNG in future energy systems and decarbonization pathways

A discussion of the role of LNG in future energy systems from a global perspective can be found in various references. A comprehensive review of the future expectations of LNG demand and supply, starting with the current status, is given by Kumar et al. [15]. The paper has been published in 2011 and provides an outlook for LNG until 2030. More recently, in 2020, Najm and Matsumoto [16] investigated whether or not international LNG trade is substituted by renewable energy in the sustainable energy transition. They find empirical evidence that energy transition policies lead to a reduction of international LNG trade, while more accessible trade policies can also stimulate it simultaneously. This equivocal tendency is closely connected to the promising role of LNG as a bridging technology toward decarbonized energy systems. One of the main ideas of LNG as a bridging technology is to replace other fossil fuels (more precisely, those with higher specific carbon emissions such as coal and oil) and thus reduce carbon emissions overall. Herath and Jung [17] focus on this carbon emission reduction potential. In their study, LNG substitutes coal in the power generation of a developing country, with a significant increase in power demand to reduce carbon emissions. The impact of LNG on the diffusion of renewable energy is also studied by Bessi et al. [18]. In line with the controversial role of LNG described above, they find that LNG can have both a competitive and collaborative effect on renewable energy. Similarly, Safari et al. [19] focus on LNG as a transition fuel for sustainable energy transformation.

In addition to the promising role of LNG as a bridging technology, there is another reason why LNG can play a role in the transition to decarbonized energy systems. As more and more high-emitting energy technology/carriers (e.g., coal and oil) are banned from energy systems and replaced with renewable energy, energy security becomes more critical. More precisely, the uncertainties of renewable energy in terms of their generation and availability demand for dispatchable and highly flexible energy generation technologies. Kotzebue and Weissenbacher [20] focus in their study on isolated energy systems and state that in such energy systems renewable energy generation alone do not foster the energy transition sufficiently. For many, LNG is one of the technology pillars that provides a dispatchable and highly flexible generation technology for sustainable energy systems. For example, Augutis et al. [21] study comprehensively the opportunities of LNG in contributing to energy security by conducting a case study at the national level. Su et al. [22] focus on analyzing energy supply reliability in integrated energy systems with uncertainties of renewable energy generation and how LNG can serve to operate those systems. The role of LNG for energy security is also addressed by Malik et al. [23] in their quantitative national analysis for a developing country.

The following are selected references of particular interest to the national perspective of LNG in future energy systems and decolonization pathways. The references are grouped according to studies that focus on the perspective of developing and developed countries. With respect to developing countries, several studies provide valuable insights into the role that LNG can play in decarbonized energy systems. For example, Yin and Lam [24] look at the case of China and the role of LNG in its energy transition. In particular, they focus on Chinese LNG supply and potential bottlenecks in LNG imports and associated supply dynamics. Emodi and Boo [25] examine the development of a sustainable energy system in one of the world's leading LNG exporters, Nigeria. They comprehensively outline the current status of LNG in Nigeria's energy system and policy options for achieving a national sustainable energy system. Esily et al. [26] also focus on the role of a major LNG exporter in the context of decarbonized energy systems. The authors thoroughly examine the case of Egypt, taking into account the decarbonization of the European energy system, one of the main customers of Egypt's LNG exports. They state that with the decline in demand for LNG in Europe, Egypt is trying to increase its share of the LNG market in Asia. Other relevant studies on the national role of LNG in sustainable energy systems are provided by Hasan et al. [27], who examine the situation in Indonesia, and Mahmood et al. [28], who explain the case of Pakistan. The latter study focuses particularly on the aspect of energy security in Pakistan and its dependence on LNG imports from Qatar.

There is a large number of studies that focus specifically on the national perspective of developed countries, particularly for Asian developed countries, but also for other countries such as European countries. For example, Nesheiwat and Cross [29] examine the Japanese case and how the transition to a sustainable energy system is linked to the national use of LNG. Further literature on the Japanese case is published by Oshiro et al. [30]. In contrast to Nesheiwat and Cross, the latter authors focus particularly on the interaction between the decarbonization of the Japanese energy system and its implications for national energy security policy and the use of LNG. Hong et al. [31] also provide a detailed analysis of an Asian country. The authors detail long-term energy transition scenarios for South Korea and show that the country, which is currently heavily dependent on LNG, can achieve a gas-free energy system and thus carbon neutrality. However, they also point out the major challenges for South Korea's energy system if it relies entirely on renewable energy sources. For the European national perspective on this topic, among other studies, Brauers et al. [32] and Grigoryev and Medzhidova [33]. While the first authors focus on the case of Germany and its lock-in effects in the face of LNG expansion plans in the context of national energy system decarbonization, the second authors focus on the energy transition of the Baltic regions and the controversial role of LNG there. Another study that focuses on a regional aspect of the global LNG trade rather than a national perspective is provided by Moryadee and Gabriel [34]. The authors focus on LNG imports to Asia, but look in particular at the impact of the Panama canal, its expectations in terms of the number of ships that can be handled there, and the impact on LNG shipping routes to support the Asian LNG market. Another interesting study that also looks at LNG carriers is published by Raju et al. [35]. The authors do not specifically study the Panama canal but analyze the volatility of new building prices for LNG carriers.

2.2 Techno-economic modeling of global LNG trade

Given the scope of this paper, studies that focus on techno-economic modeling of global LNG trade and markets are listed below. That allows the reader to put this paper and its methodology into perspective with other relevant studies. In 2008, Egging et al. [36] published a paper proposing a global gas model using complementarity. Another paper by the previous authors exists, presenting an extension of the model regarding the temporal complexity [37]. Like this paper, LNG demand and other cost components, such as the LNG tanker costs, are implicitly modeled via ex-post calculations. More recently, Lin and Brooks [38] proposed a partial equilibrium model to investigate the uncertainties and dynamics in the global gas market until 2050. They study the global LNG trade under decarbonization scenarios. Another study that focuses on modeling the dynamics of the global LNG trade, with particular emphasis on the supply side, is provided by Crow et al. [39]. In addition, Bridge and Bradshaw [40] also examine the dynamics of the global LNG trade. They concentrate, among others, on the geographical scope of the LNG trade analysis. Kompas and Che [41] use a stochastic approach to determine LNG imports and exports in the Asia-Pacific region.

In contrast to the previous studies, which are mainly dominated by a system-modeling or integrated-modeling approach, further studies propose an agent-based modeling approach. For instance, Meza et al. [42] apply an agent-based model to study the global LNG trade in 2030. Their results show that smaller LNG exporters struggle to allocate future supplies when looking at the supply side. Analogously, Guo and Hawkes [43] also use an agent-based method but consider game-theoretic aspects to determine the global LNG market trade. A coarse-grained model has been developed to devise LNG trade portfolios 2030 under secure supply by Magnier and Jrad [44]. Machine Learning Algorithms to estimate spot LNG prices are presented by Yang et al. [45]. The modeling of LNG trading routes and flows is presented exemplarily by Zhang et al. [46] using a gravity-modeling approach and Filimonova et al. [47] focusing primarily on new trade routes. New LNG trading routes are also studied by Feng et al. [48]. Other specific aspects of the techno-economic modeling of LNG trade can also be found in the literature. While Pospíšil et al. [49] evaluate the energy demand of liquefaction and regasification stations for LNG transportation, Sharafian et al. [50] investigate different design options for these stations. A case study investigating local LNG production and transportation costs is presented by Raj et al. [51].

2.3 LNG and other energy carriers as a political weapon

The instrumentalization of energy as a political weapon dates back to 1973 when OPEC ((Organization of the Petroleum Exporting Countries) used oil against those Western countries supporting Israel. During the 50 years afterward (until February 24th, 2022) energy has repeatedly shown to have broader ties within the political-economic system of international relations. Keohane and Nye [52] show that asymmetric inter-dependencies are a source of power. Franz and van der Linde [53] look at the link between geopolitics and foreign policy in the case of EU energy security. Yergin [54] provides an insightful global perspective on the link between energy transition, climate, and geopolitics. There is also a case for renewables when it comes to geopolitics as pointed out by Scholten and Bosman [55].

The EU-Russia gas trade relationship has been commented on extensively, in particular since Russia cut its natural gas supplies to Europe during its war with Ukraine in 2006 for the first time. The advent of shale gas production at a large scale in the US has triggered the vision of the US becoming a net exporter of LNG (around 2010). Available global LNG export capacities changed the landscape of natural gas geopolitics as has been noticed by several observers (i.e., Grigas [56]). The existing literature has used either a qualitative approach or a game-theoretic framework to analyze the consequences. Most frequently the focus was on pipeline gas deliveries (or a more general "supply disruption"). Gabriel [57] considers the impact of the (un-)availability of the Panama canal on international LNG flows. Although history has shown that crude oil (which is also traded internationally via carriers/tankers) can be weaponized, little attention has been paid to LNG in this respect. However, recent events such as the Houthi attacks around the Bab al-Mandab Strait, Red Sea, and Suez canal have led to the rerouting of LNG carriers leading to longer traveling time and thus also impacting spot natural gas prices in Europe (due to lower availability of cargo capacity).

2.4 Novelties and own contribution

Based on the conducted literature review, three main novel contributions of this work beyond the current state of the art can be promised.

i In this analysis of the global LNG trade anticipated for 2040, particular emphasis is directed toward the European LNG supply dynamics. The investigation delves into the complexities of supply costs associated with LNG imports in two distinct scenarios. The first scenario envisions a substantial reduction in global and European LNG demand aligned with the ambition of carbon neutrality (net zero). Conversely, the second scenario contemplates significantly heightened demand levels predominately driven by the uptake of the energy demand of developing countries, surpassing the present-day demand. This research contributes to the existing body of knowledge by illuminating the potential developments and challenges within the global LNG market in 2040, specifically within the European context.

ii Expanding upon prior investigations that have addressed the impact of geopolitical tensions on energy systems, our research specifically concentrates on the LNG trade in 2040 as a focal point within energy system analyses. By doing so, we extend the literature concerning LNG in the European context, offering insights into the potential dynamics of imports and associated supply costs for Europe in 2040. This specific consideration adds depth to the discourse on the intersection of geopolitics and energy systems, contributing novel perspectives and enriching the understanding of the evolving energy system in Europe by 2040. One of the main contributions is also to provide further insights to the future of Europe's energy supply under the absence of Russian piped gas imports.

iii Furthermore, this study presents a potentially essential contribution to ongoing analyses centered on optimizing the decarbonization of the European energy system by utilizing large-scale energy system models. These models typically determine energy imports—such as LNG, hydrogen, and other sources—alongside European energy production. Notably, these imports are described by specific costs and volumes and exogenously defined as input parameters. Our research assumes significance, offering a pivotal opportunity to deliver quantitative results for both optimistic and conservative (or pessimistic) decarbonization scenarios. By providing insights into the potential implications of LNG as a critical component within these models, our work contributes valuable quantitative data, enhancing the precision and comprehensiveness of decarbonization projections for the European energy system.

3 Method

In this section, the applied method is described. In Section 3.1, the mathematical formulation of the proposed optimization model is described in detail. Then, in Section 3.2, two different scenarios are defined. They are based on the scenarios proposed by the *International Energy Agency* (IEA) [58] and *BP* [59]. Subsequently, the description of different cases is given in Section 3.3. The cases extend the scenarios in a way that they consider the effects of different political tensions on the modeling input parameters, such as LNG liquefaction capacities and delivered ex-ship prices. Additional information on the applied method and further materials can be found in the appendices of the work. For instance, details on calculating the delivered ex-ship costs (the most relevant input parameter of the model) are described in Appendix A. More empirical data (e.g., assumptions about the LNG demand in 2040) can also be found in Appendix B.

3.1 Optimization model

3.1.1 Objective function

A simple linear optimization model is proposed to answer the research questions raised in this paper. The objective function is to meet the global LNG demand with minimum supply cost. The objective function is described in Equation 1 and consists of two separate terms. The first term considers the product of the delivered ex-ship cost ($DES_{e,i}$) and the quantity of LNG $q_{e,i}$ exchanged between exporter e and importer i. DES for each tuple of exporter and importer is calculated prior to the modeling (see also Appendix A). The corresponding cost function for determining individual DESs is described in Appendix A. The second term considers an alternative supply option for the European importers (a subset of all importers, and with index i'). This term takes into account the option, to use the European domestic production equipped with carbon capture and storage (CCS) in order to substitute LNG imports. It is used when DESs for European importers are higher than the European domestic natural gas production costs equipped with CCS. The corresponding quantity is given by $q_{i'}^{EDP}$. Our assumptions on the costs of European domestic production with CCS can be found in Appendix B. x represents a vector and contains all decision variables of the model (i.e., $q_{e,i}$, $q_{i'}^{EDP}$).

$$\min_{x} \quad \underbrace{\sum_{e}\sum_{i} DES_{e,i} \times q_{e,i}}_{\text{Global LNG trade with minimum supply cost}} \quad + \quad \underbrace{\sum_{i'} (EDP + CCS) \times q_{i'}^{EDP}}_{\text{European domestic production equipped with CCS}} \tag{1}$$

3.1.2 Constraints

Equation 2 ensures that the total export quantity (i.e. the sum over all importers i) is less than or equal to the liquefaction capacity Q_e^{Liq} per exporter e. Note that the liquefaction capacity is an exogenously defined parameter and not determined by the optimal solution.

$$\sum_{i} q_{e,i} \leq Q_e^{Liq} \quad : \forall e \tag{2}$$

Analogous to the previous equation, Equation 3 guarantees that the total import quantity (i.e. the sum over all exporters e) is less than or equal to the regasification capacity Q_i^{regas} per importer i. In other words, there is explicitly no optimal capacity planning of liquefaction or regasification capacities.

$$\sum_{e} q_{e,i} \leq Q_i^{Regas} \quad : \forall i \tag{3}$$

The Equations 4 and 5 are the demand balance constraints per importer i. There D_i is the demand per i. For European importers i', as mentioned above, European domestic production equipped with CCS can be used to satisfy European LNG demand in addition to global trade and LNG imports. Note that, for simplicity, the LNG of non-European importers can only be satisfied by imports.

$$\sum_e q_{e,i} = D_i \quad : \forall i \in \mathcal{I} \wedge \neg(i \in \mathcal{I}') \tag{4}$$

$$\left[\sum_e q_{e,i}\right] + q_{i'}^{EDP} = D_i \quad : \forall i \in \mathcal{I}' \tag{5}$$

Equation 6 limits the amount of the European domestic production with CCS to the maximum capacity Q^{EDP} (based on historical values from the European domestic natural gas production; see Appendix B).

$$\sum_{i'} q_{i'}^{EDP} \leq Q^{EDP} \tag{6}$$

Finally, Equation 7 ensures diversification of exporters for each importer i and that the supply share of each exporter e is less than or equal to the total demand divided by n_i. For example, if $n_i = 3$, the total demand is supplied by at least three different exporters, each with a maximum share of one-third.

$$q_{e,i} \leq \frac{1}{n_i} \times D_i \quad : \forall i \tag{7}$$

3.2 Scenarios

We consider two scenarios (*Net Zero* and *Persisting Fossil Demand*) which provide a particularly wide range of future developments in the global and, in particular, the European LNG market. Essentially, the scenarios define demand D_i of the different importers i with respect to the mathematical formulation of the model (Equation 4). Thus, demands are - as common in this literature - defined as exogenous parameters. The other key-determining parameters of the model ($DES_{e,i}, Q_e^{Liq}, Q_i^{Regas}, etc.$) are assumed to be independent of the scenario (variation of these given in the cases; see Section 3.3). The two scenarios are based on published scenarios from IEA [58] and BP [59]. Before describing the two scenarios in qualitative terms, Table 1 shows the total and European LNG demand in both scenarios. Global LNG demand in 2040 is more than double in the *Persisting Fossil Demand* scenario compared to the *Net Zero* scenario. At the same time, the European share of global LNG demand increases from 13 % to 20 %. More details about the specific shares of importers on the total demand are provided in the Appendix B (see Table 7).

Demand [billions of MMBtu]	Net Zero	Persisting Fossil Demand
Global	16.7	35.0
Europe	2.1	6.9
- Share of global	13%	20%

Table 1: Assumptions on the LNG demand in 2040. Based on [58] and [59].

For either scenario, we explicitly focus on the structure and cost of LNG supplies to Europe in 2040. We base our assumptions on future demand on projections from IEA and BP, who use comprehensive global energy models. Thus, we do not separate demand by sector and focus exclusively on LNG. Also, our approach does not consider investment decisions. Instead, it optimizes global LNG trade given liquefaction and regasification facilities. It does so by minimizing supply costs (delivered ex-ship costs) and neglecting contractually long-term committed capacities. Next, we define two scenarios that look at distinct pathways for future global LNG demand (and trade).

3.2.1 *Net Zero*

Taking into account the ambitions of EU energy and environmental policy, a clearly defined target of net zero carbon emission by 2050, and the efforts to replace natural gas imports to Europe from Russia we define the *Net Zero* scenario. The aim of the analysis is to identify the structure and costs of LNG supplies to Europe in 2040. In such a setting the role of natural gas in European energy demand by 2040 will have dwindled. Assuming that the global energy sector will achieve net zero carbon emissions by 2050 by implementing policies that are currently in place. This pathway is broadly in line to successfully achieve the 1.5 C climate target. For this scenario, IEA [60] expects demand for natural gas to decline to 82% by 2030 and 22% by 2050 compared to 2022.[2] As a consequence, global LNG trade will slightly increase by roughly 6% by 2030, but plummet to then only one quarter compared to 2022. For Europe, the IEA [60] suggests ample supplies of natural gas and points towards the potential re-use of import terminals for hydrogen supplies later.

3.2.2 *Persisting Fossil Demand*

Net Zero is based on the assumption that natural gas will be replaced in many applications. As negotiations at COP28 have revealed, there remain obstacles in implementing a phase-out of fossil fuels. In addition, the successful implementation of large scale (offshore) wind generation or installation of solar depends on several factors. Not only public acceptance, and low prices for carbon emissions, but also the availability of a skilled workforce may delay these efforts. Hence, there is a likelihood that global demand for natural gas will remain at substantially higher levels than anticipated in the *Net Zero* scenario for decades to come. This implies that international competition for (LNG) supplies will persist. As a result it will be an interesting question to investigate which role Europe will play in such a setting and who are the beneficiaries of such a pathway. To implement this in the analysis we base our expected demand figures on the numbers from the STEPS scenario in [58].

3.3 Cases

As mentioned above, the cases extend the scenarios by considering the effects of different political tensions on the modeling input parameters, such as LNG liquefication capacities and delivered ex-ship prices. Five different cases are considered: (1) *Diversify importers*, (2) *High price Middle East*, (3) *No export from Africa*, (4) *Panama canal restricted*, and (5) *Russia to Asia only.* They are described in detail below and summarized in Table 2.

(1) It is assumed that Europe follows a strong diversification strategy in regions where LNG is imported to reduce dependency on specific regions. In order to consider this, Equation 7 is adopted in this case compared to the two scenarios in a way that n_i is set to five for all European import regions.

(2) This case considers a situation where the delivered ex-ship costs of the Middle East region increase. Compared to the initial values of the two scenarios, the delivered ex-ship costs of Qatar, Oman, and Other ME are assumed to increase by +25 %. Note that this particularly affects the costs of three regions that initially have relatively low delivered ex-ship costs compared to other export regions. A current example of this case could be that piracy and other attacks along the transport routes

[2] It is interesting to note that demand will come from industry and that more than half of total demand will be equipped with CCUS.

of the exporters mentioned (e.g., Houthi attacks around the Bab al-Mandab Strait) drive up the chartering and insurance costs of the LNG carriers.

(3) The rapid increase in energy demand on the African continent is assumed to lead to an LNG market where no exports from African regions happen. In other words, this case considers a situation where African LNG exporters prioritize African energy demand and do not participate in the global LNG trade.

(4) This case considers the situation where the Panama canal is restricted. As a result, not only the delivered ex-ship costs of those trades passing through the Panama canal are increased, but also all other trades (e.g., due to scarcity of LNG carrier availability). The increase in delivered ex-ship costs is assumed to be +33 % for those LNG flows passing through the Panama canal and +15 % for all others. Note that this case could reflect not only political tensions as a weapon but also the situation where low water levels as a result of climate change limit the number of ships and LNG carriers passing through the canal. This has been already seen in 2023.

(5) In this case, LNG sent from Russia is allowed only to Asian regions. It takes into account the situation when Russia and Asia (e.g. China and India) intensify their cooperation and thus strengthen their LNG trade. Such a development has already been observed recently (after February 24, 2022).

Case	Extension	Input parameter	Eq.	Example
(1) *Diversify importers*	Increase number of regions importing LNG to Europe	$n_i = 5$	7	Belgium, France, Italy
(2) *High price Middle East*	Increase in delivered ex-ship costs of the Middle East	$1.25 * DES_{e,i}$	1	Qatar, Oman, Other ME
(3) *No export from Africa*	African LNG exporters do not participate in the global LNG trade	$q_{e,i} = 0$	2	Nigeria, Other Africa
(4) *Panama canal restricted*	Increase in delivered ex-ship costs of all LNG flows	$1.33/1.15 * DES_{e,i}$	1	USA to Japan
(5) *Russia to Asia only*	LNG sent from Russia to Asian regions only	$q_{e,i} \neq 0$	2	Russia to China

Table 2: Overview of the five cases extending the scenarios by considering the effects of different political tensions on the modeling input parameters.

4 Results and discussion

This section presents selected modeling results related to the research questions of this paper. Accordingly, the section is divided into two main parts. Section 4.1 mainly addresses the first research question. It presents the European LNG supply and associated supply costs in 2040 for the two scenarios *Net Zero* (Section 4.1.1) and *Persisting Fossil Demand* (Section 4.1.2). Section 4.1.3 compares the results of these two scenarios. Then, Section 4.2 turns to the modeling results exemplifying the impact of geopolitical tensions on LNG importers and exporters. In particular, it shows the supply share of importers on the European demand in 4.2.1 for the different cases, the liquefaction utilization rate of exporters in 4.2.2, and the supply share of the European domestic production equipped with CCS in 4.2.3. These results are shown for both scenarios and all cases.

4.1 LNG supply and associated supply costs to Europe 2040

4.1.1 *Net Zero*

Figure 1 shows the LNG import volumes to Europe from regions in billions of MMBtu and the associated supply costs in \$/MMBtu in 2040. In this scenario, four different exporters are required in order to meet total European demand. Algeria, Nigeria, and Qatar each account for an equal share of about one-third of the total supply. Other Europe is the marginal supplier contributing merely 4.3 % (0.053 billionMMBtu) of total European demand.

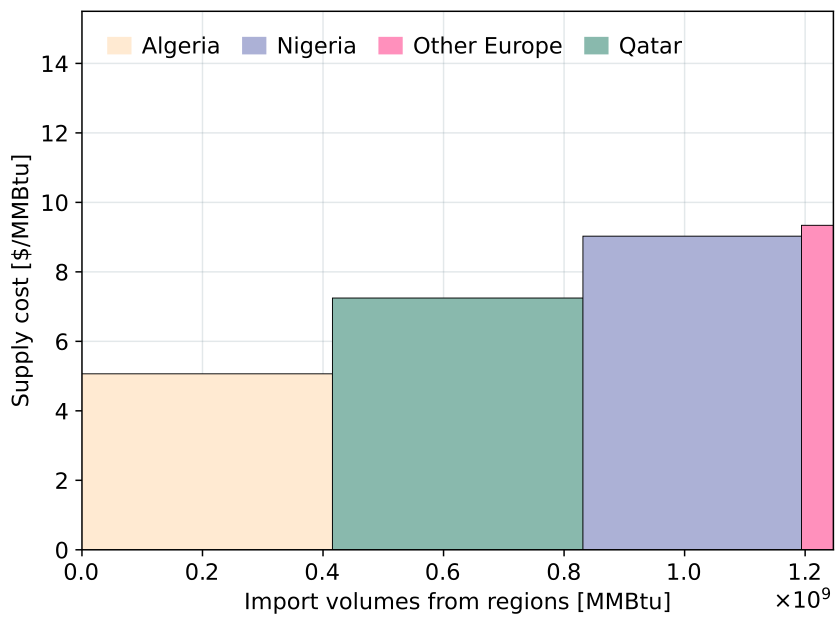


Figure 1: Import volumes of LNG from regions to meet the European demand in 2040 in billion MMBtu and associated supply costs per exporter in \$/MMBtu in the *Net Zero* scenario.

Based on the supply costs of the relevant exporters to Europe (i.e., Algeria, Nigeria, Qatar, and Other Europe), Figure 2 shows the marginal (in dark blue) and average (in sand) supply costs to Europe in 2040. The marginal costs of supply of 9.3 \$/MMBtu are determined by Other Europe. The average costs of supply cost are 7.1 \$/MMBtu.

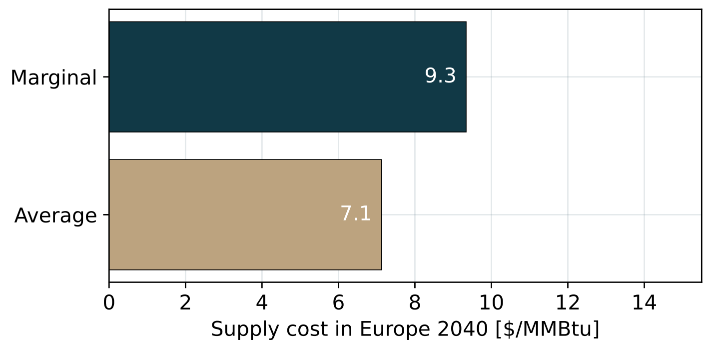


Figure 2: Marginal (top, blue) and average (bottom, brown) supply costs to meet European demand in 2040 in $/MMBtu, *Net Zero* scenario.

4.1.2 *Persisting Fossil Demand*

For the *Persisting Fossil Demand* scenario, Figure 3 shows LNG import volumes in billion of MMBtu and the associated supply costs in $/MMBtu for Europe in 2040. Compared to the previous results, the assumption of higher European LNG demand in this scenario leads to a higher number (seven) of required exporters. The regions with the highest supply shares of total demand are Nigeria, the United States, and Trinidad and Tobago. These three exporters cater for 76 % of total European demand. In addition, fringe exporters such as Other Americas, Other Europe, and Other Africa cover the remaining demand. Among these, Other Americas serves as the marginal exporter. Note the different scaling of the x-axis between Figures 1 and 3.

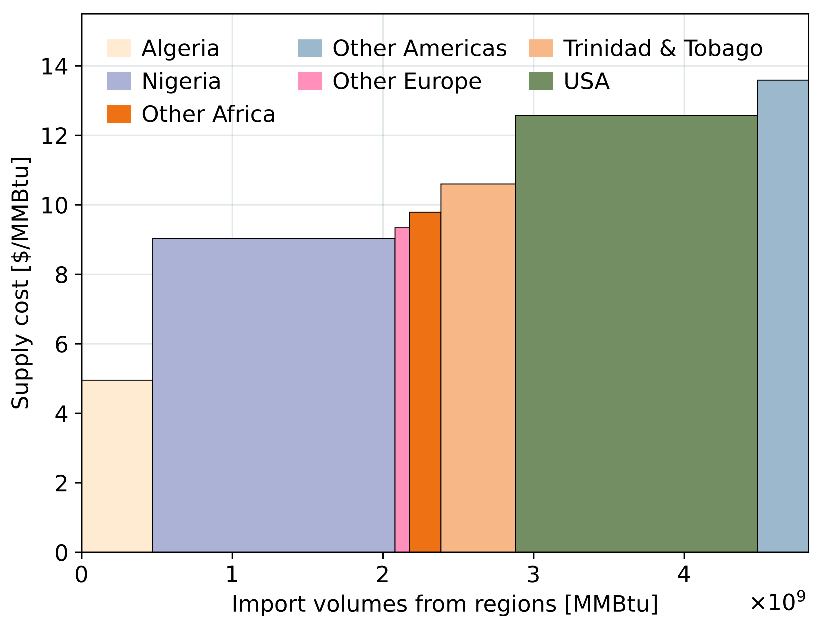


Figure 3: Import volumes of LNG from regions to meet European demand in 2040 in billion MMBtu and associated supply costs per exporter in $/MMBtu, *Persisting Fossil Demand* scenario.

As previously, Figure 2 shows the marginal (in dark blue) and average (in sand) supply costs to Europe in 2040 for the *Persisting Fossil Demand* scenario. While the marginal costs of supply, determined by Other Americas, reach 13.6 $/MMBtu, the average costs of supply is 10.3 $/MMBtu.

The results from the two scenarios do not only differ in terms of average and marginal costs of supply but also in terms of quantities supplied by each exporter. This difference in LNG import volumes to Europe per exporting region is presented in the following section.

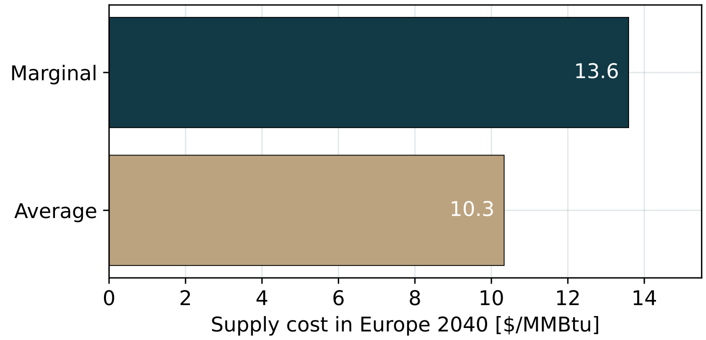


Figure 4: Marginal (in dark blue) and average (in sand) supply costs supplying the European demand in 2040 in $/MMBtu, *Persisting Fossil Demand* scenario.

4.1.3 Comparison of scenario results

The differences in the scenario results regarding import volumes from regions and average and marginal supply costs are presented in Figure 5. Specifically, it shows the change in volume for each export region (left figure) and the supply costs (right figure) to Europe in 2040.

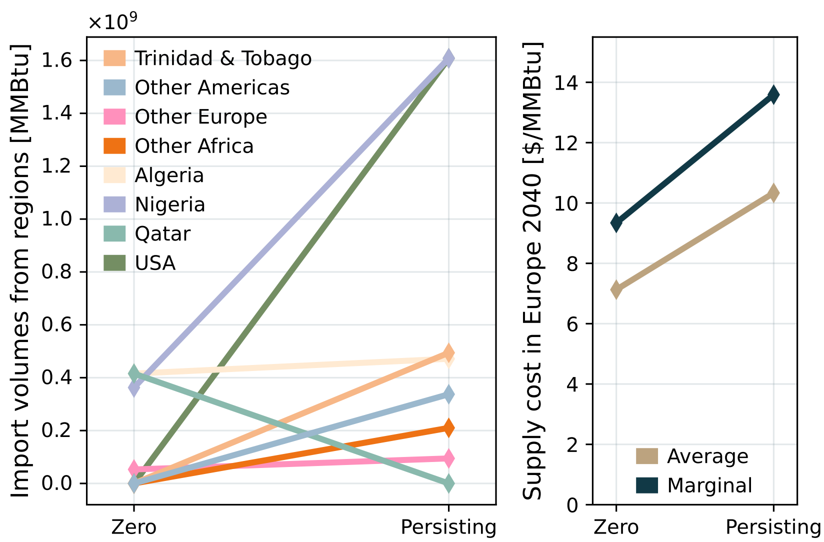


Figure 5: Comparison of the results of the *Net Zero* (Zero) and *Persisting Fossil Demand* (Persisting) scenarios showing changes in volumes for each export region (left) and the associated average and marginal supply costs (right).

Figure 5 reveals at least four interesting observations:

- Concerning exporters, the most relevant change between the two scenarios is the LNG volume sent from the USA to Europe in 2040. While the USA in the *Net Zero* scenario is irrelevant, it becomes one of the most important exporters in the *Persisting Fossil Demand* scenario. This is mainly driven by the relatively high supply costs of the USA to Europe in combination with a large number of liquefaction capacities (i.e., over-capacities) of other exporters in the *Net Zero* scenario.

- ☐ Nigeria also significantly increases its LNG volumes sent to Europe in the *Persisting Fossil Demand* scenario. Even though this increase is slightly smaller than for the USA (Nigeria already exports LNG to Europe in the *Net Zero* scenario), Nigeria becomes an essential exporter to Europe in 2040.
- ☐ Qatar only plays a role as a supplier for European LNG demand in the *Net Zero* scenario, but not in the *Persisting Fossil Demand* scenario. Given the high global LNG demand in the *Persisting Fossil Demand* scenario, other customers (especially those in the Asia-Pacific region) are preferred for Qatari exports.
- ☐ Both the average and marginal supply costs for meeting the European demand increase in the *Persisting Fossil Demand* scenario compared to the *Net Zero* scenario by 4.3 \$/MMBtu (+46 %) and 3.2 \$/MMBtu (+45 %), respectively.

4.2 Impact of geopolitical tensions on LNG imports and exports

Building upon the scenario results presented above, this section goes one step further and aims to demonstrate the impact of different geopolitical tensions (we call them cases below) on LNG flows between importers and exporters in the two main scenarios *Net Zero* and *Persisting Fossil Demand*. We show, for example, how the results change in the *Net Zero* scenario when there are no LNG exports from Africa (this case is called *No export from Africa*) available. As a short reminder, the following cases are investigated: *Diversify importers*, *High price Middle East*, *No export from Africa*, *Panama canal restricted*, and *Russia to Asia only*.

4.2.1 Supply share of exporters in the European demand

Table 3 shows the LNG import volumes from export regions to Europe 2040 in the *Net Zero* scenario and all cases in billion of MMBtu.

Exporter	Net Zero	Diversify importers	High price Middle East	No export from Africa	Panama canal restricted	Russia to Asia only
Algeria	0.415	0.249 (↘)	0.415 (∼)	- (↓)	0.415 (∼)	0.415 (∼)
Nigeria	0.362	0.249 (↘)	0.415 (↗)	- (↓)	0.415 (↗)	0.285 (↘)
Other Africa	-	0.249 (↑)	- (∼)	- (∼)	- (∼)	- (∼)
Other Europe	0.053	0.249 (↑)	0.130 (↑)	0.130 (↑)	- (↓)	0.130 (↑)
Qatar	0.415	0.249 (↘)	0.285 (↘)	0.415 (∼)	0.415 (∼)	0.415 (∼)
Trinidad & Tobago	-	- (∼)	- (∼)	0.285 (↑)	- (∼)	- (∼)
USA	-	- (∼)	- (∼)	0.415 (↑)	- (∼)	- (∼)

[1] Symbols in the brackets qualitatively indicate the change between the case and the scenario. Legend: strong decrease (↓), slight decrease (↘), constant (∼), increase (↗), strong increase (↑).

Table 3: LNG import volumes from regions to Europe 2040 in the *Net Zero* scenario and cases in billion of MMBtu.

Considering LNG import volumes to Europe in 2040 in the *Net Zero* scenario and cases, the following can be observed:

- ☐ LNG volumes from regions such as Algeria, Nigeria, and Qatar remain largely constant across cases. Of course, this does not apply to cases such as the *No export from Africa* case, where by definition no imports from African regions are permitted.
- ☐ Only in some very specific cases do regions such as Other Africa, Trinidad and Tobago, and the USA become exporters to Europe in 2040. Hence, it is really case dependent on whether these regions will send LNG in the direction of Europe.

Exporter	Persisting Fossil Demand	Diversify importers	High price Middle East	No export from Africa	Panama canal restricted	Russia to Asia only
Algeria	0.472	0.472 (∼)	0.682 (↗)	- (↓)	0.472 (∼)	0.472 (∼)
Nigeria	1.608	0.965 (↘)	1.608 (∼)	- (↓)	0.897 (↘)	1.608 (∼)
Other Africa	0.210	0.756 (↗)	- (↓)	- (↓)	- (↓)	0.541 (↗)
Other Americas	0.337	0.707 (↗)	0.337 (∼)	1.348 (↗)	- (↓)	0.101 (↘)
Other Europe	0.094	0.310 (↗)	0.094 (∼)	0.125 (↗)	- (↓)	- (↓)
Qatar	-	- (∼)	- (∼)	0.260 (↑)	- (∼)	- (∼)
Trinidad & Tobago	0.494	0.494 (∼)	0.494 (∼)	0.184 (↘)	0.612 (↗)	0.494 (∼)
USA	1.608	0.965 (↘)	1.608 (∼)	1.608 (∼)	1.608 (∼)	1.608 (∼)

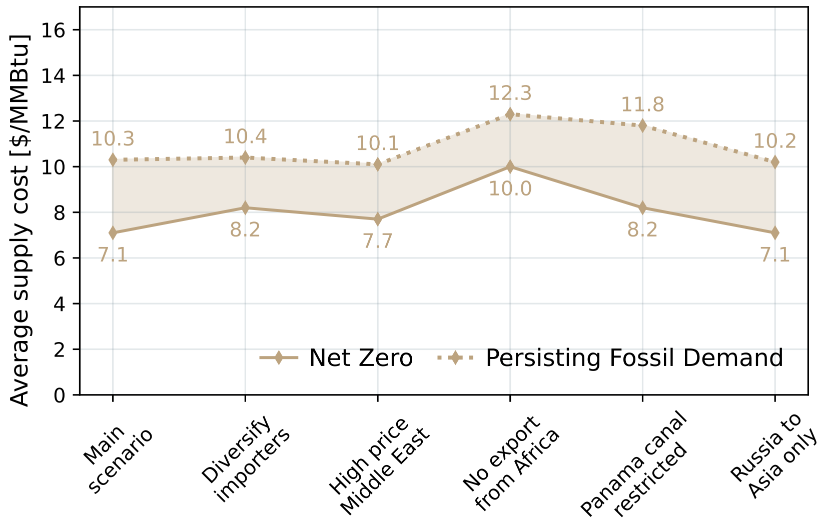
[1] Symbols in the brackets qualitatively indicate the change between the case and the scenario. Legend: strong decrease (↓), slight decrease (↘), constant (∼), increase (↗), strong increase (↑).

Table 4: LNG import volumes from regions to Europe 2040 in the *Persisting Fossil Demand* scenario and cases in billion of MMBtu.

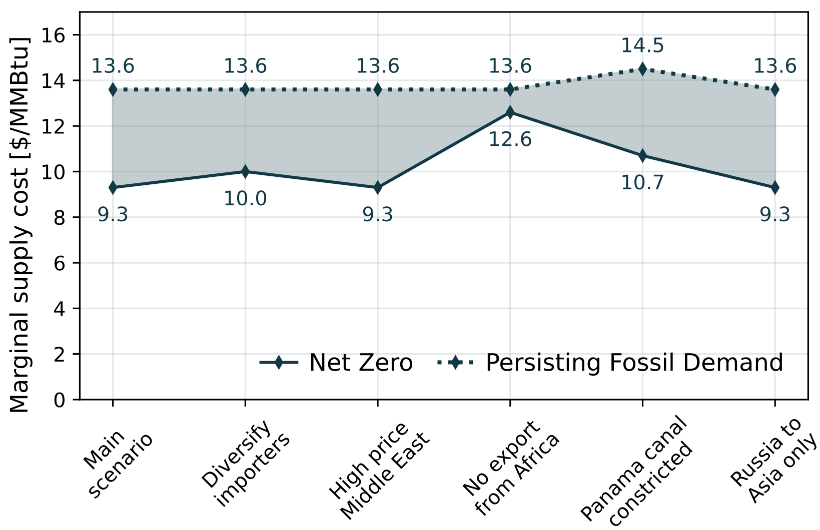
The results for the *Persisting Fossil Demand* scenario in Table 4 reveal at least two interesting insights:

- ☐ There are no clear trends for LNG imports for the different regions. Rather, volumes fluctuate significantly for most exporters (both in absolute terms and also relative to the *Net Zero* scenario and its cases).
- ☐ However, in imports to Europe from the USA, a consistent trend emerges: quantities remain relatively constant across all cases.

The average and marginal supply costs to Europe for both scenarios and all cases are illustrated in Figure 6. The results of the *Net Zero* scenario are shown as solid lines, while the results of the *Persisting Fossil Demand* scenario are as dashed lines. The highest average supply costs to Europe in 2040 are reached in the case where no exports from Africa are permitted for both scenarios. In this specific case, the average costs of supply (see Figure 6a) reach 12.3 \$/MMBtu and 10.0 \$/MMBtu in the *Persisting Fossil Demand* and *Net Zero* scenarios, respectively. The results for the marginal supply costs are similar: the case where no exports from Africa are permitted leads to the most considerable increase. The marginal supply cost (see Figure 6b) reaches 13.6 \$/MMBtu and 12.6 \$/MMBtu in the *Persisting Fossil Demand* and *Net Zero* scenarios, respectively. It is noteworthy that the difference between the marginal cost of supply in the two scenarios is the smallest in the *No export from Africa* case among all the cases.



(a) Average supply costs to Europe in 2040



(b) Marginal supply costs to Europe in 2040

Figure 6: Comparison of the average (a) and marginal (b) supply costs in the two scenarios *Net Zero* (solid) and *Persisting Fossil Demand* (dashed) cases to Europe in 2040 in $/MMBtu.

4.2.2 Utilization of liquefaction capacity

The previous section focused on the differences in volumes from regions supplying Europe and the associated average and marginal supply costs in two scenarios and cases. This section turns its focus on the results and presents results for the utilization of liquefaction (exporting) capacities. For illustrative purposes we focus on the results for the region Other Europe in the *Net Zero* scenario and the USA in the *Persisting Fossil Demand* scenario. [3] Figure 7 reveals that the exported volume of the region Other

[3] Recall that Other Europe is the marginal supplier of European demand in the *Net Zero* scenario, and the USA is one of the major suppliers in the *Persisting Fossil Demand* scenario.

Europe in the *Net Zero* scenario accounts for utilization of 17 % of the liquefaction capacity (4.3 % supply share on the total European LNG demand). This share is higher in all cases and reaches 100 % in the cases *High price Middle East*, *No export from Africa*, and *Russia to Asia only*.

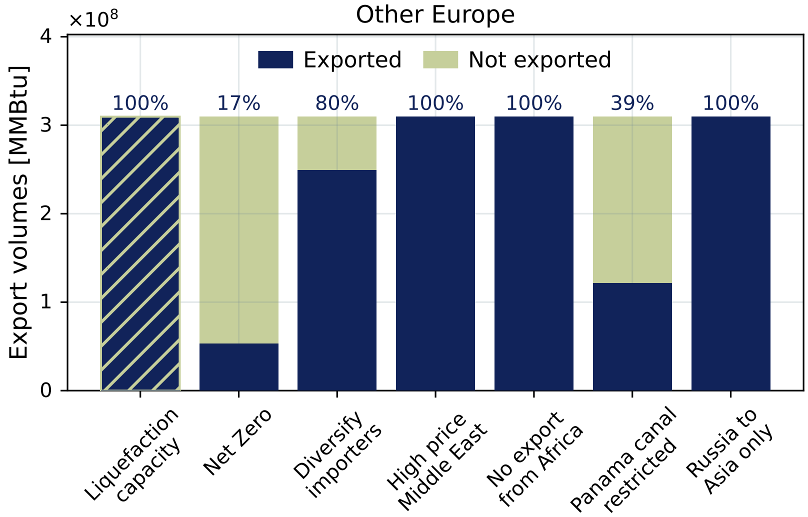


Figure 7: LNG export volumes in $MMBtu$ and the corresponding liquefaction capacity utilization rate in % of the region Other Europe in the *Net Zero* scenario and for all cases.

Figure 8 shows that the export volume of the USA in the *Persisting Fossil Demand* scenario varies between 63 % (in case of a restricted Panama canal) and 78 % (e.g., in case of high supply costs from the Middle East region).

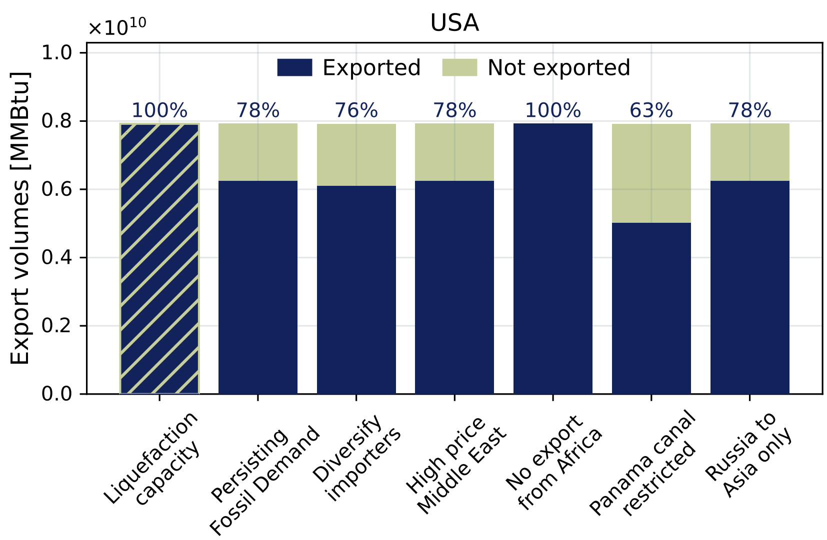
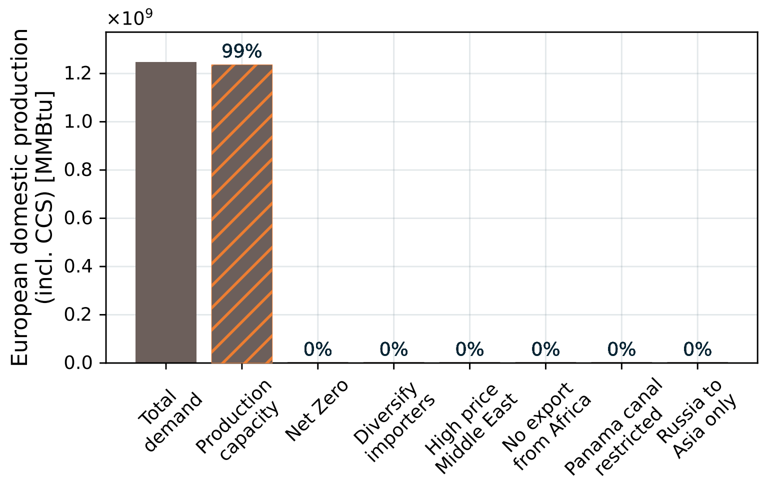


Figure 8: LNG export volumes in $MMBtu$ and corresponding liquefaction capacity utilization rate in % of the USA in the *Persisting Fossil Demand* scenario and for all cases.

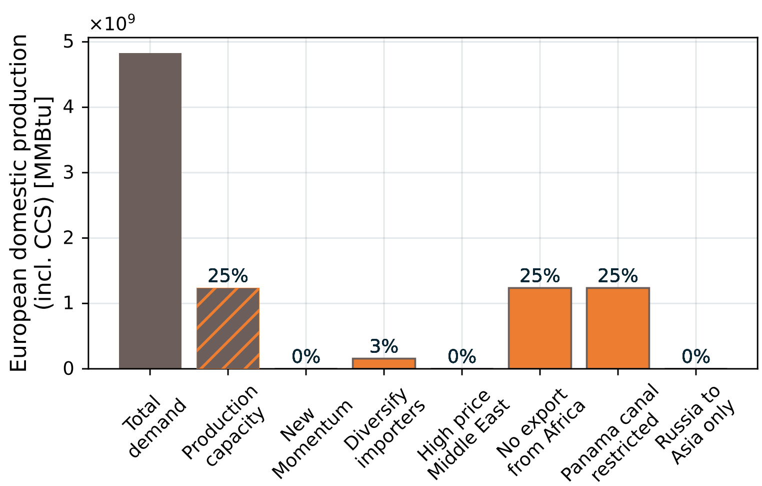
In summary, the LNG export volumes and corresponding utilization of liquefaction facilities in the USA show little variation across the cases. Nevertheless, in the case of permitted LNG exports from Africa, its liquefaction utilization rate increases to the maximum value of 100 %.

4.2.3 European domestic production with CCS

Figure 9 shows if and to what extent European domestic production of natural gas with CCS plays a role as an alternative supply option to substitute LNG imports. In the *Net Zero* scenario (Figure 9a), European domestic production with CCS is not used to substitute LNG imports from other regions. This holds for the main scenario and all cases.



(a) *Net Zero*



(b) *Persisting Fossil Demand*

Figure 9: European domestic production with CCS supplying Europe's LNG demand in 2040 in MMBtu in the two scenarios *Net Zero* (a) and *Persisting Fossil Demand* (b).

In contrast, European domestic production of natural gas with CCS is needed in some cases in the *Persisting Fossil Demand* scenario (see Subfigure 9b). In particular, for the cases where no LNG exports from Africa are permitted and where the Panama canal is restricted, LNG demand is covered by domestic production of natural gas equipped with CCS. The supply from European domestic production with CCS is at maximum capacity in these cases. By definition/assumption this maximum capacity accounts for 25 % of total European LNG demand. Considering the case with a focus on the diversification of importers (*Diversify importers*), a small share of total LNG demand (around 3 %) is also supplied by the European domestic production equipped with CCS.

5 Conclusions and outlook

This paper comprehensively examines the global liquefied natural gas (LNG) trade in 2040, with a specific emphasis on elucidating the pressing role of Europe as an LNG importer. The analysis exemplifies the complexities of Europe's strategy of simultaneously achieving decarbonization objectives and resolving energy security concerns in the context of LNG in two scenarios (*Net Zero* and *Persisting Fossil Demand*). We assess the potential susceptibility of Europe's LNG supply to geopolitical tensions through an analysis of LNG import volumes, examining their variations under different market conditions. Additionally, we explore the expected average and marginal supply costs associated with these LNG trades to Europe.

Methodologically, we use a straightforward optimization model formulated to find the optimal (i.e., with minimal costs) global LNG trade among strategically chosen nodes, representing crucial import and export regions. Our approach is based on a minimization of the delivered ex-ship costs for sending LNG between nodes. As an alternative for European LNG importers to rely solely on imports, our model contemplates the potential substitution of imports with domestic natural gas production equipped with carbon capture and storage. This allows us to provide insights into the economic feasibility and implications of prioritizing domestic production over external LNG imports.

The findings indicate a noteworthy role of Europe in the global LNG market solely in the ambitious sustainable scenario *Net Zero*, whereas its significance diminishes in the contrasting *Persisting Fossil Demand* scenario. This observation is also substantiated by our results, which show that the *Persisting Fossil Demand* scenario under geopolitical tensions prompts the adoption of the European domestic natural gas production equipped with carbon capture and storage, despite its inherently outrageous costs, as a required measure to substitute LNG imports. Examining the volumes of LNG sent toward Europe, African exporters appear as notably significant. Also in the broader context of global LNG trades, African exporters have turned out to act as crucial stabilizers, particularly in mitigating LNG import costs to Europe. However, the findings suggest that as global LNG demand rises, the discernibility of genuinely stable trends or patterns in trade declines. In light of this tendency, the value of long-term contracts may experience a resurgence in the future. Certain exporters may even be dependent on such long-term contracts, as they would otherwise (confronted with a significantly reduced global LNG demand) be unable to economically compete with other exporters in a potentially over-supplied LNG market. This could potentially result in a situation where importers, rather than selecting the least expensive exporters with long contract durations, favor those exporters who, despite slightly higher costs, demonstrate more significant economic advantages for importers over comparatively shorter contract terms.

One notable limitation of this study lies in its exclusive focus on the LNG spot market, neglecting the analysis of long-term contracts between LNG exporters and importers. To address this limitation, we propose an enhancement in the temporal resolution, extending the analysis until 2040 on an annual basis. This refined approach would include long-term contracts, allowing for examining fixed LNG volumes traded between exporters and importers over several years.

We anticipate that our study will make a helpful contribution to other modeling teams engaged in the decarbonization of European energy systems. Specifically, we see our quantitative and qualitative findings as valuable inputs for large-scale energy system models seeking to optimize the sustainable transition of Europe's energy infrastructure. We recommend integrating the average and marginal supply costs derived from our analysis into these models to enhance the accuracy of exogenously made assumptions, thereby refining their analytical tools.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The original data used in this study is publicly available. The compiled dataset is published on Zenodo at link after acceptance. The source code and further materials are published on GitHub at link after acceptance.

Acknowledgement

The authors acknowledge TU Wien Bibliothek for financial support through its Open Access Funding Programme. We thank the anonymous referees for their very helpful feedback, as well as Hans Auer and Vladimir Gloogvac for their contribution in the early phase of this work.

References

[1] Meng-Tian Huang and Pan-Mao Zhai. Achieving paris agreement temperature goals requires carbon neutrality by middle century with far-reaching transitions in the whole society. *Advances in Climate Change Research*, 12(2):281–286, 2021. doi: https://doi.org/10.1016/j.accre.2021.03.004.

[2] Xi Yuan, Chi-Wei Su, Muhammad Umar, Xuefeng Shao, and Oana-Ramona LobonŢ. The race to zero emissions: Can renewable energy be the path to carbon neutrality? *Journal of Environmental Management*, 308:114648, 2022. doi: https://doi.org/10.1016/j.jenvman.2022.114648.

[3] Zhen Wang, Yinghao Kong, and Wei Li. Review on the development of china's natural gas industry in the background of "carbon neutrality. *Natural Gas Industry B*, 9(2):132–140, 2022. doi: https://doi.org/10.1016/j.ngib.2021.08.021.

[4] Atul Rawat and Chandra Prakash Garg. Assessment of the barriers of natural gas market development and implementation: A case of developing country. *Energy Policy*, 152:112195, 2021. doi: https://doi.org/10.1016/j.enpol.2021.112195.

[5] Samuel A Igbatayo. Meeting global natural gas demand: The emergence of nigeria's lng industry. In *SPE Nigeria Annual International Conference and Exhibition*, pages SPE–98797. SPE, 2005. doi: https://doi.org/10.2118/98797-MS.

[6] Mike Fulwood and Thierry Bros. Future prospects for lng demand in ghana. *Oxford Institute for Energy Studies*, 2018.

[7] Roberto F Aguilera. The role of natural gas in a low carbon asia pacific. *Applied Energy*, 113: 1795–1800, 2014. doi: https://doi.org/10.1016/j.apenergy.2013.07.048.

[8] U.S. Energy Information Administration. As of 2021, China imports more liquefied natural gas than any other country. Accessed on 2022-12-28 under: `https://www.eia.gov/todayinenergy/detail.php?id=52258`, 2022.

[9] Kamil Kaygusuz. Energy for sustainable development: A case of developing countries. *Renewable and Sustainable Energy Reviews*, 16(2):1116–1126, 2012. doi: https://doi.org/10.1016/j.rser.2011.11.013.

[10] Statista. Russischer Anteil an Erdgasimporten von ausgewählten europäischen Ländern im Jahr 2020. Accessed on 2022-12-28 under: https://de.statista.com/statistik/daten/studie/1309007/umfrage/russischer-anteil-an-europaeischen-erdgasimporten/#:~:text=Ebenso%20wie%20beim%20Import%20von,und%20Tschechien%20(100%20Prozent), 2022.

[11] International Energy Agency. Medium-Term Gas Report 2023. Accessed on 2023-12-19 under: https://www.iea.org/reports/medium-term-gas-report-2023#overview, 2023.

[12] Thilo Wiertz, Lilith Kuhn, and Annika Mattissek. A turn to geopolitics: Shifts in the german energy transition discourse in light of russia's war against ukraine. *Energy Research & Social Science*, 98: 103036, 2023. doi: https://doi.org/10.1016/j.erss.2023.103036.

[13] Alexandros Nikas, Natasha Frilingou, Conall Heussaff, Panagiotis Fragkos, Shivika Mittal, Jon Sampedro, Sara Giarola, Jan-Philipp Sasse, Lorenzo Rinaldi, Haris Doukas, et al. Three different directions in which the european union could replace russian natural gas. *Energy*, page 130254, 2024. doi: https://doi.org/10.1016/j.energy.2024.130254.

[14] European Council - Council of the European Union. Infographic - Liquefied natural gas infrastructure in the EU. Accessed on 2022-12-30 under: https://www.consilium.europa.eu/en/infographics/lng-infrastructure-in-the-eu/, 2022.

[15] Satish Kumar, Hyouk-Tae Kwon, Kwang-Ho Choi, Jae Hyun Cho, Wonsub Lim, and Il Moon. Current status and future projections of lng demand and supplies: A global prospective. *Energy Policy*, 39(7):4097–4104, 2011. doi: https://doi.org/10.1016/j.enpol.2011.03.067.

[16] Sarah Najm and Ken'ichi Matsumoto. Does renewable energy substitute lng international trade in the energy transition? *Energy Economics*, 92:104964, 2020. doi: https://doi.org/10.1016/j.eneco.2020.104964.

[17] HMS Amanda Herath and Tae Yong Jung. Carbon pricing and supporting policy tools for deep decarbonization; case of electricity generation of sri lanka. *Carbon Management*, 12(5):465–484, 2021. doi: https://doi.org/10.1080/17583004.2021.1966514.

[18] Alessandro Bessi, Mariangela Guidolin, and Piero Manfredi. The role of gas on future perspectives of renewable energy diffusion: Bridging technology or lock-in? *Renewable and Sustainable Energy Reviews*, 152:111673, 2021. doi: https://doi.org/10.1016/j.rser.2021.111673.

[19] Amir Safari, Nandini Das, Oluf Langhelle, Joyashree Roy, and Mohsen Assadi. Natural gas: A transition fuel for sustainable energy system transformation? *Energy Science & Engineering*, 7(4): 1075–1094, 2019. doi: https://doi.org/10.1002/ese3.380.

[20] Julia R Kotzebue and Manfred Weissenbacher. The eu's clean energy strategy for islands: A policy perspective on malta's spatial governance in energy transition. *Energy Policy*, 139:111361, 2020. doi: https://doi.org/10.1016/j.enpol.2020.111361.

[21] Juozas Augutis, Ricardas Krikstolaitis, Linas Martisauskas, and Sigita Peciulyte. Energy security level assessment technology. *Applied Energy*, 97:143–149, 2012. doi: https://doi.org/10.1016/j.apenergy.2011.11.032.

[22] Huai Su, Enrico Zio, Jinjun Zhang, Zhenlin Li, Haifeng Wang, Fang Zhang, Lixun Chi, Lin Fan, and Wei Wang. A systematic method for the analysis of energy supply reliability in complex integrated energy systems considering uncertainties of renewable energies, demands and operations. *Journal of Cleaner Production*, 267:122117, 2020. doi: https://doi.org/10.1016/j.jclepro.2020.122117.

[23] Sadia Malik, Maha Qasim, Hasan Saeed, Youngho Chang, and Farhad Taghizadeh-Hesary. Energy security in pakistan: Perspectives and policy implications from a quantitative analysis. *Energy Policy*, 144:111552, 2020. doi: https://doi.org/10.1016/j.enpol.2020.111552.

[24] Yuwei Yin and Jasmine Siu Lee Lam. Bottlenecks of lng supply chain in energy transition: A case study of china using system dynamics simulation. *Energy*, 250:123803, 2022. doi: https://doi.org/10.1016/j.energy.2022.123803.

[25] Nnaemeka Vincent Emodi and Kyung-Jin Boo. Sustainable energy development in nigeria: Current status and policy options. *Renewable and Sustainable Energy Reviews*, 51:356–381, 2015. doi: https://doi.org/10.1016/j.rser.2015.06.016.

[26] Rehab R Esily, Yuanying Chi, Dalia M Ibrahiem, and Mustafa A Amer. The potential role of egypt as a natural gas supplier: A review. *Energy Reports*, 8:6826–6836, 2022. doi: https://doi.org/10.1016/j.egyr.2022.05.034.

[27] Muhammad H Hasan, TM Indra Mahlia, and Hadi Nur. A review on energy scenario and sustainable energy in indonesia. *Renewable and Sustainable Energy Reviews*, 16(4):2316–2328, 2012. doi: https://doi.org/10.1016/j.rser.2011.12.007.

[28] Anzar Mahmood, Nadeem Javaid, Adnan Zafar, Raja Ali Riaz, Saeed Ahmed, and Sohail Razzaq. Pakistan's overall energy potential assessment, comparison of lng, tapi and ipi gas projects. *Renewable and Sustainable Energy Reviews*, 31:182–193, 2014. doi: https://doi.org/10.1016/j.rser.2013.11.047.

[29] Julia Nesheiwat and Jeffrey S Cross. Japan's post-fukushima reconstruction: A case study for implementation of sustainable energy technologies. *Energy Policy*, 60:509–519, 2013. doi: https://doi.org/10.1016/j.enpol.2013.04.065.

[30] Ken Oshiro, Mikiko Kainuma, and Toshihiko Masui. Assessing decarbonization pathways and their implications for energy security policies in japan. *Climate Policy*, 16(sup1):S63–S77, 2016. doi: https://doi.org/10.1080/14693062.2016.1155042.

[31] Jong Ho Hong, Jitae Kim, Wonik Son, Heeyoung Shin, Nahyun Kim, Woong Ki Lee, and Jintae Kim. Long-term energy strategy scenarios for south korea: Transition to a sustainable energy system. *Energy Policy*, 127:425–437, 2019. doi: https://doi.org/10.1016/j.enpol.2018.11.055.

[32] Hanna Brauers, Isabell Braunger, and Jessica Jewell. Liquefied natural gas expansion plans in germany: The risk of gas lock-in under energy transitions. *Energy Research & Social Science*, 76:102059, 2021. doi: https://doi.org/10.1016/j.erss.2021.102059.

[33] Leonid Grigoryev and Dzhanneta Medzhidova. Energy transition in the baltic sea region: A controversial role of lng? *The Future of Energy Consumption, Security and Natural Gas: LNG in the Baltic Sea region*, pages 61–91, 2022. doi: https://doi.org/10.1007/978-3-030-80367-4_3.

[34] Seksun Moryadee and Steven A Gabriel. Panama canal expansion: Will panama canal be a game-changer for liquefied natural gas exports to asia? *Journal of Energy Engineering*, 143(1):04016024, 2017. doi: https://doi.org/10.1061/(ASCE)EY.1943-7897.0000365.

[35] T Bangar Raju, Vikas S Sengar, R Jayaraj, and N Kulshrestha. Study of volatility of new ship building prices in lng shipping. *International Journal of e-Navigation and Maritime Economy*, 5:61–73, 2016. doi: https://doi.org/10.1016/j.enavi.2016.12.005.

[36] Ruud Egging, Steven A Gabriel, Franziska Holz, and Jifang Zhuang. A complementarity model for the european natural gas market. *Energy Policy*, 36(7):2385–2414, 2008. doi: https://doi.org/10.1016/j.enpol.2008.01.044.

[37] Ruud Egging, Franziska Holz, and Steven A Gabriel. The world gas model: A multi-period mixed complementarity model for the global natural gas market. *Energy*, 35(10):4016–4029, 2010. doi: https://doi.org/10.1016/j.energy.2010.03.053.

[38] Ning Lin and Robert E Brooks. Global liquified natural gas trade under energy transition. *Energies*, 14(20):6617, 2021. doi: https://doi.org/10.3390/en14206617.

[39] Daniel JG Crow, Sara Giarola, and Adam D Hawkes. A dynamic model of global natural gas supply. *Applied Energy*, 218:452–469, 2018. doi: https://doi.org/10.1016/j.apenergy.2018.02.182.

[40] Gavin Bridge and Michael Bradshaw. Making a global gas market: territoriality and production networks in liquefied natural gas. *Economic Geography*, 93(3):215–240, 2017. doi: https://doi.org/10.1080/00130095.2017.1283212.

[41] Tom Kompas and Tuong Nhu Che. A structural and stochastic optimal model for projections of lng imports and exports in asia-pacific. *Heliyon*, 2(6), 2016. doi: http://dx.doi.org/10.1016/j.heliyon.2016.e00108.

[42] Abel Meza, Ibrahim Ari, Mohammed Saleh Al-Sada, and Muammer Koc. Future lng competition and trade using an agent-based predictive model. *Energy Strategy Reviews*, 38:100734, 2021. doi: https://doi.org/10.1016/j.esr.2021.100734.

[43] Yingjian Guo and Adam Hawkes. Simulating the game-theoretic market equilibrium and contract-driven investment in global gas trade using an agent-based method. *Energy*, 160:820–834, 2018. doi: https://doi.org/10.1016/j.energy.2018.07.024.

[44] Hamza J Magnier and Asmaa Jrad. A minimal simplified model for assessing and devising global lng equilibrium trade portfolios while maximizing energy security. *Energy*, 173:1221–1233, 2019. doi: https://doi.org/10.1016/j.energy.2019.02.134.

[45] Sun-Feel Yang, So-Won Choi, and Eul-Bum Lee. A prediction model for spot lng prices based on machine learning algorithms to reduce fluctuation risks in purchasing prices. *Energies*, 16(11):4271, 2023. doi: https://doi.org/10.3390/en16114271.

[46] Hai-Ying Zhang, Wen-Wen Xi, Qiang Ji, and Qi Zhang. Exploring the driving factors of global lng trade flows using gravity modelling. *Journal of Cleaner Production*, 172:508–515, 2018. doi: https://doi.org/10.1016/j.jclepro.2017.10.244.

[47] IV Filimonova, AV Komarova, R Sharma, and AY Novikov. Transformation of international liquefied natural gas markets: New trade routes. *Energy Reports*, 8:675–682, 2022. doi: https://doi.org/10.1016/j.egyr.2022.07.069.

[48] Sida Feng, Huajiao Li, Yabin Qi, Qing Guan, and Shaobo Wen. Who will build new trade relations? finding potential relations in international liquefied natural gas trade. *Energy*, 141:1226–1238, 2017. doi: https://doi.org/10.1016/j.energy.2017.09.030.

[49] Jiří Pospíšil, Pavel Charvát, Olga Arsenyeva, Lubomír Klimeš, Michal Špiláček, and Jiří Jaromír Klemeš. Energy demand of liquefaction and regasification of natural gas and the potential of lng for operative thermal energy storage. *Renewable and Sustainable Energy Reviews*, 99:1–15, 2019. doi: https://doi.org/10.1016/j.rser.2018.09.027.

[50] Amir Sharafian, Hoda Talebian, Paul Blomerus, Omar Herrera, and Walter Mérida. A review of liquefied natural gas refueling station designs. *Renewable and Sustainable Energy Reviews*, 69:503–513, 2017. doi: https://doi.org/10.1016/j.rser.2016.11.186.

[51] Ratan Raj, Ravi Suman, Samane Ghandehariun, Amit Kumar, and Manoj K Tiwari. A techno-economic assessment of the liquefied natural gas (lng) production facilities in western canada. *Sustainable Energy Technologies and Assessments*, 18:140–152, 2016. doi: https://doi.org/10.1016/j.seta.2016.10.005.

[52] Robert O Keohane and Joseph S Nye. Power and interdependence revisited. *International organization*, 41(4):725–753, 1987.

[53] Luca Franza and Coby Van Der Linde. Geopolitics and the foreign policy dimension of eu energy security. *Energy Union: Europe's New Liberal Mercantilism?*, pages 85–98, 2017. doi: https://doi.org/10.1057/978-1-137-59104-3_5.

[54] Daniel Yergin. *The new map: Energy, climate, and the clash of nations*. Penguin Uk, 2020.

[55] Daniel Scholten and Rick Bosman. The geopolitics of renewables; exploring the political implications of renewable energy systems. *Technological Forecasting and Social Change*, 103:273–283, 2016. doi: https://doi.org/10.1016/j.techfore.2015.10.014.

[56] Agnia Grigas. *The new geopolitics of natural gas*. Harvard University Press, 2017.

[57] Seksun Moryadee, Steven A Gabriel, and François Rehulka. The influence of the panama canal on global gas trade. *Journal of Natural Gas Science and Engineering*, 20:161–174, 2014. doi: https://doi.org/10.1016/j.jngse.2014.06.015.

[58] Understanding GEC Model scenarios. International Energy Agency. Accessed on 2023-12-19 under: `https://www.iea.org/reports/global-energy-and-climate-model/understanding-gec-model-scenarios`.

[59] BP p.l.c. bp Energy Outlook: 2023 Edition. Accessed on 2023-12-19 under: `https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/energy-outlook/bp-energy-outlook-2023.pdf`.

[60] International Energy Agency (IEA). World Energy Outlook 2023 (License: CC BY 4.0 (report); CC BY NC SA 4.0 (Annex A)). Accessed on 2023-01-15 under: `https://www.iea.org/reports/world-energy-outlook-2023`, 2023.

[61] Macrotrends LLC. Natural Gas Prices - Historical Chart. Accessed on 2023-11-27 under: `https://www.macrotrends.net/2478/natural-gas-prices-historical-chart`.

[62] Argus Media: Commodity & Energy Price Benchmarks. Cheniere long-term LNG sales data excludes some fees. Accessed on 2023-11-27 under: `https://www.argusmedia.com/en/news/1431713-cheniere-longterm-lng-sales-data-excludes-some-fees`.

[63] Argus Media: Commodity & Energy Price Benchmarks. Sonatrach offers spot LNG cargoes as exports slow. Accessed on 2023-11-27 under: `https://www.argusmedia.com/en/news/2098570-sonatrach-offers-spot-lng-cargoes-as-exports-slow`, 2023.

[64] Crude Oil Prices Today. Low Gas Prices Could Derail Papua New Guinea's LNG Ambitions. Accessed on 2023-11-27 under: `https://oilprice.com/Energy/Energy-General/Low-Gas-Prices-Could-Derail-Papua-New-Guineas-LNG-Ambitions.html`.

[65] MEES: Data Driven Middle East Oil & Gas Analysis. Egypt 2019 LNG Exports. Accessed on 2023-11-28 under: https://www.mees.com/2020/4/10/oil-gas/egypt-2019-lng-exports/2aa75e10-7b34-11ea-9c97-c54251792df2.

[66] Hellenic Shipping News Worldwide. Russian LNG Exports: A Year in Review. Accessed on 2023-11-28 under: https://www.hellenicshippingnews.com/russian-lng-exports-a-year-in-review/.

[67] Timera Energy. Deconstructing LNG shipping costs. Accessed on 2023-01-15 under: https://timera-energy.com/deconstructing-lng-shipping-costs/, 2023.

[68] Council of the EU and the European Council. Infographic - Liquefied natural gas infrastructure in the EU. Accessed on 2023-01-15 under: https://www.consilium.europa.eu/en/infographics/lng-infrastructure-in-the-eu/, 2022.

[69] Statista. Number of operated and planned terminals for liquefied natural gas in Europe by country in 2023. Accessed on 2023-01-15 under: https://de.statista.com/statistik/daten/studie/1154199/umfrage/lng-terminals-in-europa/, 2023.

[70] Lawrence Irlam (Global CCS Institute). Global costs of carbon capture and storage: 2017 Update. Accessed on 2023-01-15 under: https://www.globalccsinstitute.com/archive/hub/publications/201688/global-ccs-cost-updatev4.pdf, 2017.

[71] Statista. Natural gas production in the European Union from 1998 to 2022. Accessed on 2023-01-15 under: https://www.statista.com/statistics/265345/natural-gas-production-in-the-european-union/#:~:text=In%202022%2C%20the%20natural%20gas,around%2041.1%20billion%20cubic%20meters, 2023.

Appendices

A Delivered-ex ship costs (DES)

A.1 Nomenclature and empirical assumptions

Set and index			
$e \in \mathcal{E} = \{1, \dots, E\}$	Exporter, index by e		
$i \in \mathcal{I} = \{1, \dots, I\}$	Importer, index by i		
Variable	**Description**	**Value**	**Unit**
$DES_{e,i}$	Delivered ex-ship cost from exporter e to importer i	See Appendix B	\$/MMBtu
BEP_e	Break-even price of e	See Table 5	\$/MMBtu
$TC_{e,i}$	Transportation cost of e to i		\$/MMBtu
$CC_{e,i}$	Cost of chartering an LNG carrier between e and i		\$/MMBtu
$FC_{e,i}$	Fuel cost of an LNG carrier between e and i		\$/MMBtu
$BC_{e,i}$	Boil-off cost of an LNG carrier between e and i		\$/MMBtu
$FEE_{e,i}$	Fee cost of an LNG carrier between e and i		\$/MMBtu
PC	Port cost of an LNG carrier		\$/MMBtu
$HeelRate$	Heel rate of an LNG carrier	4	%
$Time_{e,i}$	Time for transporting LNG between e and i	See Appendix B	day
$Distance_{e,i}$	Distance for transporting LNG between e and i	See Appendix B	km
$Speed$	Speed of an LNG carrier	17	knots/hour
$CharterRate$	Charter rate of an LNG carrier	69 340	\$/day
$Bunker$	Weight of an LNG carrier's bunker	100	Mton/day
$EmptyBunker$	Weight of an empty LNG carrier's bunker	25	Mton/day
$BunkerPrice$	Price of an LNG carrier's bunker	670	\$/Mton
$BoilOff$	Boil-off rate of an LNG carrier (share on bunker)	0.1	%
$Capacity$	Transport capacity of an LNG carrier	160 000	m^3
$BoilOffCostRate$	Boil-off cost rate	5	\$/MMBtu
$FeeRate$	Fee rate of an LNG carrier	See Table 6	
$RouteFee_{e,i}$	Fee rate of an LNG carrier between e and i		\$/MMBtu
$PortRate$	Port rate for an LNG carrier	133 333	\$/day

A.2 Cost function

$$DES_{e,i} = BEP_e + TCe, i \tag{8}$$

$$TC_{e,i} = (CC_{e,i} + FC_{e,i} + BCe, i + FEE_{e,i} + PC) \times \frac{1}{1 - HeelRate} \tag{9}$$

$$Time_{e,i} = \frac{Distance_{e,i} \times 2}{Speed} \times \frac{1}{24} \tag{10}$$

$$CC_{e,i} = \frac{Time_{e,i}}{CharterRate} + \underbrace{\frac{3}{CharterRate}}_{\text{Gasification at the port}} \tag{11}$$

$$FC_{e,i} = Time_{e,i} \times (Bunker \times BunkerPrice) + \underbrace{3 \times 25 \times BunkerPrice}_{\text{Empty LNG carrier}} \tag{12}$$

$$BC_{e,i} = Time_{e,i} \times BoilOff \times Capacity \times BoilOffCostRate \tag{13}$$

$$FEE_{e,i} = Time_{e,i} \times FeeRate + RouteFee_{e,i} \tag{14}$$

$$PC = 3 \times PortRate \tag{15}$$

A.3 Empirical assumptions

Exporter	BEP_e in \$/MMBtu	Q_e^{Liq} in billion MMBtu/year
Algeria	4.9	0, 720
Australia	7.5	5, 040
Indonesia	6.0	1, 357
Malaysia	6.0	1, 548
Nigeria	4.1	2, 520
Oman	3.7	0, 571
Other Africa	4.5	3, 600
Other Americas	6.0	2, 160
Other Asia Pacific	8.4	0, 752
Other Europe	5.0	0, 310
Other Middle East	3.0	0, 277
Qatar	2.4	6, 255
Russia	4.5	3, 060
Trinidad & Tobago	5.1	0, 612
USA	5.9	7, 920

Table 5: Exporter's 2019 break-even price (BEP_e) and assumed liquefaction capacities (Q_e^{Liq}). Based on [61, 62, 63, 64, 65, 66].

Component	Value	Unit
Fee for LNG carrier in the Suez canal	1 000 000	\$/cargo
Fee for LNG carrier in the Panama canal	950 000	\$/cargo
Insurance cost of an LNG carrier	2600	\$/day
Other costs (share on the total charter cost $CC_{e,i}$)	2	%

Table 6: Components of the fee cost ($Fee_{e,i}$) of an LNG carrier (see [67]).

B Data

For empirical data assumptions ($DES_{e,i}$, $time_{e,i}$, and $distance_{e,i}$, etc.), it is referred to the data availability statement, as all empirical data of this paper is published on Zenodo.

B.1 Regions

- The following exporting nodes are considered in the model: Algeria, Australia, Indonesia, Malaysia, Nigeria, Oman, Other Africa, Other Americas, Other Asia Pacific, Other Europe, Other Middle East, Qatar, Russia, Trinidad & Tobago, and USA.
- The following importing nodes are considered in the model: Belgium, China, France, India, Italy, Japan, Other Asia Pacific, Other Europe, Pakistan, South Korea, Spain, Taiwan, Total Middle East and Africa, Total North America, Total South and Central America, Turkey, and the United Kingdom.
- Note the following with respect to the selection of nodes in the model:
  - The European LNG regasification terminals and capacities (can be found exemplarily in [68] and [69]) are distributed according to their geographical proximity to the nodes considered in the model. That applies in particular to the regasification capacities of Germany but also to the Netherlands and Poland. Accordingly, the same procedure is applied to distribute the total European LNG demand to the different nodes.
  - The Other Europe export node considers LNG exports from Norway and other countries, particularly those on the Caspian Sea, such as Azerbaijan. In general, the maximum LNG export capacity of Other Europe is intentionally conservatively estimated (compare the relatively low value of Q_e^{Liq} for Other Europe in Table 5) as it is assumed that high shares of the natural gas production there are transported via pipelines to Europe.
  - Other Africa includes, among other countries, Ghana, Egypt, and Mozambique.

B.2 LNG demand

Region	Import 2019 [MMBtu]	Expectation for the demand	Max increase (2008 to 2018) [MMBtu/year]	(*Net Zero*) Import 2040 [MMBtu]	(*Persisting*) Import 2040 [MMBtu]
Belgium	254 268 000	Constant	-	107 517 087	415 997 730
China	2 994 712 000	Increasing	253 090 833	2 789 885 000	4 590 950 000
France	808 713 500	Constant	-	341 964 069	1 323 103 890
India	1 161 863 500	Increasing	158 917 500	3 407 897 500	5 473 825 000
Italy	476 752 500	Constant	-	201 594 538	779 995 743
Japan	3 725 732 500	Constant	-	2 235 439 500	3 154 806 667
Other Asia Pacific	731 020 500	Increasing	52 972 500	877 224 600	52 972 500
Other Europe	826 371 000	Increasing	113 008 000	537 585 435	1 351 992 621
Pakistan	416 717 000	Increasing	116 539 500	895 023 360	3 037 090 000
South Korea	1 936 514 000	Constant	-	1 133 611 500	1 577 403 333
Spain	773 398 500	Constant	-	327 031 140	1 265 326 427
Taiwan	805 182 000	Increasing	123 602 500	579 731 040	3 037 090 000
Total ME & Africa	335 492 500	Increasing	282 520 000	1 526 490 875	2 566 223 333
Total N. America	303 709 000	Constant	-	364 450 800	353 150 000
Total S. & C. America	462 626 500	Increasing	123 602 500	757 683 325	1 283 111 667
Turkey	455 563 500	Increasing	116 539 500	352 072 513	745 329 265
UK	635 670 000	Constant	-	268 792 718	1 039 994 324

Table 7: LNG demand in the model's importer nodes in 2019, 2030, and 2040. Based on [58, 59].

B.3 European domestic natural gas production equipped with carbon capture and storage

We assume the following to calculate the supply costs of the European domestic natural gas production with carbon capture and storage, which can be used in the model to substitute LNG imports. In general, said supply costs consist of the production costs for natural gas and the carbon capture and storage costs. For the production costs, we assume 1.5 \$/MMBtu, which is around double the production costs of Russian piped gas[4] The costs of carbon capture and storage are assumed to be 138 \$/tCO2 [70]. The content of CO2 in LNG is assumed to be 0.053 tCO2/MMBtu.[5] Based on the historical natural gas production in Europe, the max capacity of the European domestic production with carbon capture and storage (Q^{EDP}) has been set to 1 236 025 000 MMBtu/year [71]. This value is approximately equal to the total European demand in the *Net Zero* scenario and around one-quarter of the total European demand in the *Persisting Fossil Demand* scenario.

[4] Production costs of Russian piped gas is estimated by 0.75 \$/MMBtu (https://ceenergynews.com/voices/the-myth-and-reality-behind-high-european-energy-prices/).

[5] https://www.eia.gov/environment/emissions/co2_vol_mass.php