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

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**Abstract**

This study examines the LNG trade in 2040, focusing on the role of Europe as an LNG importer. The analysis reveals the complexities of Europe’s strategy of simultaneously achieving decarbonization objectives and resolving energy security concerns regarding LNG. The study proposes an optimization model to determine the optimal global LNG trade between exporters and importers. As an alternative for Europe to solely rely on imports, the potential substitution of imports with domestic natural gas production equipped with carbon capture and storage is considered. Herein, two scenarios (low and high LNG demand) are examined. The findings indicate that Europe plays a pivotal role 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 to 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 resurgence in the future. Future work should include long-term contracts, allowing for fixed volumes of LNG to be traded. Furthermore, our obtained LNG supply costs for Europe can be seen 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

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# Introduction

With the 2015 Paris Agreement, the world is committed to achieving carbon neutrality by mid-century [[1].](#_bookmark41) Toward carbon neutrality, indisputably renewable energy resources will play a key role in reducing the use of fossil fuels such as oil and coal [[2].](#_bookmark42) To date, the extent to which natural gas, also a key fossil fuel, will play a role in future energy systems during their transition to carbon neutrality remains controversial. Despite the ambitious climate targets of some countries and regions, substantial global demand for natural gas 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 via gas pipelines, limiting 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 that have access to natural gas through LNG imports via cargo transport has rapidly increased. 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],](#_bookmark43) but other countries such as India [[4],](#_bookmark44) Nigeria [[5],](#_bookmark45) and Ghana [[6]](#_bookmark46) could also be mentioned. Traditionally, the Asian energy market, particularly the Japanese market, firmly focused on LNG. Other countries in the Asian Pacific, for example, South Korea and, as aforementioned, China, have shifted to LNG and exhibited increased demand in the past decades [[7].](#_bookmark47) Notably, China has become the largest LNG importer worldwide, with more than half of its total natural gas imports via LNG [[8].](#_bookmark48) In developing countries, increasing demand for natural gas not only replaces coal and oil but is expected to enable energy accessibility [[9].](#_bookmark49)

Contrary to developing countries, the situation and expectations regarding LNG demand for Europe are different and mainly 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,](#_bookmark50) [11].](#_bookmark51) The geographical proximity, generally low price of Russian pipeline imports, and low level of active short-term gas trading in Europe were key factors for making Europe unattractive for LNG imports. However, this situation has substantially changed 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 that have also led to the collapse of Russian piped gas imports to Europe and, consequently, a rethinking of natural gas policies in Europe (see, e.g., Wiertz et al. [[12]).](#_bookmark52) On the one hand, measures were taken to reduce the demand for energy, particularly natural gas. On the other hand, Europe had to find alternatives to replace the imports from Russia.

Nikas et al. explored in detail the question of how Europe could replace Russian natural gas imports [[13].](#_bookmark53) The authors examined 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 those from Norway and other regions, the main consequence is also that LNG is (back) on Europe’s agenda. Scrutiny of the second corner, about the acceleration of European energy production, is imperative, particularly when considering its application for the revival of European fossil fuel production. In other words, it is probably necessary to be critical to adopt a discerning perspective, especially in terms of the potential impact on European natural gas production (e.g., in Groningen, the Netherlands). While we generally include reactivated natural gas fields in Europe in our analysis, we claim that carbon capture and storage (CCS) emerges thereby as an integral component. The revival of European natural gas production without CCS would not only substantially jeopardize the achievement of European decarbonization targets but 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. Thus, Europe was willing to pay high prices in 2022, facing the risk of not being able to meet all the natural gas demands otherwise. 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, Greece, and Italy have already built or are currently in the process of building LNG terminals [[14].](#_bookmark54) In view of the above, LNG is expected to play a pivotal 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](#_bookmark0). The potential contribution of LNG to European and global climate goals and regional demand projections is uncertain.

Against this background, this study 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 the increased global LNG demand mainly driven 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 CCS in Europe, the following question arises: Can European domestic natural gas production equipped with CCS be part of the solution for covering the demand in a decarbonized European energy system?

Consequently, the core objective of this study 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 the 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 estimation of LNG price developments until 2040, which is not only a main novelty of the study 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, particularly 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). In the model, import and export countries are represented by nodes. The 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. In addition, spatial and further techno-economic data are used to calculate LNG transportation costs between each export and each import region.

The remainder of this paper is organized as follows. Section [2](#_bookmark1) provides relevant background information from the scientific literature and outlines the novelties of this work beyond existing research. Section [3](#_bookmark6) 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](#_bookmark20) presents the results of this work, including the impact of political tensions on the European LNG imports and supply costs. Section [5](#_bookmark40) discusses the results, concludes the paper, and outlines possible future research.

# Background

This section contains background literature on the broad topic of LNG in sustainable energy systems, which is the focus of this study. It is divided into three subsections. Subsection [2.1](#_bookmark2) deals with the role of LNG in future energy systems and decarbonization pathways. Among other things, the view 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. Simultaneously, literature is highlighted that critically questions the feasibility of the fossil fuel LNG when aiming for zero-emission future energy systems. Furthermore, 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. Subsection [2.2](#_bookmark3) is dedicated to the literature dealing specifically with the modeling of LNG and, in particular, the global LNG trade. The focus is mainly on the different techno-economic modeling approaches for determining LNG trading volumes between exporters and importers and LNG supply costs. Finally, Subsection [2.3](#_bookmark4) elaborates on LNG and other energy carriers as a political weapon. Selected studies examining the association between geopolitical tensions and energy systems are listed. The most important aspects of the historical context of this association are also subject to this discussion. Finally, Subsection 2.4 outlines the novelties and own contributions of this study.

## 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. conducted a comprehensive review of the future expectations of LNG demand and supply, starting with the current status [[15].](#_bookmark55) The study has been published in 2011 and provides an outlook for LNG until 2030. In 2020, Najm and Matsumoto [[16]](#_bookmark56) determined whether international LNG trade is substituted by renewable energy in the sustainable energy transition. They found empirical evidence that energy transition policies lead to a reduction of international LNG trade whereas more accessible trade policies can also stimulate it simultaneously. This equivocal tendency is closely associated with 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]](#_bookmark57) focused 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. [18] also studied the impact of LNG on the diffusion of renewable energy. In line with the controversial role of the aforementioned LNG, they found that LNG can exert both a competitive and collaborative effect on renewable energy. Similarly, Safari et al. [[19]](#_bookmark59) focused 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 an increasing number of high-emitting energy technologies/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]](#_bookmark60) focused on isolated energy systems and stated that in such energy systems, renewable energy generation alone does not sufficiently promote energy transition

. 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]](#_bookmark61) comprehensively studied the opportunities of LNG in contributing to energy security by conducting a case study at the national level. Su et al. [[22]](#_bookmark62) focused on analyzing energy supply reliability in integrated energy systems with uncertainties of renewable energy generation and how LNG can serve to operate those systems. Malik et al. [[23]](#_bookmark63) in their quantitative national analysis for a developing country addressed the role of LNG for energy security.

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 focusing 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]](#_bookmark64) examined the case of China and the role of LNG in its energy transition. In particular, they focused on Chinese LNG supply and potential bottlenecks in LNG imports and associated supply dynamics. Emodi and Boo [[25]](#_bookmark65) explored the development of a sustainable energy system in one of the world’s leading LNG exporters, Nigeria. They comprehensively outlined the current status of LNG in Nigeria’s energy system and policy options for achieving a national sustainable energy system. Furthermore, Esily et al. [[26]](#_bookmark66) focused on the role of a major LNG exporter in the context of decarbonized energy systems. The authors thoroughly examined 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 stated that with the decline in demand for LNG in Europe, Egypt is attempting to increase its share of the LNG market in Asia. Hasan et al. [[27],](#_bookmark67) who examined the situation in Indonesia, and Mahmood et al. [[28],](#_bookmark68) who explained the case of Pakistan, conducted other relevant studies on the national role of LNG in sustainable energy systems. Mahmood et al. focused particularly on the aspect of energy security in Pakistan and its dependence on LNG imports from Qatar.

Numerous studies focused specifically on the national perspective of developed countries, particularly for the developed countries in Asia but also for other countries, such as European countries. For example, Nesheiwat and Cross [[29]](#_bookmark69) examined the Japanese case and how the transition to a sustainable energy system is associated with the national use of LNG. published further literature on the Japanese case [[30].](#_bookmark70) Contrary to Nesheiwat and Cross, Oshiro et al. focused 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]](#_bookmark71) also conducted a detailed analysis of an Asian country. The authors detailed long-term energy transition scenarios for South Korea and showed that the country, which is currently heavily dependent on LNG, can achieve a gas-free energy system and thus carbon neutrality. However, they also pointed out the major challenges for South Korea’s energy system if it entirely relies on renewable energy sources. For the European national perspective on this topic, among other studies, Brauers et al. [[32]](#_bookmark72) and Grigoryev and Medzhidova [[33].](#_bookmark73) While the first authors focused 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 focused on the energy transition of the Baltic regions and the controversial role of LNG there. Moryadee and Gabriel [34] conducted another study that focused on the regional aspect of the global LNG trade rather than a national perspective. The authors focused on LNG imports to Asia but examined in particular 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 examined LNG carriers was conducted by Raju et al. [[35].](#_bookmark75) The authors did not specifically study the Panama Canal but analyzed the volatility of new building prices for LNG carriers.

## Techno-economic modeling of the global LNG trade

Given the scope of this paper, studies that focused on techno-economic modeling of global LNG trade and markets are listed below, allowing the reader to put this study and its methodology into perspective with other relevant studies. In 2008, Egging et al. [[36]](#_bookmark76) proposed a global gas model using complementarity. Previous authors also conducted another study presenting an extension of the model regarding temporal complexity [[37].](#_bookmark77) Similar to this study, LNG demand and other cost components, such as the LNG tanker costs, were implicitly modeled via *ex post* calculations. More recently, Lin and Brooks [[38]](#_bookmark78) proposed a partial equilibrium model to investigate the uncertainties and dynamics in the global gas market until 2050. They studied the global LNG trade under decarbonization scenarios. [39] conducted another study that focused on modeling the dynamics of the global LNG trade, with particular emphasis on the supply side. In addition, Bridge and Bradshaw [[40]](#_bookmark80) examined the dynamics of the global LNG trade. They concentrated, among others, on the geographical scope of the LNG trade analysis. Kompas and Che [[41]](#_bookmark81) employed a stochastic approach to determine LNG imports and exports in the Asia Pacific region.

Contrary to the previous studies, which were mainly dominated by a system- or integrated-modeling approach, further studies proposed an agent-based modeling approach. For instance, Meza et al.

[[42]](#_bookmark82) applied an agent-based model to study the global LNG trade in 2030. Their results indicated that smaller LNG exporters struggle to allocate future supplies when looking at the supply side. Analogously, Guo and Hawkes [[43]](#_bookmark83) used an agent-based method but considered game-theoretic aspects to determine the global LNG market trade. Magnier and Jrad [44] developed a coarse-grained model to devise 2030 LNG trade portfolios under secure supply.[45] proposed machine learning algorithms to estimate spot LNG prices. Furthermore, Zhang et al. [[46]](#_bookmark86) proposed the modeling of LNG trading routes and flows using a gravity-modeling approach, and Filimonova et al. [[47]](#_bookmark87) focused mainly on new trade routes. [48] also studied new LNG trading routes. Other specific aspects of the techno-economic modeling of LNG trade can also be found in the literature. While Posp´ıˇsil et al. [[49]](#_bookmark89) evaluated the energy demand of liquefaction and regasification stations for LNG transportation, Sharafian et al. [[50]](#_bookmark90) investigated different design options for these stations. [[51]](#_bookmark91) conducted a case study investigating local LNG production and transportation costs.

## LNG and other energy carriers as a political weapon

The instrumentalization of energy as a political weapon dates back to 1973 when Organization of the Petroleum Exporting Countries used oil against Western countries supporting Israel. During the 50 years afterward (until February 24, 2022), energy has repeatedly shown to have broader ties within the political-economic system of international relations. Keohane and Nye [[52]](#_bookmark92) showed that asymmetric interdependencies are a source of power. Franz and van der Linde [[53]](#_bookmark93) examined the association between geopolitics and foreign policy in the case of EU energy security. Yergin [[54]](#_bookmark94) provided an insightful global perspective on the association 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].](#_bookmark95)

The EU–Russia gas trade relationship has been commented on extensively, particularly 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 USA has triggered the vision of the country becoming a net exporter of LNG (around 2010). Available global LNG export capacities changed the landscape of natural gas geopolitics, as has been observed by several observers (i.e., Grigas [[56]).](#_bookmark96) The existing literature has used either a qualitative approach or a game-theoretic framework to analyze the consequences. The focus was most frequently on pipeline gas deliveries (or a more general ”supply disruption”). Gabriel [[57]](#_bookmark97) considered 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,

negligible 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).

## 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.

1. 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 consistent with the ambition of carbon neutrality (Net Zero). Conversely, the second scenario contemplates considerably increased demand levels mainly 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.
2. Expanding upon previous 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 on LNG to the European context, providing 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 into the future of Europe’s energy supply in the absence of Russian piped gas imports.
3. Furthermore, this study presents a potentially essential contribution to ongoing analyses centered on the optimization of the decarbonization of the European energy system by using 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 importance, 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.

# Method

This section describes the method applied in this study. Section [3.1](#_bookmark7) discusses in detail the mathematical formulation of the proposed optimization model. Section [3.2](#_bookmark15) defines the two different scenarios. These scenarios are based on those proposed by the *International Energy Agency* (IEA) [[58]](#_bookmark98) and *BP* [[59].](#_bookmark99) Subsequently, Section [3.3.](#_bookmark17) describes the different cases. The cases extend the scenarios in a manner 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 the calculation of the delivered ex-ship costs (the most relevant input parameter of the model) are described in Appendix [A.](#_bookmark112) More empirical data (e.g., assumptions about the LNG demand in 2040) can also be found in Appendix [B.](#_bookmark115)

## Optimization model

### Objective function

A simple linear optimization model is proposed to answer the research questions raised in this study. The objective function is to meet the global LNG demand with minimum supply cost. This objective function is expressed in Equation [1](#_bookmark8) and consists of two separate terms. The first term considers the product of the delivered ex-ship cost (*DESe,i*) and the quantity of LNG *qe,i* exchanged between exporter *e* and importer *i*. The Delivered ex-ship (DES) for each tuple of exporter and importer is calculated before the modeling (see also Appendix [A).](#_bookmark112) The corresponding cost function for determining individual DESs is described in Appendix

[A.](#_bookmark112) The second term considers an alternative supply option for the European importers (a subset of all importers and with index *i′*). This term considers the option to use the European domestic production equipped with CCS to substitute LNG imports. It is used when DESs for European importers are higher than the European domestic natural gas production cost equipped with CCS. The corresponding quantity is given by *qEDP* . Our assumptions on the costs of European domestic production with CCS can be found in Appendix [B.](#_bookmark115) *x* represents a vector and contains

*i′*

*i′*

all decision variables of the model (i.e., *q*

*e,i*

, *qEDP* ).

min

*x*

X X *DESe,i* × *qe,i*

+ X (*EDP* + *CCS*) × *qEDP*

(1)

*e i i′*

*i′*

Global LN..G trade with,.minimum supply cost

### Constraints

European domestic production equipped with CCS

Equation [2](#_bookmark9) ensures that the total export quantity (i.e., the sum over all importers *i*) is less than or equal to the liquefaction capacity *QLiq* per exporter *e*. Note that the liquefaction capacity is an exogenously defined parameter and not determined by the optimal solution.

*e*

X *qe,i* ≤ *QLiq*

*e*

: ∀*e* (2)

*i*

Analogous to the previous equation, Equation [3](#_bookmark10) guarantees that the total import quantity (i.e., the sum over all exporters *e*) is less than or equal to the regasification capacity *Qregas* per importer *i*. In other words, there is explicitly no optimal planning of liquefaction or regasification capacities.

*i*

X *qe,i* ≤ *QRegas*

*i*

: ∀*i* (3)

*e*

Equations [4](#_bookmark11) and [5](#_bookmark12) present the demand balance constraints per importer *i*, where *Di* denotes the demand per *i*. For European importers *i′*, as aforementioned, European domestic production equipped with CCS can be used to satisfy European LNG demand in addition to global trade and LNG imports. Notably, for simplicity, the LNG of non-European importers can only be satisfied by imports.

*qe,i* = *Di* : ∀*i* ∈ I ∧ ¬(*i* ∈ I*′*) (4)

X

*e*

"X *qe,i*# + *qEDP* = *Di* : ∀*i* ∈ I*′* (5)

*i′*

*e*

Equation [6](#_bookmark13) limits the amount of the European domestic production with CCS to the maximum capacity *QEDP* (based on historical values from the European domestic natural gas production; see Appendix [B).](#_bookmark115)

X *qEDP* ≤ *QEDP* (6)

*i′*

*i′*

Finally, Equation [7](#_bookmark14) 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 *ni*. For example, if *ni* = 3, the total demand is supplied by at least three different exporters, each with a maximum share of one-third.

1

*qe,i* ≤

*n*

*i*

× *Di* : ∀*i* (7)

## Scenarios

We consider two scenarios (*Net Zero* and *Persisting Fossil Demand* ) that provide a particularly wide range of future developments in the global and, in particular, the European LNG market. Essentially, the scenarios define demand *Di* of the different importers *i* with respect to the mathematical formulation

of the model (Equation [4).](#_bookmark11) Thus, demands are—as common in this literature—defined as exogenous

parameters. The other key-determining parameters of the model (*DES*

*, QLiq, QRegas, etc.*) are assumed

*e,i e* *i*

to be independent of the scenario (variation of these given in the cases; see Section [3.3).](#_bookmark17) The two scenarios

are based on published scenarios from the IEA [[58]](#_bookmark98) and BP [[59].](#_bookmark99) Before describing the two scenarios in qualitative terms, Table [1](#_bookmark16) presents the total and European LNG demand in both scenarios. The global LNG demand in 2040 is more than double in the *Persisting Fossil Demand* scenario compared with 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 Appendix [B](#_bookmark115) (see Table [7).](#_bookmark116)

|  |  |  |
| --- | --- | --- |
| 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]](#_bookmark98) and [[59].](#_bookmark99)

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 the IEA and BP, which use comprehensive

global energy models. Thus, we do not separate demand by sector and exclusively focus on LNG. Furthermore, 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 examine distinct pathways for future global LNG demand (and trade).

#### 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]](#_bookmark100) expects demand for natural gas to decrease to 82% by 2030 and to 22% by 2050 compared with 2022.[2](#_bookmark18) As a consequence, the global LNG trade will slightly increase by roughly 6% by 2030 but plummet to only one-quarter compared with 2022. For Europe, the IEA [[60]](#_bookmark100) suggests ample supplies of natural gas and points toward the potential re-use of import terminals for hydrogen supplies later.

#### 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, obstacles remain in the implementation of fossil fuel phase-out. In addition, the successful implementation of large-scale (offshore) wind generation or installation of solar

depends on several factors. These efforts may be delayed by not only public acceptance and the low prices for carbon emissions but also the availability of a skilled workforce. Hence, there is a likelihood that the 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 the international competition for (LNG) supplies will persist. As a result, which role will Europe play in such a setting and who

the beneficiaries are of such a pathway will be interesting questions to address. To implement this in the analysis, we base our expected demand figures on the numbers from the STEPS scenario in [[58].](#_bookmark98)

## Cases

As aforementioned, the cases extend the scenarios by considering the effects of different political tensions on the modeling input parameters, such as LNG liquefaction 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.](#_bookmark19)

1. It is assumed that Europe follows a strong diversification strategy in regions where LNG is imported to reduce dependency on specific regions. To consider this, Equation [7](#_bookmark14) is adopted in this case compared with the two scenarios in a manner that *ni* 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 with the initial values of the two scenarios, the delivered ex-ship costs of Qatar, Oman, and other ME are assumed to increase by +25%. Notably, this particularly affects the costs of three regions that initially have relatively lower delivered ex-ship costs than 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) increase the chartering and insurance costs of the LNG carriers.

1. The rapid increase in energy demand in the African continent is assumed to lead to an LNG market where no exports from African regions occur. 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.
2. This case considers the situation where the Panama Canal is restricted. This increases not only the delivered ex-ship costs of the trades passing through the Panama Canal but also those of all other trades (e.g., due to the scarcity of available LNG carriers). 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 the others. Notably, 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 already been observed in 2023.
3. In this case, LNG sent from Russia is allowed only to Asian regions. It takes into account the situation where 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 in the number of regions importing LNG to Europe | *ni* = 5 | [7](#_bookmark14) | Belgium, France, Italy |
| (2) *High price Middle East* | Increase in the delivered ex-ship costs of the Middle East | 1*.*25 ∗ *DESe,i* | [1](#_bookmark8) | Qatar, Oman, Other ME |
| (3) *No export from Africa* | Nonparticipation of African LNG exporters in the global LNG | *qe,i* = 0 | [2](#_bookmark9) | Nigeria, Other Africa |
|  | trade |  |  |  |
| (4) *Panama Canal restricted* | Increase in the delivered ex-ship costs of all LNG flows | 1*.*33*/*1*.*15 ∗ *DESe,i* | [1](#_bookmark8) | USA to Japan |
| (5) *Russia to Asia only* | LNG sent from Russia to Asian regions only | *qe,i* ̸= 0 | [2](#_bookmark9) | 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.

# 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](#_bookmark21) 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)](#_bookmark22) and *Persisting Fossil Demand* (Section [4.1.2).](#_bookmark25) Section [4.1.3](#_bookmark27) compares the results of these

two scenarios. Section [4.2](#_bookmark29) turns to the modeling results indicating 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](#_bookmark30) for the different cases, the liquefaction utilization rate of exporters in [4.2.2,](#_bookmark34) and the supply share of the European domestic production equipped with CCS in [4.2.3.](#_bookmark38) These results are shown for both scenarios and all cases.

## LNG supply and associated supply costs to Europe 2040

#### Net Zero

Figure [1](#_bookmark23) presents 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 to meet the 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 billion MMBtu) of the total European demand.

14

Algeria

Nigeria

Other Europe

Qatar

12

10

Supply cost [$/MMBtu]

8

6

4

2

0

0.0 0.2 0.4 0.6 0.8 1.0 1.2

Import volumes from regions [MMBtu] ×109

Figure 1: Import volumes of LNG from regions to meet the European demand in 2040 in billions of 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](#_bookmark24) presents the marginal (in dark blue) and average (in sand) supply costs to Europe in 2040. The marginal costs of supply of 9*.*3$*/*MMBtu are determined by Other Europe. The average supply cost is 7*.*1$*/*MMBtu.

Marginal

9.3

7.1

Average

0 2 4 6 8 10 12 14

Supply cost in Europe 2040 [$/MMBtu]

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

#### Persisting Fossil Demand

For the *Persisting Fossil Demand* scenario, Figure [3](#_bookmark26) presents the LNG import volumes in billions of MMBtu and the associated supply costs in $*/*MMBtu for Europe in 2040. Compared with 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 USA, and Trinidad and Tobago. These three exporters cater for 76% of the total European demand. In addition, fringe exporters such as Other Americas, Other Europe, and Other Africa cover the remaining demand. Among these, Other Americas serve as the marginal exporter. Note the different scaling of the x-axis between Figures [1](#_bookmark23) and [3.](#_bookmark26)

14

Algeria

Nigeria Other Africa

Other Americas

Other Europe

Trinidad & Tobago

USA

12

10

Supply cost [$/MMBtu]

8

6

4

2

0

0 1 2 3 4

Import volumes from regions [MMBtu] ×109

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

Figure [2](#_bookmark24) presents the marginal (in dark blue) and average (in sand) supply costs to Europe in 2040 for the *Persisting Fossil Demand* scenario. While the marginal supply cost, determined by Other Americas, reaches 13*.*6$*/*MMBtu, the average supply cost is 10*.*3$*/*MMBtu.

The results from the two scenarios differ not only 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.

Marginal

13.6

10.3

Average

0 2 4 6 8 10 12 14

Supply cost in Europe 2040 [$/MMBtu]

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

### *Comparison of Scenario Results*

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

1.6

[Import volumes fr](#_bookmark28)om regions [MMBtu]

1.4

1.2

1.0

0.8

×109

14

Trinidad & Tobago Other Americas Other Europe Other Africa Algeria

Nigeria Qatar USA

Average Marginal

Supply cost in Europe 2040 [$/MMBtu]

12

10

8

0.6 6

0.4 4

0.2

0.0

Zero Persisting

2

0

Zero Persisting

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](#_bookmark28) presents at least four interesting observations:

□ Regarding 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 and the large number of liquefaction capacities (i.e., overcapacities) of other exporters in the *Net Zero* scenario.

* Nigeria also significantly increases its LNG volumes sent to Europe in the *Persisting Fossil Demand* scenario. Although this increase is slightly smaller than that 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 acts 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 (particularly 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 with the *Net Zero* scenario by 4*.*3$*/*MMBtu (+46%) and 3*.*2$*/*MMBtu (+45%), respectively.

## Impact of geopolitical tensions on LNG imports and exports

Building upon the aforementioned scenario results, this section goes one step further and demonstrates the impact of different geopolitical tensions (we call them cases below) on LNG flows between importers and exporters in the two main scenarios, namely, *Net Zero* and *Persisting Fossil Demand*. We show, for

example, how the results change in the *Net Zero* scenario when there are no available LNG exports from Africa

(this case is called *No export from Africa*). 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*.

### *Supply Share of Exporters in the European Demand*

Table [3](#_bookmark31) presents the LNG import volumes from export regions to Europe 2040 in the *Net Zero* scenario and all cases in billions 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 The 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 in 2040 in the *Net Zero* scenario and cases in billions of MMBtu.

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

* The LNG volumes from regions such as Algeria, Nigeria, and Qatar remain largely constant across cases. Certainly, this does not apply to cases such as *No export from Africa*, 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, whether these regions will send LNG in the direction of Europe is case-dependent.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| 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 The 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 billions of MMBtu.

The results for the *Persisting Fossil Demand* scenario in Table [4](#_bookmark32) indicate at least two interesting insights:

* There are no clear trends for LNG imports for the different regions. Rather, volumes substantially fluctuate 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: the quantities remain relatively constant across all cases.

The average and marginal supply costs to Europe for both scenarios and all cases are presented in Figure [6.](#_bookmark33) The results of the *Net Zero* scenario are denoted by solid lines, whereas the results of the *Persisting Fossil Demand* scenario are denoted by 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)](#_bookmark33) reach 12*.*3 and 10*.*0$*/*MMBtu in the *Persisting Fossil Demand* and *Net Zero* scenarios, respectively. The results for the marginal supply costs are similar: the case where no exports from Africa are permitted leads to the most considerable increase. The marginal supply cost (see Figure [6b)](#_bookmark33) reaches 13*.*6 and 12*.*6$*/*MMBtu in the *Persisting Fossil Demand* and *Net Zero* scenarios, respectively. Notably, the difference between the

marginal supply cost in the two scenarios is the smallest in the *No export from Africa* case among all the cases.

16

12.3

11.8

10.3

10.4

10.1

10.2

10.0

8.2

7.1

7.7

8.2

7.1

Net Zero

Persisting Fossil Demand

Average supply cost [$/MMBtu]

14

12

10

8

6

4

2

0

Main

scenario

Diversify

importers

High price

Middle East

No export

from Africa

Panama canal

restricted

Russia to

Asia only

1. Average supply costs to Europe in 2040

16

14.5

13.6

13.6

13.6

13.6

13.6

12.6

10.7

10.0

9.3

9.3

9.3

Net Zero

Persisting Fossil Demand

Marginal supply cost [$/MMBtu]

14

12

10

8

6

4

2

0

Main

scenario

Diversify

importers

High price

Middle East

No export

from Africa

Panama canal

constricted

Russia to

Asia only

1. 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.

### *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](#_bookmark35) Figure [7](#_bookmark36) demonstrates 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 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*.

×108

4



Exported

Not exported

100% 17%

80% 100% 100% 39% 100%

Other Europe

3

Export volumes [MMBtu]

2

1

0

Liquefaction

capacity

Net Zero

Diversify

importers

High price

Middle East

No export

from Africa

Panama canal

restricted

Russia to

Asia only

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

Figure [8](#_bookmark37) demonstrates that the export volume of the USA in the *Persisting Fossil Demand* scenario varies between 63% (in the case of *Panama Canal* *restricted*) and 78% (in the case of high price Middle East).

1.0

×1010

USA

0.8



Exported

Not exported

100% 78%

76%

78% 100% 63%

78%

Export volumes [MMBtu]

0.6

0.4

0.2

0.0

Liquefaction

capacity

Persisting

Fossil Demand

Diversify

importers

High price

Middle East

No export

from Africa

Panama canal

restricted

Russia to

Asia only

Figure 8: LNG export volumes in *MMBtu* and corresponding liquefaction capacity utilization rate (%) 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 exhibit negligible 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%.

### *European Domestic Production with CCS*

Figure [9](#_bookmark39) shows if and to what extent European domestic production of natural gas with CCS serves as an alternative supply option to substitute LNG imports. In the *Net Zero* scenario (Figure [9a),](#_bookmark39) European domestic production with CCS is not used to substitute LNG imports from other regions. This holds for the main scenario and all cases.

×109

European domestic production (incl. CCS) [MMBtu]

1.2



99%

0% 0% 0% 0% 0% 0%

1.0

0.8

0.6

0.4

0.2

0.0

Total

demand

Production

capacity

Net Zero

Diversify

importers

High price

Middle East

No export

from Africa

Panama canal

restricted

Russia to

Asia only

* + - 1. *Net Zero*

×109

European domestic production (incl. CCS) [MMBtu]

5



25%

25% 25%

0%

3%

0%

0%

4

3

2

1

0

Total

demand

Production

capacity

New

Momentum

Diversify

importers

High price

Middle East

No export

from Africa

Panama canal

restricted

Russia to

Asia only

* + - 1. *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).

Contrarily, European domestic production of natural gas with CCS is needed in some cases in the *Persisting Fossil Demand* scenario (see Subfigure [9b).](#_bookmark39) In particular, for the *No export from Africa* and *Panama Canal restricted* cases, LNG demand is covered by the domestic production of natural gas equipped with CCS. The supply from European domestic production with CCS is at a maximum capacity in these cases. By definition/assumption, this maximum capacity accounts for

25% of the total European LNG demand. Considering the case with a focus on the diversification of importers (*Diversify importers*), a small share of the total LNG demand (around 3%) is also supplied by the European domestic production equipped with CCS.

# Conclusions and outlook

This study comprehensively investigated the global liquefied natural gas (LNG) trade in 2040, elucidating the pressing role of Europe as an LNG importer. The analysis revealed 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 assessed the potential susceptibility of Europe’s LNG supply to geopolitical tensions by analyzing

LNG import volumes, examining their variations under different market conditions. In addition, we explored the expected average and marginal supply costs associated with these LNG trades to Europe.

Methodologically, we used a straightforward optimization model developed to find the optimal (i.e., with minimal costs) global LNG trade among strategically selected nodes, representing crucial import and export regions. Our approach was based on the minimization of the delivered ex-ship costs for sending LNG between nodes. As an alternative for European LNG importers to solely rely on imports, our model contemplates the potential substitution of imports with domestic natural gas production equipped with CCS. This enables 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 importance diminishes in the contrasting *Persisting Fossil Demand* scenario. This observation is also substantiated by our results, which indicate that the *Persisting Fossil Demand* scenario under geopolitical tensions prompts the adoption of the European domestic natural gas production equipped with CCS, despite its inherently outrageous costs

as a required measure to substitute LNG imports. Examining the volumes of LNG sent to Europe, African exporters appear as notably significant. Furthermore, 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 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 oversupplied 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, exhibit 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 recommend enhancing the temporal resolution, extending the analysis until 2040 on an annual basis. This refined approach would include long-term contracts, allowing for the examination of fixed LNG volumes traded between exporters and importers over several years.

We expect our study to contribute to other modeling teams engaged in the decarbonization of European energy systems. Specifically, we perceive 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 assumptions exogenously established, 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.

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**Appendices**

# Delivered ex-ship costs (DES)

|  |  |  |  |
| --- | --- | --- | --- |
| **A.1 Nomenclature and empirical assumptions** | |  | |
| **Set and index** | |  |  |
| *e* ∈ E = {1*, . . . , E*} Exporter, index by *e*  *i* ∈ I = {1*, . . . , I*} Importer, index by *i* | |  |  |
| **Variable Description** | | **Value** | **Unit** |
| *DESe,i* Delivered ex-ship cost from exporter *e* to importer *i* | | See Appendix [B](#_bookmark115) | $*/*MMBtu |
| *BEPe* Break-even price of *e* | | See Table [5](#_bookmark113) | $*/*MMBtu |
| *TCe,i* Transportation cost of *e* to *i* | |  | $*/*MMBtu |
| *CCe,i* Cost of chartering an LNG carrier between *e* and *i* | |  | $*/*MMBtu |
| *FCe,i* Fuel cost of an LNG carrier between *e* and *i* | |  | $*/*MMBtu |
| *BCe,i* Boiloff cost of an LNG carrier between *e* and *i* | |  | $*/*MMBtu |
| *FEEe,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 | % |
| *Timee,i* Time for transporting LNG between *e* and *i* | | See Appendix [B](#_bookmark115) | day |
| *Distancee,i* Distance for transporting LNG between *e* and *i* | | See Appendix [B](#_bookmark115) | 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* Boiloff rate of an LNG carrier (share on bunker) | | 0.1 | % |
| *Capacity* Transport capacity of an LNG carrier | | 160 000 | m3 |
| *BoilOff CostRate* | Boiloff cost rate | 5 | $*/*MMBtu |
| *FeeRate* | Fee rate of an LNG carrier | See Table [6](#_bookmark114) |  |
| *RouteFeee,i* | Fee rate of an LNG carrier between *e* and *i* |  | $*/*MMBtu |
| *PortRate* | Port rate for an LNG carrier | 133 333 | $*/*day |

## Cost function

*DESe,i* = *BEPe* + *TCe, i* (8)

1

*TCe,i* = (*CCe,i* + *FCe,i* + *BCe, i* + *FEEe,i* + *PC*) × 1 − *HeelRate* (9)

*Time*

= *Distancee,i* × 2 × 1

(10)

*e,i*

*Speed* 24

*Timee,i*  3

*CC* = +

(11)

*e,i*

*CharterRate*

*CharterRate*

Gasification at the port

.. \_,. ..

*FCe,i* = *Timee,i* × (*Bunker* × *BunkerPrice*) + 3 × 25 × *BunkerPrice* (12)

.. Empty L\_N,.G carrier ..

*BCe,i* = *Timee,i* × *BoilOff* × *Capacity* × *BoilOff CostRate* (13)

*FEEe,i* = *Timee,i* × *FeeRate* + *RouteFeee,i* (14)

*PC* = 3 × *PortRate* (15)

## Empirical assumptions

|  |  |  |
| --- | --- | --- |
| Exporter | *BEPe* in $*/*MMBtu | *QLiq* in billions of MMBtu*/*year  *e* |
| 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* ) and assumed liquefaction capacities (*QLiq*). Based on

*e e*

[[61,](#_bookmark101) [62,](#_bookmark102) [63,](#_bookmark103) [64,](#_bookmark104) [65,](#_bookmark105) [66].](#_bookmark106)

|  |  |  |
| --- | --- | --- |
| 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 *CCe,i*) | 2 | % |

Table 6: Components of the fee cost (*Feee,i*) of an LNG carrier (see [[67]).](#_bookmark107)

# Data

For empirical data assumptions (*DESe,i*, *timee,i*, and *distancee,i*, etc.), refer to the data availability statement, as all empirical data of this paper is published on Zenodo.

## 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 and 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 UK.
    - 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]](#_bookmark108) and [[69])](#_bookmark109) are distributed according to their geographical proximity to the nodes considered in the model. That applies particularly 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 *QLiq* for Other Europe in Table [5)](#_bookmark113) as it is assumed that high shares of the natural gas production there are transported via pipelines to Europe.

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* + - * Other Africa includes, among other countries, Ghana, Egypt, and Mozambique.

## LNG demand

Region

Import 2019 Expectation

[MMBtu] for the demand

Max increase

(2008 to 2018)

[MMBtu*/*year]

(*Net Zero*) (*Persisting* )

Import 2040 Import 2040

[MMBtu] [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,](#_bookmark98) [59].](#_bookmark99)

## 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 utilized in the model to substitute LNG imports. In general, the aforementioned supply costs consist of the production cost for natural gas and the carbon capture and storage cost. For the production cost, we assume 1*.*5$*/*MMBtu, which is around double the production cost of Russian piped gas[4](#_bookmark117) The cost of carbon capture and storage is assumed to be 138$*/*tCO2 [[70].](#_bookmark110) The content of CO2 in LNG is assumed to be 0*.*053 tCO2*/*MMBtu.[5](#_bookmark118) Based on the historical natural gas production in Europe, the maximum capacity of the European domestic production with carbon capture and storage (*QEDP* ) has been set to 1 236 025 000 MMBtu*/*year [[71].](#_bookmark111) 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 The production cost of Russian piped gas is estimated to be 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>