

Response to reviewers

To the editor and reviewers,

Thank you for taking the time to consider our paper for *Energy*. The detailed feedback received has allowed the paper to be improved considerably. The suggestions and feedback have been incorporated into the revised manuscript, and a point-by-point response to feedback with changes made is detailed below. We hope the revised manuscript can be considered for publication.

Changes to the manuscript have been made visible in blue color.

Best regards, Sebastian Zwickl-Bernhard and Anne Neumann

Reviewer #1: The authors might improve the paper by following the below comment/suggested revisions:

- The authors need to provide the highlights of this paper. The authors might provide a graphical abstract, in which the linkages between motivation, methodology, and outcome are shown, for the potential readers to follow this paper efficiently/fluently.

Author's response: We have included the following highlights of the paper:

- Global LNG trade dynamics in 2040 with a focus on European supply
- Geopolitical tensions' influence on LNG imports and costs to Europe in 2040
- Substituting LNG imports with domestically produced gas equipped with CCS studied
- African exporters emerge notably significant for Europe's LNG supply
- Resurgence expected in the value of long-term contracts in the future

We express our gratitude to the reviewer for the recommendation to include a graphical abstract. While we acknowledge the utility of graphical abstracts in facilitating rapid comprehension of a paper's content, we believe that in our particular context, such an addition may not be essential.

- The authors state on p.13 that Figure 2 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. Is it Figure 2 or Figure 4?

Author's response:

Thank you for your feedback. As suggested by the reviewer, we acknowledge that the passage should reference Figure 4 (Marginal (in dark blue) and average (in sand) supply costs to meet the European LNG demand in 2040 in \$ per MMBtu, Persisting Fossil Demand scenario) instead of Figure 2.

- In Appendix B2, the authors can explain more about how the expectations for the demand for different countries and regions are determined. For instance, why China has increasing expectations while France has constant expectations for the demand?

Author's response:

We revisited our assumptions concerning demand in detail. It is noteworthy that the estimations regarding the evolution of LNG demand entail considerable uncertainties. Our approach involved referencing multiple published studies and reports to forecast LNG demand in 2040. Notably, we deliberately selected two extreme (agnostic) scenarios, namely "Persisting Fossil Demand" and "Net Zero," with the aim of illustrating a broad spectrum of potential future developments in LNG demand, both globally and specifically for Europe.

Regarding the two countries mentioned, France and China, several assumptions in our study are relevant. Firstly, we posit robust ambitions within Europe to diminish the consumption of fossil fuels, consequently leading to a decrease in the requirement for LNG imports. This is chiefly responsible for the observed reduction in considered LNG imports for France. Conversely, estimating LNG import needs for China presents a formidable challenge due to multifaceted factors. However, a pivotal factor contributing to the increase in China's demand is its aim to achieve carbon neutrality at a later date than Europe (2060 instead of by 2050 at the latest, as in Europe).

Reviewer #2: This article focuses on Europe's role as an importer of liquefied natural gas (LNG) in 2040, and explores the complexities of meeting Europe's decarbonization goals and addressing LNG energy security at the same time. The study presents an optimization model to determine the best scenario for global LNG trade between exporting and importing countries. The paper also considers the potential for Europe to substitute imports through domestic gas production and carbon capture and storage technology. Although the article has some contributions, there are parts that need further improvement:

- In the calculation of LNG supply costs, the impacts of various key parameters such as transport and insurance on the total supply costs have been fully considered, but more parameters imply greater uncertainty, and as a predictive study, the values of these parameters should be subjected to uncertainty analyses, e.g., by using interval analyses or probabilistic statistics to make the parameters discrete rather than a definite value, which may be difficult to do, of course. this may be difficult.

Author's response:

We agree that probabilistic statistics can indeed offer a valuable approach for addressing parameter uncertainties. As the reviewer rightly pointed out, empirically scaling such an approach in this context presents considerable challenges, particularly given that our modeling involves firm decisions concerning the transportation of LNG from origin to destination only at an aggregated level. Nonetheless, to pick up the significance of the reviewer's suggestion, we have explicitly incorporated this point into the revised version of the manuscript for consideration in future research endeavors.

...Furthermore, future work should address the uncertainties surrounding key parameters, such as specific components of delivered ex-ship costs, through probabilistic statistical methods.

- The optimization model is the core of this paper, so the review of the optimization model is also a key point, firstly, the structure of the optimization model in this paper is relatively simple, with the objective function of supply cost minimization, and the constraints include the supply balance, liquefaction capacity, regasification capacity, natural gas + CCS production and supply diversification, but since it is a trade model, the past trade structure and the network of trade relationships should have a future trade to have a large impact, how the authors consider this issue, please explain. Secondly there is also an uncertainty issue here, both the value coefficients and resource constraints in the optimization model should be subject to appropriate sensitivity analysis.

Author's response:

Overall, we concur with the observation that the applied model is relatively simplistic. However, as delineated by the reviewer, it encompasses a range of functionalities that enable us to address the research inquiries posed in this analysis. Consequently, we assert

that the proposed model is suitable for furnishing insights into the global LNG market in 2040, with particular emphasis on Europe's role therein.

Regarding the "past trade structure," we fully agree with the reviewer on its significance in shaping the evolution of the global LNG market. We would like to direct attention to our response below regarding the reviewer's query about the rationale behind selecting 2040 as the target year. In that response, we provide a comprehensive explanation of the role played by LNG exporters' flexibility, its correlation with long-term contracts, and the extent to which LNG export flexibilities diminish the relevance of historical LNG trades between importers and exporters. It is important to note that our interpretation of the reviewer's comment on the "network of trade" assumes reference to historical trades and flows. Should the reviewer intend a different interpretation, we kindly request clarification on this point.

Furthermore, concerning the recommendation for additional sensitivity analyses, we would like refer to the cases already included in our study. We have incorporated these cases to demonstrate the impact of various parameter sensitivities on the results, such as import flows and associated marginal and average supply costs. Internally, we deliberated multiple times on the potential inclusion of further sensitivity analyses in our paper. However, each time, we reached the conclusion that a combination of our existing cases and additional sensitivity analyses could potentially lead to confusion among readers.

- Since geopolitical and international risks have been considered, should the supply constraints of European gas + CCS be appropriately relaxed, and if faced with a greater risk of war, the localized resource exploration and exploitation may be increased; fourthly, in the diversification constraints of LNG imports, can the energy security of the importing country be reasonably taken into account, e.g., if self-sufficiency is too low, and therefore, should there be an increase in the constraints on the self-sufficiency rate to meet the national energy security objective; finally, although this model is an optimization model, it also has some simulation effect, and how accurate the model is in simulating the reality needs to be further explained.

Author's response:

We concur with the reviewer's observation regarding the potential impact of geopolitical tensions and risks on the heightened likelihood of Europe engaging in localized resource exploration to safeguard its energy supply. This aspect was indeed addressed in the concluding section of the original manuscript (page 20).

...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.

Regarding the comment on self-sufficiency, it is crucial to clarify that our approach does not explicitly model self-sufficiency. Instead, we focus solely on the demand present at

each node within the global LNG market. This demand represents only the portion necessitating coverage from the global LNG supply, rather than the total natural gas demand at the node. Implicit consideration of self-sufficiency occurs through the variation of pre-defined demand assumptions. This was specifically undertaken in our scenarios "Persisting Fossil Demand" and "Net Zero", where the LNG imports persisted and became obsolete respectively. However, we have included the following sentence in the conclusions of the revised version of the manuscript.

...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. This measure could become even more pertinent in the future, especially given the critical concerns surrounding Europe's self-sufficiency.

Moreover, we emphasize the role of Carbon Capture and Storage (CCS) in our analysis, as outlined in the introduction on page 3.

...Specifically, for European importers, optimality encompasses the evaluation of the potential for domestic natural gas production equipped with CCS to substitute LNG imports from the global market.

Regarding the simulation's alignment with reality, we acknowledge that we may not have fully grasped the intended meaning of this comment. While we recognize the potential value of validating the model, it is worth noting that in techno-economic analyses like ours, validation often leans more towards verification. As highlighted by the reviewer, our model is relatively simplistic, aiming to simulate a global LNG market trade with a focus on high proportions of flexible LNG export capacities. However, it is important to acknowledge that today's LNG market is significantly characterized by long-term contracts, a factor we discuss in further detail below, particularly in response to the reviewer's critique regarding our choice of 2040 as the target year. We assert that our model serves as a valuable tool for providing insights into the dynamics of the global LNG market.

- In the scenario analysis of geopolitical risk, the authors used many parameters of hypothetical nature, whether these parameters have a realistic basis, if so, please add further, if only hypothetical, but also need to do the uncertainty analysis, the geopolitical situation is changing a lot, and it is less persuasive to use only a fixed parameter; in addition, in the geopolitical analysis, there is an inappropriate situation in which China and Taiwan are two nodes, and it is necessary to correct it.

Author's response:

Thank you for your response. We deem it essential to clarify that the proposed scenarios should be interpreted from a "what-if" perspective. While we endeavored to convey this concept in the initial version of the manuscript (pages 9-12), we concur with the reviewer's observation that the degree to which the scenarios are grounded in realism versus being hypothetical has not been sufficiently elucidated. To address this concern, we have

augmented Section 3.3 (pages 10 and 11) with additional information about each scenario. Specifically, we have incorporated references to existing studies that analyze the global LNG markets under conditions consistent with our scenarios. For example, our scenario labeled "Diversify importers" aligns closely with the focal point of Vivoda's LNG study (doi: <https://doi.org/10.1016/j.enpol.2022.113218>), published in 2022. Similar references have been included for the other four scenarios as well. This approach aims to provide further context and grounding for the scenarios outlined in our analysis.

(1) Diversify importers:

- Vivoda (2022), <https://doi.org/10.1016/j.enpol.2022.113218>

(2) High price Middle East:

- Wietfeld (2011), <https://doi.org/10.5547/ISSN0195-6574-EJ-Vol32-No2-8>

(3) No export from Africa:

- Andersen and Sitter (2018), https://doi.org/10.1007/978-3-319-93360-3_3

(4) Panama Canal restricted:

- Moryadee et al. (2014), <https://doi.org/10.1016/j.jngse.2014.06.015>

(5) Russia to Asia only:

- Paltsev (2014), <https://doi.org/10.1016/j.eneco.2014.01.005>

Regarding the inquiry about the names or labels of the nodes, we wish to clarify the following: The nodes are organized based on the localization of liquefaction and regasification stations rather than strictly adhering to country boundaries. This orientation is evident even when examining the nodes within Europe. Notably, we have not listed Germany as a separate node but have included both Belgium and France to account for the anticipated localization of regasification terminals. We have explicitly addressed this aspect in the revised version of the manuscript.

- The research time of this paper is only 2040, what is the basis for the selection of this time node, and whether the model can be adjusted to simulate the dynamics year by year, and the optimization using only the results of 2040 cannot show the temporal trend of the global LNG market.

Author's response:

We appreciate the reviewer's insightful comment, which aligns with extensive internal discussions among the authors. We wholeheartedly concur with the observation that our findings for the year 2040 alone may not adequately capture the temporal dynamics of the global LNG market. Therefore, it is essential to consider the years leading up to 2040 as equally relevant in understanding these trends. Particularly, for studies aiming to analyze the temporal evolution of the global LNG market, a higher temporal resolution may be necessary. We have explicitly addressed this consideration in the conclusions of the revised manuscript and intend to enhance our model's temporal dimension accordingly.

However, we maintain the conviction that our approach, focusing on the target year of 2040, yields valuable insights despite not encompassing the interim years. The following two reasons underpin our selection of 2040:

1. For the target year 2030 and the intervening years, a plethora of comprehensive studies already exists, providing valuable insights into the evolution of the global LNG market. Notably, studies such as those conducted by Mike Fulwood and published by The Oxford Institute for Energy Studies, such as "A New Global Gas Order? (Part 1): The Outlook to 2030 after the Energy Crisis" (link: <https://www.oxfordenergy.org/wpcms/wp-content/uploads/2023/07/NG-184-A-New-Global-Gas-Order-Part-1.pdf>), offer detailed analyses of historical LNG trading patterns ("past trade"), as well as projections for future market dynamics up to 2030. These studies not only illuminate historical trading patterns but also forecast shifts in market flows leading up to 2030. Importantly, they suggest that the demand-side of the market is expected to remain relatively stable compared to current LNG demand values, particularly in Europe. Beyond 2030, however, there is greater uncertainty regarding potential changes in both demand and supply dynamics. Furthermore, these studies delve into the intricate role of long-term contracts in shaping the LNG market landscape. They highlight the pivotal role of long-term contracts at present and their anticipated significance leading up to 2030. Additionally, these reports underscore the substantial increase in LNG export capacities from the United States, with flexible export capacities already comprising two-thirds of the market today. This trend is expected to continue as market liquidity increases, facilitating the expansion of vessel numbers and further enhancing flexibility in LNG trading. In light of these findings, our study can be regarded as a logical progression building upon existing research focusing on the 2030 horizon. By extending the analysis to the target year of 2040 (but also 2050 could be possible then), our study aims to provide additional insights into the medium- to long-term dynamics of the global LNG market, particularly emphasizing the growing role of flexible LNG export capacities in shaping future market trends.
2. Examining Norwegian LNG imports to Europe and other regions reveals a discernible trend towards increased flexibility in LNG exports from the supply side. This trend underscores the growing importance of detailed insights into a global LNG market characterized by high proportions of flexible export capacities. Notably, our analysis focuses on a market where all considered capacities are inherently flexible, as long-term contracts are not factored into our modeling approach. This perspective acknowledges the evolving nature of LNG trade dynamics, where flexibility in export arrangements becomes increasingly prevalent. By omitting long-term contracts from our considerations, we aim to capture the nuances of a market characterized by fluidity and adaptability in LNG transactions, thereby providing valuable insights into the future trajectory of the global LNG market.

We have integrated key aspects of our response into the revised version of the manuscript at various junctures. For instance, we have elaborated on the concept of flexible LNG export capacities and their influence on the selection of the target year in the methodology section. Additionally, we have outlined possible implications in the revised conclusions, emphasizing the significance of these factors in shaping our analytical approach and the insights derived from our study.