

Balancing Supply Security and Decarbonization: Optimizing Germany's LNG port Infrastructure under the European Green Deal

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Abstract

The European Green Deal depends on a coordinated common policy for demand, renewable generation, supply security, and infrastructure. To ensure supply security after 2022 gas supply interruptions, the German government diversified energy imports into liquefied natural gas (LNG) through the use of floating storage and regasification units (FSRU). We test whether the current plan for Germany is consistent with the Green Deal objectives for decarbonization. We use a cost-minimizing facility location model in accordance with European policy objectives, combined with a network flow model, to optimize the assignment of FSRUs among German ports to ensure gas supply. Six scenarios are investigated: three greenfield models, with different demand scenarios, in which all locations are possible, a brownfield model in which the existing terminals are imposed, a no-FSRU scenario and a peace scenario between Ukraine and Russia. The optimal solutions for the base greenfield scenarios use the FSRU port infrastructures to expand the regasification capacity to 45 bcm per year. The model validates actual current decisions as optimal for supply security, but the two greenfield and long-term decisions differ in length and investment intensity, challenging policy consistency. Potentially, the impact of anticipatory hydrogen transport investments can distort the analysis.

Keywords: Liquefied Natural Gas; Floating Storage and regasification

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1. Introduction

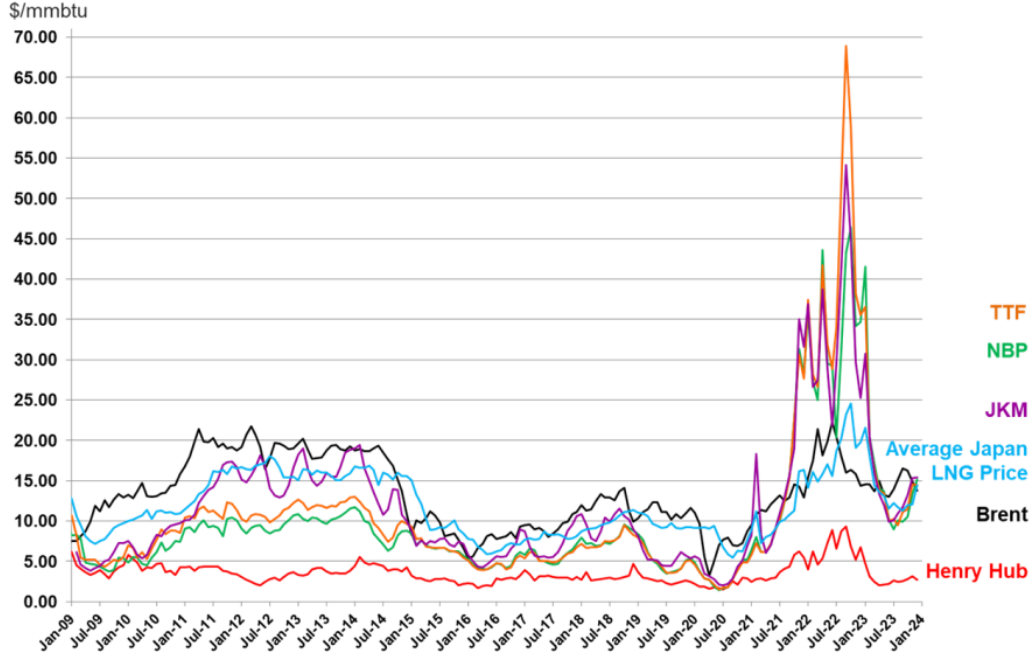
The European Union (EU) is embarking on an ambitious climate change response policy through the Green Deal ([European Commission, 2019](#)), aiming at a 55% reduction in CO₂ emissions by 2030 and complete carbon neutrality by 2050. The plan concerns regulation, financing, access, and market conditions for a new revitalized energy sector, tightly monitored through the new Energy Union. Germany is a key player in the plan, being the largest emitter of CO₂ in Europe in absolute terms and above average per capita due to its industrial structure and dependence on fossil fuels for power generation, especially natural gas.

Natural gas has played an important role as a transition energy for heating and peak load management in Europe and elsewhere. Although combustion of this gas produces CO₂ emissions lower than those of coal or petroleum products, the convenience of using natural gas as a transition fuel to soften the temporary economic impact provoked by the adoption of renewable energy on a full scale has been widely debated. [Gürsan and de Gooyert \(2021\)](#) review the literature on the role of natural gas in reducing carbon emissions, acting as a bridge to renewable technologies. One of the main arguments against the use of natural gas as a transition energy source is precisely that new investments in natural gas could displace future investments in renewable alternatives. In this context, the object of this work is pertinent, provided the versatility, lower unit investment costs, and mobility of the FSRUs, compared to onshore regasification plants.

Natural gas is delivered by long-distance maritime or land transport. On land, natural gas transportation mobilizes a massive pipeline network divided into transmission, regional transmission, and distribution systems with associated storage and compressor stations. By sea, transport is carried out in three steps. First, natural gas is liquefied in dedicated facilities (liquefaction plants) located in loading ports, obtaining LNG that is shipped at -162°C in LNG carriers, double-hulled ships with insulated tanks. At the destination ports, it is loaded into insulated storage tanks to be later regasified and injected into the pipeline distribution network. The regasification process is carried out in dedicated plants that can be of two types: onshore plants or FSRUs. The technology is the same in both types, the only difference being that in FSRUs all equipment is adapted to marine operations.

Due to its strong dependency on imports and the decrease in production volumes, Europe faces serious challenges in maintaining a balanced energy

Figure 1: Global gas and Brent prices in US Dollars per million British thermal units: Jan 2009 – Dec 2023. (Heather, 2024)



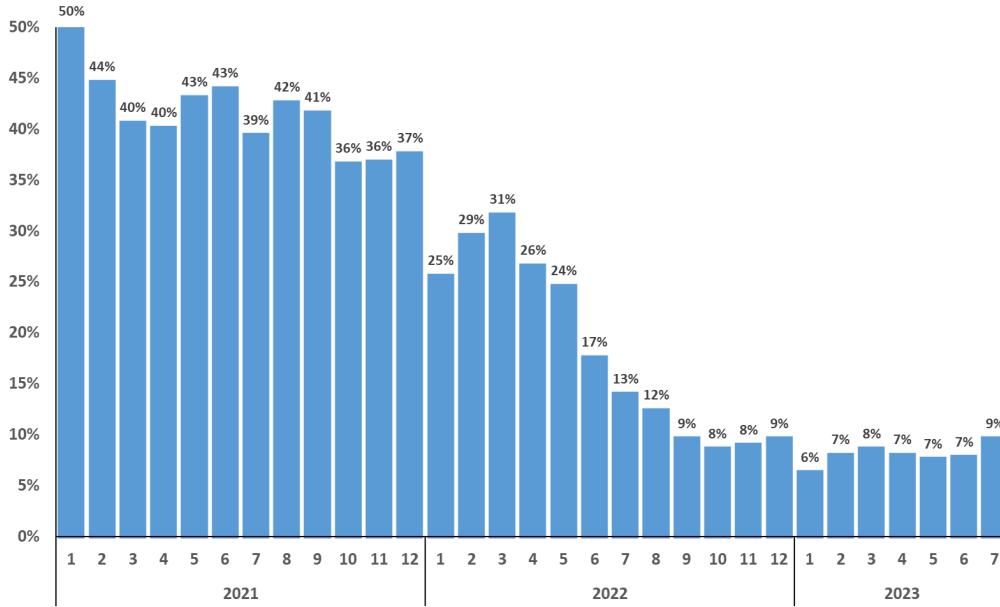
mix, aggravated by the geopolitical risks associated with the natural gas supply. The 2022 war in Ukraine changed the scenario in which Europe had evolved in the last few years, based mainly on gas imports via pipeline from Russian producers. The cuts in Russian gas supply to the EU, and especially to Germany, triggered a fossil fuels crisis of global proportions with a particular incidence in Europe, resulting in high volatility of the price of oil and gas in the international market (see Figure 1).

To date, the diversification of gas imports remains one of the greatest challenges facing Europe. European imports depend on a gas oligopoly with very few actors: pipeline gas from Norway, Algeria, and Russia, and LNG from the USA, Qatar, and Nigeria (Jaller-Makarewicz, 2024). Since the Russian attack on Ukraine, the EU has strongly reduced its gas imports from Russia (Figure 2), compensating for this reduction with demand reductions and increased LNG imports, especially from the United States.

1.1. Germany in the European Energy Union

Germany is by size, industrial structure, and electricity generation pool, the most important country in Europe in terms of CO₂ emissions, since the country emits 24% of the total EU emissions derived from fuel combustion (IEA, 2023). It is also the third highest per capita emitter (7,501 tCO₂ per

Figure 2: Share of Russian pipeline gas in total EU natural gas imports. Source: ([European Commission, 2023](#))



capita), even though considerable efforts have been made to reduce this figure (-38% since 2000). Fossil fuel consumption has been equally reduced, particularly coal (-48% between 2000 and 2020) and oil (-29% between 2000 and 2022). In any case, natural gas had remained a constant in the German energy mix until 2022. The supply shock triggered by the war resulted in a dual response: natural gas consumption declined, and a strategy was devised to expeditiously construct gas infrastructures, particularly LNG regasification plants. Following this strategy, Germany has already built three LNG terminals in record time at the Wilhelmshaven, Brunsbüttel, and Lubmin ports. Two additional facilities will be in operation at the ports of Mukran and Stade in 2024 and 2025, respectively. All of them operate FSRUs to supply the German gas distribution network. In parallel, plans have been launched to build onshore regasification plants, some of them in an advanced stage. The German government’s master plan ([European Commission, 2023](#)) is to use natural gas as energy to transition to a green economy based on renewable energies. Thus, some of these gas facilities would eventually be retrofitted, enabling import and production of green hydrogen in the future. Given its decentralized gas transmission infrastructure with 12 independent (private) gas transmission system operators (TSO) ([ENTSO, 2024](#)) with separated accounts, the economic energy system planning in Germany is ultimately dependent on the federal regulatory authority, Bundesnetzagentur

(BNetzA) in collaboration with the EU Agency for the Cooperation of Energy Regulators (ACER). The choices made to meet legitimate short-term needs for supply security in terms of natural gas can therefore be seen as indications of the overall policy direction for Germany and Europe towards the Green Deal objectives.

2. Objective

The consistency of the policy of natural gas supply decisions in Germany has been the subject of critical discussion, based on various projections of demand, pricing, and competitive factors. However, the urgency to maintain the natural gas supply in the short term to ensure economic and social conditions is an obvious imperative for any government planner. Moreover, the complexity of the gas transmission system network, the demand locations, and the sequence of potential investments in port-side, maritime, or land-based infrastructure call for a deeper techno-economic analysis before passing to conclusions. However, the evaluation of the consistency of the claimed, potential and actual policy is often left to an arbitrary assessment based on hypothetical arguments and assumptions, rather than an objective framework.

The objective of this work is therefore to assess the policy consistency of the German short-term and medium-term natural gas supply investments in LNG import facilities, more specifically in FSRU port infrastructures, using operations research to model the optimal decision-making process under the stated constraints and comparing the model solutions to the actual policy. We investigate the deployment of a set of FSRU-operating LNG terminals located in 11 German candidate ports. These terminals can unload one or several ships depending on the infrastructure work carried out in each of them. The time frame of the deployment comprises 28 years, that is, 2023 to 2050. In this period, we are considering that the demand linearly decreases year by year, reaching zero by 2050. In other words, we assume a steady transition to carbon neutrality by 2050 in accordance with the stated European policy objectives in the Green Deal and associated agreements, cf. ([European Commission, 2019](#)). Two assumptions have been made: (i) a linear demand decrease and (ii) no seasonality. Although it is unlikely that the exact demand development will follow a linear curve, the objective of this paper is still adherence to the final policy objective of the Green Deal for 2050. The exact phase-out pattern is unknown and any assumptions about the functional form for it would be as arbitrary as the simple linear assumption. Since the horizon involves no specific temporal events, the linear phase-out can be seen as an unbiased average from a series of stochastic outcomes

converging to the final known point. Likewise, seasonality is managed with a cycle of storage injections and withdrawals each heating year, as a function of exogenous factors such as weather and business cycle. We address this limitation by modeling only the expected net consumption by (heating) year under the assumption that in-period storage effects net out in the time period. Seen in aggregate over a 28-year horizon, this assumption is likely relatively harmless. Finally, we recognize that climate changes that would significantly change heating demand in the area could have an impact on the overall slope and, ultimately, on the feasibility of the Green Deal economically and technically. However, since such large unknowns may also have an impact on LNG supply and pricing, natural gas pricing, and demand globally and regionally, it is beyond the scope of this paper.

Our contributions are twofold: First, we inform the energy policy discussion for collective European versus national (German) supply security objectives based on an ex post investment review for recent LNG import choices. Second, we formulate and solve a gas infrastructure location model with a directional flow network to optimize a dynamic investment policy in FSRU and LNG terminals to meet demand objectives. The latter has to our knowledge not been presented in the literature, and the current application to Germany is without loss of generality; the model can be used to inform an individual operator, another country, or higher level planning, e.g. the European level.

The remainder of this paper is organized as follows: the relevant literature is reviewed in Section 3. The model is described in Section 4 and applied in Section 5; the obtained results are analyzed in Section 6. Section 7 compares our findings with the actual German planning, and finally Section 8 is dedicated to the final policy conclusions and possible further research.

3. Relevant literature

Among the existent literature about the European energy infrastructure and policy, and more particularly, the natural gas industry, three streams of research are relevant to this study: studies related to the consequences of the invasion of Ukraine, those related to the European energy policy, and literature dealing with optimization models. The energy shock caused by the Ukraine war in Central and Eastern Europe is analyzed by [Gritz and Wolff \(2024\)](#) studying the gas flow into the region, the consumption, and the diversification policies adopted by the European countries to mitigate the impact of the Russian gas cuts. [Halser and Paraschiv \(2022\)](#) discuss possible demand corrections and regulatory measures to cope with the post-Ukraine invasion energy crisis, highlighting the use of FSRUs to shelter the supply

of gas and finally concluding that delaying the phase-out of coal and nuclear power could avoid the foreseeable German economic contraction. [Kędziński \(2023\)](#) examines equally the post-invasion changes in the German gas sector and the adopted emergency measures, among others the construction of port LNG terminals and the control of part of the German gas infrastructure. [Overland \(2022\)](#) concludes that the post-invasion increase of fossil fuel prices will encourage global renewable energy investments, favor the perspectives of the nuclear industry, and reducing the demand in fossil fuels, whereas in Europe, the high prices scenario will harm energy-intensive industries. [Jirušek \(2022\)](#) shows the EU's difficulties dealing with the Russian energy import restrictions and the post-invasion geopolitical scenario, highlighting problems for the adoption of a common policy, and indicating that even so, the EU has room to improve a policy through specific regulations for pipeline interconnections with third-party countries and promotion of international cooperation in infrastructure-building. Considering the available infrastructure, the long-term contracts, and the post-Ukraine invasion geopolitical situation in Europe, [Chyong and Henderson \(2024\)](#) propose different future Russian gas export scenarios to Europe, modeling a base case and comparing it with four scenarios with a wide range of flows for the years 2023 to 2030, concluding that although the total resumption of the Russian gas exports to Europe is highly unlikely, depending on the outcome of the war, its partial resumption cannot be ruled out. Analyzing European energy policy responses to the war and its implications for sustainable transformations [Kuzemko et al. \(2022\)](#) study what those policies mean for environmental sustainability, energy equity, and social justice, revealing the strong potential for the implantation of clean energy supply, the difficulties for fossil fuel phase-out, the negative perspectives for sustainable transitions in the Global South, the implications for energy equity within Europe, and a partial return of the states as energy actors. Linking the invasion of Ukraine to the European energy policies, [Emiliozzi et al. \(2023\)](#) analyze the post-invasion gas markets and their incidence on the global economic landscape: macroeconomic deterioration, reduced growth prospects, inflationary pressures, severe strain on global value chains and increasing geo-economic fragmentation. Regarding Europe, they focus on implemented fiscal support to shield vulnerable households from high energy prices, ensure business continuity, and secure substitute energy sources. They conclude that Europe must adopt a clean-energy paradigm, not only increasing renewable energy investments but also pursuing a long-term strategy to avoid the risks derived from the potential scarcity of critical minerals necessary for the transition.

Examining the EU energy policy and specifically the impact of the National Energy and Climate Plans (NECP19) ([European Parliament, 2018](#))

and REPowerEU ([European Commission, 2022](#)), [Ah-Voun et al. \(2024\)](#) conclude that, by the application of the latter, Europe could be independent of Russian gas by 2030, indicating that since the execution of REPowerEU is based on the implementation of clean technologies, a substantial effort in the deployment of wind and solar installations in Europe is required. The uncertainties in the European natural gas market about demand and supply are analyzed by [Riepin et al. \(2022\)](#) who propose an adaptive robust optimization framework for the expansion planning of gas infrastructure according to these uncertainties. Using a mixed-integer linear model, they analyze the interest of strategic infrastructure projects supported by EU funds, the so-called "Projects of Common Interest", to warrant supply security by 2030, finding that up to date the investment preferences have been oriented to the most favorable projects from a business perspective. They also find that most projects are difficult to execute without public financial support. Regarding the role that hydrogen will play in a future decarbonized Europe, [Durakovic et al. \(2023\)](#), analyze whether blue and green hydrogen are complementary or competitive depending on electrolyzer costs and natural gas prices. Using a multi-horizon stochastic capacity expansion model, they show that early deployment of green hydrogen leads to higher hydrogen costs and CO2 prices in 2030 whereas the blue hydrogen option presents notable benefits in 2030, allowing cheaper hydrogen with less socioeconomic impact. However, the adoption of green hydrogen and the competitive aspects between blue and green hydrogen are short-term, and by 2050 green and blue hydrogen will be complementary. Investigating barriers and constraints in EU policies for natural gas decarbonization [Khatiwada et al. \(2022\)](#) examine the costs of hydrogen production applied to a specific case in Portugal, and find that with the natural gas prices of 2020, there is a significant gap between the cost of green (electrolysis fueled by renewable energy sources) and gray hydrogen (methane electrolysis without carbon capture) and that of natural gas, indicating that the inclusion of a carbon tax would be necessary to incentivize hydrogen production. The energy transition in Germany and the risk of gas lock-in under that transition are treated by [Brauers et al. \(2021\)](#) in connection with the LNG expansion plans of the German government, arguing that the plans for the construction of LNG import terminals are contradictory to the country's climate objectives and promote increases rather than decreases in natural gas consumption.

Optimization models for gas transmission networks focused on short-term storage (line-packing problems), gas quality satisfaction (pooling problems), and compressor station modeling (fuel cost minimization problems) are addressed in the survey in [Ríos-Mercado and Borraz-Sánchez \(2015\)](#). [Sesini et al. \(2020\)](#) use a minimum-cost linear programming model to study the

resilience of the EU natural gas network in case of supply disruptions or unexpected peak demand periods by minimizing costs with respect to gas transmission, capacity and storage. The model enables the import of LNG to meet the demand. Using a mixed-integer programming formulation, [Melkote and Daskin \(2001\)](#) presents a capacitated facility location/network design problem as a generalization of the classical facility location problem, concluding that, compared to the models where capacity constraints are imposed, the network is denser and both link and transport costs decrease. [Zwickl-Bernhard et al. \(2024\)](#) study the development of the current Austrian gas grid by 2040 by using a mixed integer optimization model, considering different decarbonization scenarios and analyzing the optimal cost balance between underutilized gas pipelines and external supply alternatives such as trucking. The level of spatial resolution is very high to allow for detailed recommendations. [Masudin \(2013\)](#) uses a Mixed Integer Linear Programming (MILP) formulation to develop a model of the Indonesian gas distribution system, studying the relationship between distribution and facility location costs in that country. The formulation includes transportation and inventory decisions in a joint multiechelon and multihierarchy location-allocation model that defines the optimal facility locations and customer allocations given a set of existing assets. Using the connections between the different elements of the transmission and distribution networks and introducing six levels for the natural gas supply chain, [Hamed et al. \(2009\)](#) define a multi-period MILP model whose objective function minimizes total costs associated to the distribution and utilization of the nominal and operational capacities of the system. Another facility location approach is used by [Derse et al. \(2020\)](#) to minimize the costs of the production, storage and transportation, safety, location, and staff assignment decisions of green hydrogen, developing a mixed-integer non-linear programming (MINLP) model to integrate all those aspects. Focusing on the resource planning and management problem of a biomass transportation and conversion network covering the entire syn-gas (synthesis gas) production process, [Sarker et al. \(2022\)](#) develop a MINLP model minimizing the costs and optimally allocating the different elements of the productive process. The impact of LNG and the Nord Stream 2 pipeline on European gas trade and supply security by 2030 is examined by [Eser et al. \(2019\)](#). They find that increased LNG imports would require part of European gas pipelines to be bidirectional, leading to a substantial need for investments in the European gas infrastructure. Halfway between the three above-mentioned streams this paper aims to answer two research questions not sufficiently addressed as far as we know in the current literature: First, the development of an optimization model combining a facility location and a network flow model including candidate ports, regasification and pipeline

Table 1: Description of sets and subsets.

Symbol	Label
C	Neighboring countries.
$C_i \subset C$	Countries with import demand.
$C_e \subset C$	Countries with export capacity.
E	Edges (pipelines).
F	Fleet of FSRUs.
T	Time periods.
V	Nodes.
$V(c) \subset V$	Nodes in country c .
$V_d \subset V$	Domestic demand nodes.
$V_g \subset V$	Domestic production nodes.
$V_i \subset V$	Industrial demand nodes.
$V(n) \subset V$	Neighbor nodes of node n .
$V_p \subset V$	Candidate port nodes.

investments for a given demand profile. Second, the application of optimization models to validate the strategic investment decisions in countries facing gas supply risks, while still respecting overarching demand reductions in the long term. Even if the body of literature on facility location and distribution models is rich, to our knowledge only one paper uses a similar approach for gas networks, the already mentioned [Zwickl-Bernhard et al. \(2024\)](#) for the Austrian networks but without the FSRU and port dimensions. Secondly, while the European and German energy policies, separately or jointly, are subject to a series of papers, no paper has been found comparing the empirical FSRU investments with the consistency of stated policy objectives using an optimization approach

4. Model

We model the dynamic investment decision problem as a multi-period facility location problem combined with a network flow problem. Specifically, the model represents the German pipeline network as a digraph $G = (V, E)$ where each node is associated with a natural gas demand, a supply source, or both. The facility location aspect of the model comes from the possibility of building the necessary infrastructure for berthing one or several FSRUs at a selected candidate *port node*. This investment is referred to as an *upgrade* in the remainder of this article.

The sets, parameters, and variables of the model are listed in Tables 1, 2, and 3, respectively. The model is detailed in Formulation 1.

Formulation 1

$$\min \sum_{t \in T} (1-r)^t \left(\sum_{p \in V_p} U_{p,t} \text{capex}_p + \sum_{p \in V_p} A_{p,f,t} \text{opex}_p + \sum_{p \in V_p} U_{p,t} b_p \right. \\ \left. + \sum_{p \in V_p} Y_p^f \hat{p} + \sum_{n \in V_g} Y_{n,t}^d p_{\text{DE},t} + \sum_{c \in C_e} \sum_{n \in V(c)} Y_{n,t}^i p_{c,t} \right) \quad (1)$$

subject to

$$Y_{n,t}^d + Y_{n,t}^i + Y_{n,t}^f + \sum_{u \in V(n)} l_{(u,n)} X_{(u,n),t} \\ = \sum_{u \in V(n)} X_{(n,u),t} + Y_{n,t}^e + d_{n,t}, \quad \forall t \in T, n \in V, \quad (2)$$

$$G_{p,t} = \sum_{k=1}^t u_{p,k}, \quad \forall t \in T, p \in V_p, \quad (3)$$

$$X_{e,t} \leq k_e, \quad \forall t \in T, e \in E, \quad (4)$$

$$\sum_{f \in F} A_{p,f,t} \leq q_p G_{p,t}, \quad \forall t \in T, p \in V_p, \quad (5)$$

$$\sum_{p \in V_p} A_{p,f,t} \leq 1, \quad \forall t \in T, f \in F, \quad (6)$$

$$Y_{p,t}^f \leq \sum_{f \in F} A_{p,f,t} w_f, \quad \forall t \in T, p \in V_p, \quad (7)$$

$$\sum_{n \in V(c)} Y_{n,t}^i \leq s_c, \quad \forall t \in T, c \in C_e, \quad (8)$$

$$\sum_{n \in V(c)} Y_{n,t}^e = m_{c,t}, \quad \forall t \in T, c \in C_i, \quad (9)$$

$$U_{p,t} \in \{0, 1\}, G_{p,t} \in \{0, 1\}, \quad \forall t \in T, p \in V_p,$$

$$A_{p,f,t} \in \{0, 1\} \quad \forall t \in T, f \in F, p \in V_p,$$

$$X_{e,t} \geq 0 \quad \forall t \in T, e \in E,$$

$$Y_{n,t}^i \geq 0 \quad \forall t \in T, c \in C_e, n \in V(c),$$

$$Y_{n,t}^e \geq 0 \quad \forall t \in T, c \in C_i, n \in V(c),$$

$$Y_{p,t}^f \geq 0 \quad \forall t \in T, p \in V_p$$

Table 2: Description of parameters.

Symbol	Index sets	Label [units]
b_p	$p \in V_p$	Cost of new pipeline construction if infrastructure investment at p [M€].
capex_p	$p \in V_p$	Net Present Value of capital expenditures to upgrade port p [M€].
$d_{n,t}$	$n \in V, t \in T$	Nodal demand at node n in year t [bcm].
h_n	$n \in V_g$	Domestic production capacity at node n [bcm].
k_e	$e \in E$	Flow capacity in pipeline e [bcm/year].
l_e	$e \in E$	Losses and compression gas usage through pipeline e [%].
$m_{c,t}$	$c \in C_i, t \in T$	Import demand of country c in year t [bcm].
opex_p	$p \in V_p$	Operational expenditures per FSRU in use for a year at port p [M€].
$p_{c,t}$	$c \in C_e, t \in T$	Price of exports from country c in year t [M€/bcm].
$\hat{p}$	-	Price of LNG imported via FSRU [M€/bcm].
q_p	$p \in V_p$	Berthing capacity of port p [# ships].
s_c	$c \in C_e$	Supply capacity of country c [bcm/year].
w_f	$f \in F$	Processing capacity of FSRU f [bcm/year].
r	-	Yearly discount rate.

Table 3: Description of variables

Symbol	Index sets	Label
$A_{p,f,t}$	$p \in V_p, f \in F, t \in T$	1 if FSRU f is assigned to port p in year t . Used to compute the available capacity at the ports.
$G_{p,t}$	$p \in V_p, t \in T$	1 if port p was upgraded for FSRU berthing during the current or a past year. Used to define whether $A_{p,f,t}$ may be 1.
$U_{p,t}$	$p \in V_p, t \in T$	1 if port p is upgraded for FSRU berthing during the year t . Used to define the year when the capex are paid.
$X_{e,t}$	$e \in E, t \in T$	Flow of gas in pipeline e during year t .
$Y_{n,t}^d$	$n \in V_g, t \in T$	Quantity of gas produced at domestic node n .
$Y_{n,t}^e$	$n \in V_i, t \in T$	Quantity of gas exported via the foreign node n .
$Y_{n,t}^i$	$n \in V_e, t \in T$	Quantity of gas imported via the foreign node n .
$Y_{p,t}^f$	$p \in V_p, t \in T$	Quantity of gas imported via FSRU at port p .

abca Equation (1) minimizes the discounted sum of capital expenditures, operational expenditures, pipeline construction costs, and gas purchase costs. Constraint (2) ensures the conservation between input and output flows in a node. On the left-hand side, the input flows are the imports (if the node is in an exporting country $c \in C_e$), the imports from an FSRU facility (if the node is a port), and the incoming flow from neighboring nodes. On the right-hand side, the output flows are the outgoing flows to neighboring nodes, the exports (if the node is in an importing country $c \in C_i$), and the demand of the node (if the node is in Germany). The incoming flows from neighboring nodes via pipelines are multiplied by a factor $0 < l_e < 1$ that represents the losses due to leakage during transport and the gas used by the network for compressors. In practice, this constraint is generated per node by only including variables that are defined for the respective node. For example, for a node n in a country set $V(c)$ where $c \in C_e \setminus C_i$, the variables $Y_{n,t}^e$, $Y_{n,t}^f$, and the parameter $d_{n,t}$ are not defined and thus not present in the constraint. The same is true for the variable $X_{e,t}$ if $e \notin E$. Constraint (3) ensures that $G_{p,t} = 1$ if and only if an infrastructure upgrade was performed in the past. Constraint (4) ensures the respect of the capacity of each pipeline. Constraint (5) sets the limit on the number of FSRU ships that can be berthed in an upgraded port. Constraint (6) ensures that an FSRU can be assigned to one port only in each period. Constraint (7) sets the processing capacity of the upgraded ports. Constraint (8) limits the total import from a country to the supply capacity of that country. Constraint (9) enforces the satisfaction of the demand of neighboring countries.

5. Application

5.1. Data collection

The main data source for this model is the open source IGGIELGN database, which provides data for the European gas transmission network (Diettrich et al., 2021; Pluta et al., 2022). From this dataset, we extracted the sets of arcs (E) and nodes (V) that constitute the German transmission network along with the associated metadata. This dataset provides geographical information on the European pipeline network in the form of pairs of coordinates that indicate the endpoints of each pipeline. Each pipeline is also accompanied by the following parameters relevant to the model: endpoint countries, diameter, length, and maximum flow capacity. It also provides a collection of nodes with their coordinates, country codes, and a NUTS2 regional identifier. We exploit pipelines with at least one endpoint in Germany and only the nodes that correspond to the endpoints of these arcs.

Based on their geographical position and technical characteristics, we identified 11 candidate ports (Bremerhaven, Brunsbüttel, Duisburg, Emden, Hamburg, Lübeck, Lubmin, Mukran, Rostock, Stade and Wilhelmshaven) suitable for the construction of LNG terminals. Then each port was assigned to the closest node with at least one outgoing pipeline to form the subset V_p . Each port can accommodate a single ship, that is, $q_p = 1$, except for Wilhelmshaven, where an extension of the capacity to host a second FSRU (i.e. $q_{\text{Wilhelmshaven}} = 2$) is planned for 2024 (EConnect, 2024).

The investment costs for connection pipelines and port facilities are based on flow volume and connection points to the existing network. The local site characteristics such as slope, soil, land cover, humidity, accessibility for construction, and others, as mentioned in Agrell et al. (2023), are not considered in the cost function, since the exact location has not been determined for the pipeline construction and the cost data for all port facilities are not public. The distance between a port's coordinates and that of its assigned node was used to estimate the construction cost of the pipeline (b_p) with 450 mm diameter (Khoiriyah et al., 2023) by multiplying this length by a construction cost of 455 k€/km (Sumicsid, 2019) times the number of ships that can be accommodated at the port (q_p).

We modelled the cost of gas transportation through the pipeline network as an internal gas usage for compressor stations equal to 0.005% of the volume transported per km, as suggested in (Molnar, 2022). To this we add the losses that occur during transport due to leakage, estimated to 0.0425347% of the transported volume (Abrell et al., 2016). This is modelled by the parameter $l_e = 1 - \text{length}_e \cdot 0.00005 - 0.000425347$ that multiplies the pipeline inputs of a node in Constraint (2) of the model.

We assume that the investment required to equip each port with FSRU infrastructure, that is, to *upgrade* it, depends on the number of FSRU that can be berthed (q_p) and is estimated according to the investment breakdown in Table 6.1 in Songhurst (2017), from which we removed the vessel investment (leasing fee in our case), and adjusted for 22.8% of inflation since 2017. We thus have the *upgrade investment cost*

$$\text{up}_p = 1.228 \times ((80q_p + 30) \times 1.1 + 54).$$

We model the capital investment cost (capex_p) as the Net Present Value of this investment, paid with ten equal annuities and a discount rate of $r = 0.0175$ (Agrell et al., 2024). This gives the formula

$$\text{capex}_p = \sum_{t=1}^{10} \frac{\text{up}_p}{10 \times (1 + r)^{t-1}}.$$

This amounts to a capex of 214.9M€ for a one-FSRU infrastructure, and 322.9M€ for a two-FSRUs one. Annual operating expenses for an FSRU include the annual lease cost of 46M€ (Reuters, 2022), plus 2.5% of the undiscounted upgrade investment cost (Songhurst, 2017), that is,

$$\text{opex}_p = 71.5 + 0.025 \times \text{up}_p / q_p.$$

Note that the investment value is divided by q_p as the opex is paid annually per FSRU *in use*. The final values are 76.9M€ and 75.5M€ per year for $q_p = 1$ and $q_p = 2$, respectively. Without loss of generality, we assumed a fleet of 12 identical FSRU with $w_f = 5$ (LNG Prime, 2024).

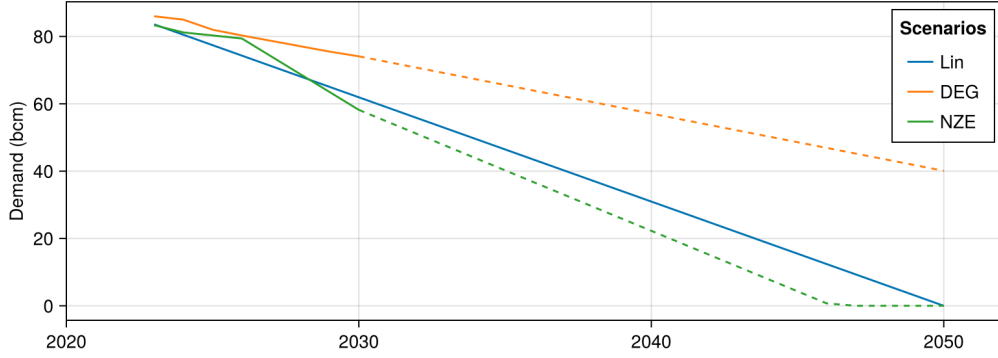
5.2. Demand estimation

The objective of the model is to represent the gas flow in Germany to explain the decision about the location of LNG port terminals. As the flow is driven by domestic consumption in addition to transit engagements, we assign an estimate of demand to each node in the country. This demand is divided into two categories: residential and industrial load. Industrial and commercial demand, dominated by power plants, accounts for 59 % of the total demand for the country, which was 86.7 bcm in 2022 (Enerdata, 2023). The share of each industrial node $n \in V_i$ from this dataset is estimated proportionally to their power in MW (Pluta et al., 2022).

Geographic data for the local residential load are not available. Therefore, we base our estimations on the assumption that residential consumption is proportional to the residents' local Gross Domestic Product (GDP) per capita. To do this, we use public Eurostat data on the average GDP per capita aggregated at the geographical level NUTS2 and the population of each NUTS2 area to estimate their respective GDP (Eurostat, 2023a,b). This demand is distributed between all nodes within the NUTS2 region, proportional to the total input capacity of their respective incoming arcs (Pluta et al., 2022).

Finally, since the goal of this paper is to model the supply of gas in the context of the green transition, we analyzed three demand scenarios. First, we considered the *linear* scenario (LIN) where we linearly decreased the national demand ($d_{n,t}$) and the international demand ($m_{c,t}$) starting from the demand observed in 2022 to reach zero in the last period (2050). Second, we linearly projected the gas demand prediction of German government (BMWK, 2023a) beyond 2030 by assuming a yearly decrease in consumption equal to the average decrease between 2023 and 2030. Specifically, this scenario (DEG) entails a decrease of 1.7 bcm per year to reach a yearly consumption of 40 bcm in 2050. We applied the same extrapolation method

Figure 3: Comparison of the demand scenarios from 2023 to 2050. The Model scenario demand decreases linearly. Forecasts from the DE government (DEG) (BMWK, 2023a) and Net Zero Emission (NZE) (David et al., 2023) are limited to 2030. The dashed lines correspond to the linear projections from 2030 to 2050.



to the Net Zero Emissions Scenario (NZE) from David et al. (2023). The decrease is the steepest in this scenario, leading to an end of consumption as soon as 2046. The three scenarios are shown in Figure 3. We note that in all scenarios, the decrease in demand from other countries remains linear for simplicity.

5.3. Import and export

The current main supply source of natural gas for Germany is imports from neighboring countries through its pipeline network. Germany is also an exporter of gas that transits through its network. We obtained the sets of exporting (C_e) and importing (C_i) countries along with their respective volumes from Bundesnetzagentur (2023). The base supply capacity from Russia is set to zero. We constructed the corresponding subsets of nodes, $V(c), \forall c \in C_e \cup C_i$, by taking all non-German nodes from the IEGGELGN dataset that are connected by an arc to at least one German node. We assume that, unlike the dynamic demand ($m_{c,t}$), supply capacities ($s_{c,t}$) of the relevant connected countries remain constant over the years and equal to the amount that was actually supplied in 2022. The t index exists in the supply parameter as we consider a change of supply capacity for a set of countries in the “Peace” scenario later in section 6.

5.4. Domestic production

The IGGIELGN dataset provides a set of nodes where natural gas is produced. We extracted the nodes on the German territory to account for domestic production. Each node is accompanied by a production capacity.

However, the capacities of the six nodes sum up to 3490 bcm per year according to the dataset. We rescaled the values to a realistic estimate assuming that the production sites were used up to their desired maximum capacity in 2022, to a total of 4.68 bcm ([Federal Statistical Office Germany, 2024](#)). We maintained the relative capacities between the production sites identical to that provided by the dataset.

5.5. Market prices

We used a constant price ($p_{c,t}$) for each country with a supply capacity, again, the t index exists as we consider a change of price in the “Peace” scenario later in section 6. To estimate the price at which each country supplies Germany, we separated them into three categories: those that sell regasified LNG, those that sell domestically produced natural gas, and those that only act as transit countries. Table 4 summarizes this classification.

We based the prices of the LNG category on the Total Transfer Facility (TTF) virtual trading point. We used the Henry Hub (HH) natural gas spot price for the Producers category, including Germany’s domestic production. To obtain the prices, we used average historical values available from January 2023 to September 2024, obtained from [ACER \(2023\)](#) and [EIA \(2023\)](#), for the TTF and HH indices, respectively. The price of LNG paid by Germany in its ports is equal to the “EU LNG spot price” also provided by [ACER \(2023\)](#), averaged over the same dates. We obtained a price for FSRU imports ($\hat{p}$) of 303 M€/bcm, a TTF price of 325 M€/bcm, and an HH price of 90 M€/bcm. For the last category, that of transit countries, we averaged the historical prices for the Austrian imports of 397 M€/bcm over the same period, as reported in [E-Control \(2024\)](#), and we assumed an identical price for the other countries in the same category.

Furthermore, we assumed that the real market prices would remain constant over time. As we do not consider alternative sources of energy, this only implies the weak assumption that the supply prices from different countries and LNG are strongly correlated. This is confirmed in [IEA \(2021\)](#), where the authors note a 0.81 correlation between HH and TTF prices, with an increasing trend. However, the respective mean levels of the two prices are different due to the higher number of market actors and transactions operating with the international HH price compared to the Continental European TTF price index. Although the higher volatility of the TTF index may temporarily change the arbitrage between the two indexes, the observation that the TTF index is bounded below by the HH index confirms the ordinal preference ranking of the two indices that is underlined in the model. Thus, temporal price changes are not likely to change the qualitative outcome of the model.

Table 4: Classification of countries exporting to Germany. The LNG category is that of countries that sell regasified LNG; Producers that sell domestically produced natural gas; and Transit that only act as transit countries.

LNG	Producers	Transit
Belgium, France, Netherlands, Switzerland	Denmark, Germany, Norway, Russia	Austria, Czechia, Poland

5.6. Graph construction

The set V of nodes that make up the network is the union of three sets: the sets of nodes with German NUTS2 identifiers ($V_i \cup V_d$) and the set of foreign nodes connected to a German node with an arc. The set E of arcs is the set of all arcs that connect any pair of nodes in V . However, the data provided by the IGGIELGN dataset does not immediately construct a usable graph due to missing pipelines, incorrect flow capacities, and some pipelines being incorrectly labeled as unidirectional. We address these issues as follows. First, missing pipelines create disconnected components in the graph due to some nodes not having any arc linking them to another node, or due to some subset of nodes being linked together but not to the rest of the graph. We identified such nodes with the Floyd-Warshall shortest path algorithm (Floyd, 1962) on an undirected version of the graph. The nodes were then grouped into subsets for which there exists a path from each member to every other member. We identified 10 groups of disconnected nodes for a total of 13 nodes. We manually added pipelines to reconnect each component to the main network to avoid removing important import corridors and industrial consumption nodes. Second, some nodes remain unattainable due to the incorrect directionalities of some pipelines, and therefore have no path from any gas import source on the directed graph. For each unattainable node u that we identified, all of its outgoing arcs were changed to be bidirectional. Finally, the pipeline capacities provided by the IGGIELGN dataset do not allow for a feasible solution. To fix this issue while manipulating the provided data as little as necessary, we relaxed the pipeline capacity by allowing the model to violate constraints (4), only for arcs with both endpoints in Germany. This is addressed with a two-step multiobjective lexicographic model, first minimizing the violation of the constraint, then minimizing the cost while ensuring that the violation is kept at most at 120% of the minimal level found in the first step. This ensures the feasibility of the model while minimizing the use of capacity relaxation. The 20% leeway in the capacity violation is there to ensure that the model is not restricted to a single optimal solution found at the first step.

Table 5: Summary of scenario-specific changes to the model and parameters.

Scenario	Demand	Port upgrades	Import capacities and prices of Russia and Transit countries
Greenfield DEG	DEG	Free	Base
Greenfield NZE	NZE	Free	Base
Greenfield LIN	LIN	Free	Base
Brownfield LIN	LIN	German plan	Base
No-FSRU	LIN	None	Base
RUS-UKR Peace	LIN	Free	Uncapacitated and HH priced in 2027

The resulting graph network has 674 nodes and 1047 arcs and can be visualized in Figure 4 on top of a German map colored by NUTS2 regions. The resulting spatial granularity is similar to that in Zwickl-Bernhard et al. (2024). The arcs highlighted in red are those that required a penalized capacity increase in our base scenario solving.

6. Results

In this Section, we analyze the policies obtained in six different scenarios. Three “Greenfield” scenarios, where the model is free to upgrade any candidate port, are analyzed in Section 6.1. Each uses one of three demand decrease predictions described in Section 5.2. A “Brownfield” scenario, in Section 6.2, where the model is forced to upgrade the ports in which Germany has already invested. Additionally, we investigate a “no-FSRU” scenario in Section 6.3 where Germany decides not to invest in FSRU port infrastructures; and a “Peace” scenario in Section 6.4 where we assume a resumption of trade with Russia in 2027, following a hypothetical end of the war. Finally, we strengthen our findings by presenting the results of a sensitivity analysis in Section 6.5. Table 5 summarizes the differences between each scenario.

All models converged in less than five minutes on a laptop computer using the open-source HiGHS solver (Huangfu and Hall, 2018). The source code to fully reproduce the results, tables and figures is available at <https://github.com/HenriDeh/FSRU.jl>.

6.1. Greenfield scenarios

The unrestricted greenfield scenarios aim to validate the actual FSRU import capacity expansion plan for Germany. The model invests for a total of 45 bcm of regasification capacity through FSRUs in the three scenarios. This is achieved by upgrading the same selection of eight ports. The exact plans obtained by the model are shown in the three upper plots of Figure 5.

Figure 4: Map of Germany, divided in NUTS2 regions, with the modelled gas transmission network. Arcs with an overcapacity relaxation are emphasized in red. Cropped-out nodes are import nodes.

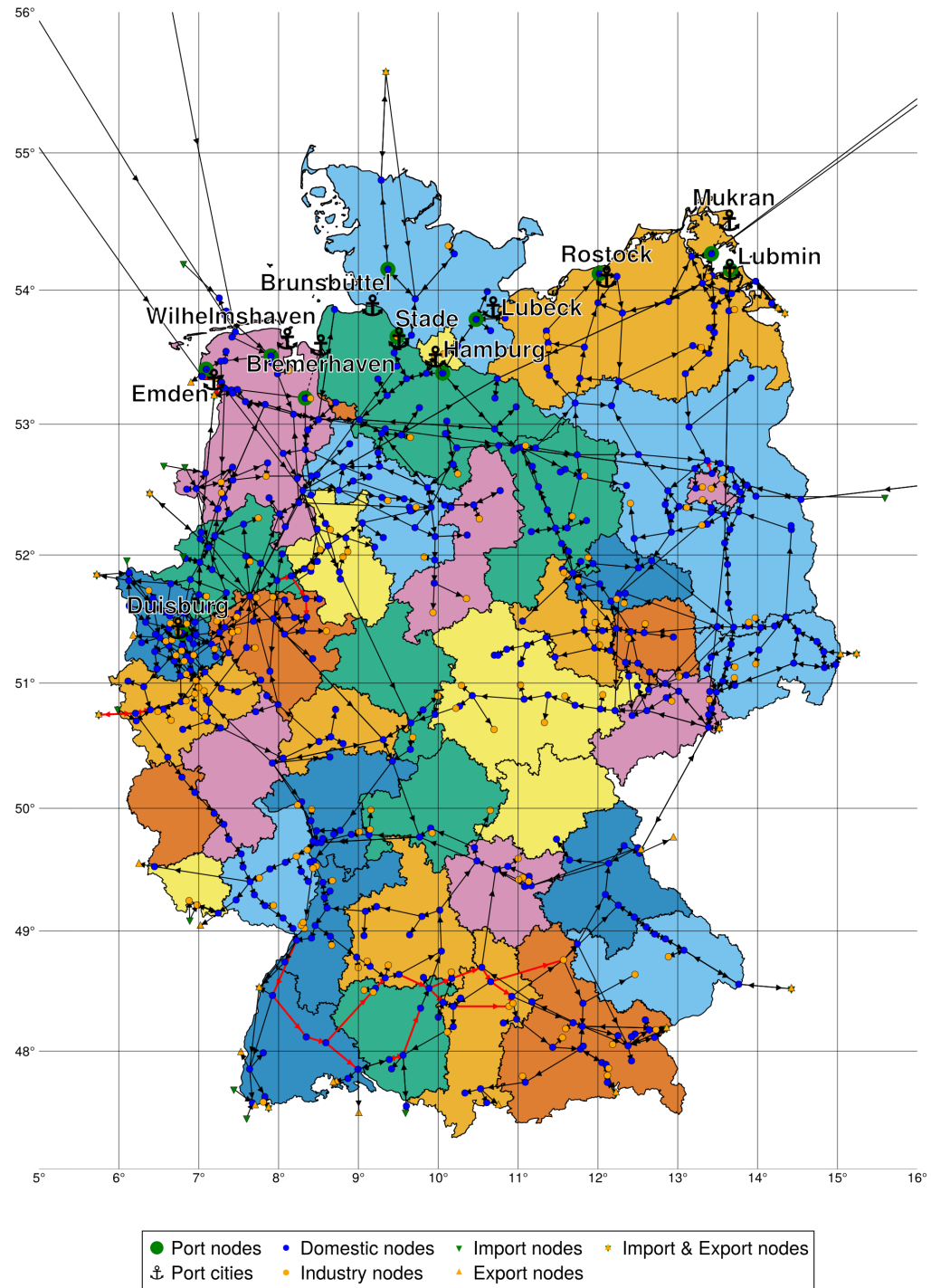


Figure 5: FSRU imports over time by port and scenario.

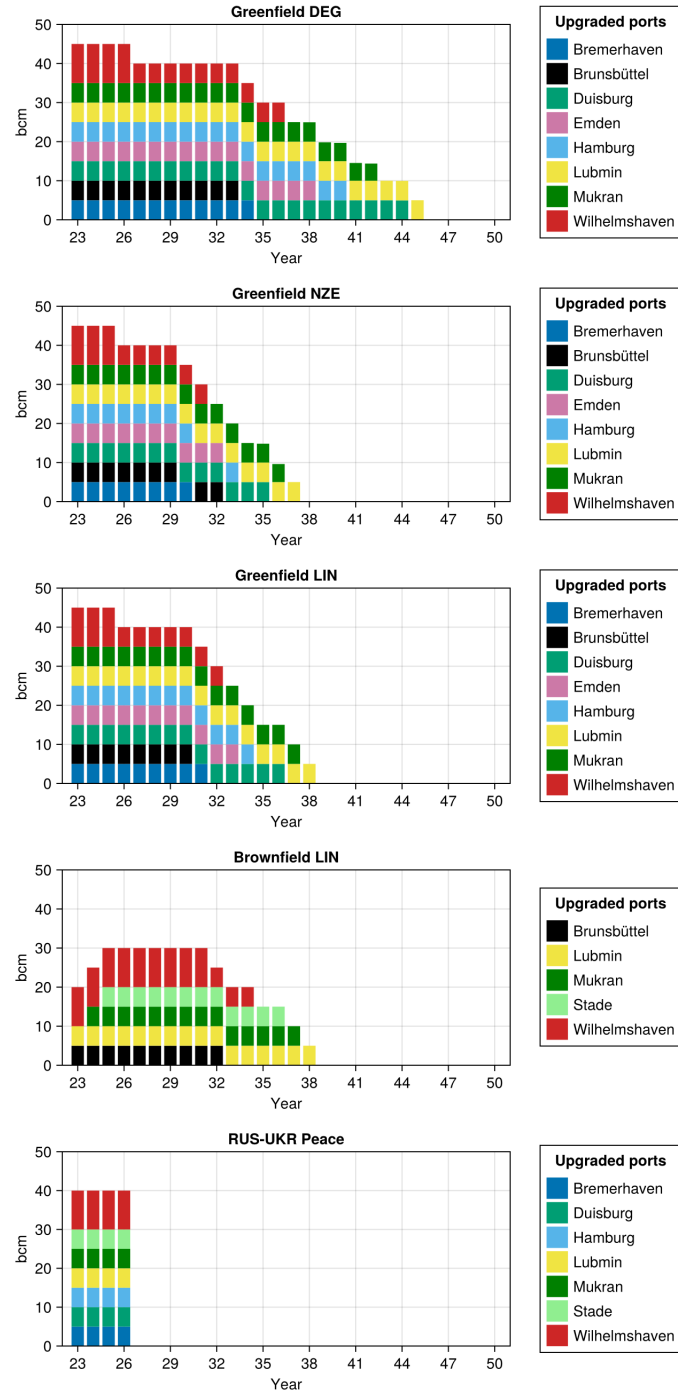


Figure 6: Pipeline import from connected countries over time for each scenario. Countries with a dotted supply line are that of the LNG category in Table 4. For clarity, the lines are rendered only where strictly positive.

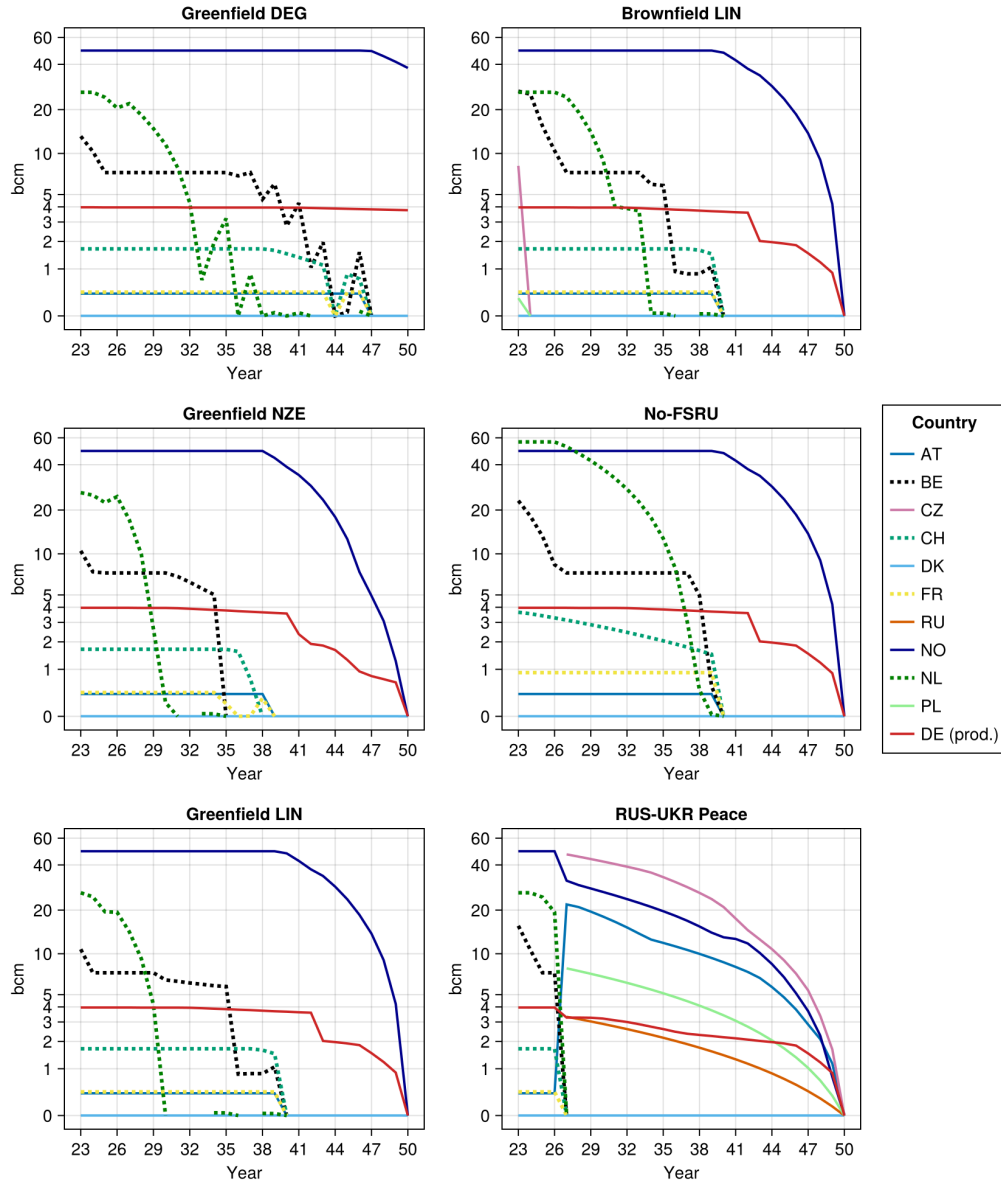


Table 6: Comparison between the optimal solutions of the scenarios. Capex includes pipeline construction costs. Pipeline gas import costs are divided between the source categories of Table 4 in addition to FSRU imports. All costs are nominal (undiscounted) over the 2023-2050 horizon.

Scenario		Total	Capex	Opex	FSRU imports	LNG imports	Producers imports	Transit imports	Domestic production
Greenfield DEG									
	M€	476,922	1,720	7,168	212,093	119,975	122,345	3,716	9,905
	bcm	2,541	-	-	698	368	1,355	9	110
Greenfield NZE									
	M€	322,723	1,720	4,607	136,494	79,374	90,712	2,478	7,338
	bcm	1,785	-	-	449	244	1,005	6	81
Greenfield LIN									
	M€	345,829	1,720	5,017	148,811	80,675	98,994	2,632	7,979
	bcm	1,929	-	-	490	248	1,097	7	88
Brownfield LIN									
	M€	346,931	1,110	3,722	110,848	118,285	98,994	5,993	7,979
	bcm	1,928	-	-	365	363	1,097	15	88
No-FSRU									
	M€	350,121	0	0	0	240,515	98,994	2,632	7,979
	bcm	1,930	-	-	0	738	1,097	7	88
RUS-UKR Peace									
	M€	243,015	1,512	1,633	48,592	47,361	50,883	86,693	6,340
	bcm	1,894	-	-	160	145	564	955	70

The three scenarios exhibit a short-term investment behavior: the installed capacity (5 bcm) becomes unused after only three to four years. After that, the use of FSRUs remains constant until 2029 (NZE), 2030 (LIN), or 2033 (DEG), where a progressive decommissioning begins. The port of Lubmin is the last to cease operations in 2037 and 2038 in the NZE and LIN scenarios, respectively. In the DEG scenario, the FSRUs remain in use significantly longer, with a cease-of-operations in 2047.

As can be seen in the three left plots in Figure 6, the logic followed by the solutions obtained in the flow model is to use import sources in increasing price order, beginning with the least expensive HH nodes, the FSRU ports, the import nodes indexed by TTF and finally the expensive *Transit* countries. The model avoids the expensive imports from Czechia and Poland altogether by increasing the FSRU regasification capacity higher than what is strictly necessary to satisfy the demand (which would be 20 bcm). These results indicate that in addition to being a source of supply security, the installation of FSRU terminals is also an economical choice in the context of onerous alternative sources. However, the model does not choose to upgrade all ports and is still based on supply from Austria and the countries in the LNG category (Table 4). This is because all port locations are concentrated in

the north of the country, meaning that pipeline capacities and the costs associated with longer transportation to the southern demand nodes (e.g., due to compression and leakage usage) are enough to justify purchasing from more expensive suppliers.

Unsurprisingly, all infrastructure investments are made in the first period, as the regasification capacity is the most needed when the demand is highest.

6.2. *Brownfield scenario*

In the brownfield scenario, we impose that the upgrading of the ports' infrastructures aligns with the actual plan of the German authorities, i.e., the upgrading of the ports of Lubmin, Brunsbüttel, and Wilhelmshaven in 2023, Mukran in 2024 and Stade in 2025. The model is not allowed to upgrade additional ports. The results are shown in Figures 5 and 6. As shown in Table 6, the total cost difference between this scenario and the *Greenfield LIN* scenario is minimal and mainly entails a different balance between FSRU imports and LNG imports. We note that the only new port selection compared to the Greenfield case is Stade. In the Greenfield scenario, Hamburg is instead selected, the difference is likely due to Hamburg sharing less pipeline capacity with Brunsbüttel, another port selected in all scenarios.

6.3. *No-FSRU scenario*

The No-FSRU scenario assumes that investments in regasification capacities are not considered by German authorities. Instead, to ensure feasibility in supply quantities, we suppose that such increases in regasification capacities will be made by neighboring LNG exporters (Belgium, France, the Netherlands and Switzerland). Specifically, the parameter $s_{c,t}$ for the four countries is increased by a volume equal to a share of the 63.43 bcm formerly delivered by Russia, before the war in Ukraine ([Bundesnetzagentur, 2023](#), averaged from January 1st to May 30th, 2022). This share is equal to the relative supply capacities of the countries in the base *Greenfield LIN* scenario. All other parameters are set to the values in the *Greenfield LIN* scenario.

Again, the total cost is not significantly higher than that in the *Greenfield LIN* scenario.

6.4. *Peace scenario*

The peace scenario assumes a resumption of trade with Russia following a peace agreement with Ukraine in 2027. This timing is purposely very optimistic. Further delaying this event would gradually converge this scenario towards the *Greenfield LIN* scenario. We modeled the resumption of trade by relaxing the supply capacity, $s_{c,t}$, of Russia and transit countries (namely

Austria, Czechia, and Poland) from 2027. These countries also see their selling prices set to the HH index from 2027 on. All other parameter values remain equal to that of the *Greenfield LIN* scenario. A renewed dependence on Russian gas would naturally reduce the total expenditure by 29% compared to the *Greenfield LIN*, using FSRU only for the initial period until 2026. As the scenario neither seems politically desirable nor environmentally compatible with the EU policy objectives, the calculations can be seen as a lower bound to the attainable cost for the gas supply until 2050.

6.5. Sensitivity analysis

To test the robustness of our policy results versus our data estimates, we performed a sensitivity analysis on several parameters. First, the most uncertain parameter is probably the price of imported gas from neighboring countries. We tested the sensitivity of our estimates by fixing the HH price and simultaneously changing the value of the LNG, TTF, and Austrian prices by equal relative changes. Second, our estimates of capex and opex costs are based on the 2017 article by [Songhurst](#). Although we corrected for inflation since 2017, the estimate does not account for several location-specific factors, as mentioned earlier. Thus, we test the sensitivity to the value of up_p (Equation 5.1). This also affects the opex by a small margin. Third, the lease cost of 46M€ per year we used is that of the agreement disclosed by Finnish authorities ([Reuters, 2022](#)). It is possible that the increased attractiveness of FSRUs due to the Ukrainian conflict resulted in an increase in charter rates since 2022. Finally, we tested the sensitivity to the discount rate (r) and to the number of annuities in the calculation of the capex parameter. For the latter, we only tested a change from 10 to 28 annuities (the horizon length).

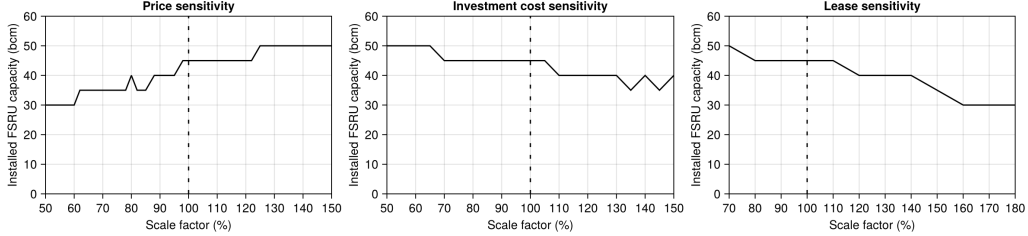
The sensitivity we tested is that of the total installed FSRU capacity, that is, how the value of

$$\sum_{p \in V_p, t \in T} U_{p,t} \times q_p \times 5$$

varies when changing parameter values by small increments. All tests were performed relative to the *Greenfield LIN* scenario. The results are shown in Figure 7.

The analysis reveals that a decrease of 5% in price, an increase of 10% in the investment cost, or 20% of the lease cost would result in a reduction of the optimal installed capacity by 5 bcm. This observation is not surprising considering that the last 5 bcm of capacity are only used for three years in the base scenario (see Figure 5). An increase of 60% of the lease cost or a reduction of 50% of prices is necessary to reach an optimal installed

Figure 7: Sensitivity of the optimal investment policy to four parameters. All horizontal axes are in percentages relative to the default values of the *Greenfield LIN* scenario (vertical dashed lines).



capacity equal to that of the *Brownfield LIN* scenario (30 bcm). We found no sensitivity to the discount rate (r) for values between 0.25% and 9.25%, nor to the number of annuities for the estimation of the capex. We note that the non-monotonicity of the sensitivity that can be observed at the 80% and 140% marks of the left and center plots of Figure 7 is due to the inability of the model to always converge to the optimal solution under the allowed five minutes of compute per iteration.

7. Comparison with actual planning in Germany

As a consequence of the war in Ukraine, the German government issued in March 2023 a report on the planning and capacities of the FSRUs and on-shore LNG terminals, (BMWK, 2023a). Prepared by the Federal Ministry for Economic Affairs and Climate Protection (BMWK) and based on a study of the Energy Economics Institute at the University of Cologne (EWI) (David et al., 2023), the report highlights the main milestones of the implementation process for regasification terminals in Germany. By 2025, five federal FSRUs (Wilhelmshaven I and II, Brunsbüttel, Stade, and Lubmin) should be operating all year round with a joint (nominal) regasification capacity of around 27 bcm/ year. To substitute the corresponding FSRUs, between 2026 and 2027, three onshore terminals (Stade, Brunsbüttel, and Wilhelmshaven) would be implemented to reach a total (nominal) regasification capacity of the system of 54 bcm/year, although the final investment decisions for these last three terminals were not made at the publishing date of the report. Currently, it seems that the Stade terminal will be the only one operational in 2027, as it is expected to receive the final investment decision (FID) before the end of 2024 (Global-LNG, 2024). Of the three terminals, Brunsbüttel and Stade are alleged to be prepared for later operation with hydrogen derivatives, whereas the onshore terminal at Wilhelmshaven would be designed as a green gas terminal for synthetic methane derived from green hydrogen. In February

2024, a terminal on the island of Mukran, close to Lubmin, planned for two FSRUs, started its operations with one FSRU (Energy, 2024). The second FSRU is scheduled to be transferred from Lubmin, where it is currently operating, to Mukran by the summer of 2024 (Energy, 2024). We note two critical differences in the assumptions in our model compared to the German government plans.

First, the demand scenario in BMWK (2023a) differs from both the one in our model and the background data in David et al. (2023). As can be observed in Figure 3, we consider an initial demand (2022) of 86.7 bcm versus 81.5 and 85.5 bcm in the BMWK and EWI studies, respectively. By 2030 the figures are 61.92, 74.1, and 58.2 bcm respectively, that is, the German government assumes a final demand that is 19.6 % to 27 % higher than the policy predictions and the EWI estimates. From 2030 on, we consider our model scenario decreasing linearly to reach zero demand in 2050 under the European policy objectives. The slow phase-out is in contradiction with the actual demand reactions in 2022/2023 to the supply reductions, as well as with the Green Deal projections.

Second, our brownfield model investment budget is estimated to be 4,832 M€ (capex + opex) compared to an initial budget of 6,560 M€ (later expanded to 9,800 M€ for the period 2022-28) in BMWK (2023a). This may be due to the stated hydrogen refitting, but given a lack of clear indications of the future infrastructure for hydrogen, it may also be a signal of overinvestment.

Third, a significant cause of the demand differences between our model and the public plans stems from the supply safety margin, planned to increase from 3,5 bcm in 2024 to 34,4 bcm in 2030. Hence, the German government effectively plans to increase the LNG import capacity radically to create energy autonomy in natural gas.

8. Conclusions and Policy Implications

The underpinnings of the ambitious European Green Deal (European Commission, 2019) and related policies resemble a dynamic game-theoretic problem with a common Pareto-optimal final equilibrium. By coordinating national energy policies for decarbonization of the economy, electrification of transport and heating, massive investments in renewable generation electricity and strengthening the cross-border infrastructure, Europe can achieve a quantum leap in terms of limiting climate change. However, on the path to 2050, each member state needs to ensure a socially and economically acceptable national trajectory to implement these objectives. The radical and unpredicted interruption of the natural gas supply for Europe is not only a

socio-economic challenge for the highly indebted continent after COVID-19, but also an acid test for the consistency of the common versus individual objectives, beyond the political boundaries. Initially, few believed that the European energy sector would be able to replace the shortfall with other sources and simultaneously dampen the price impact by resolute demand shocks using the price instruments.

We put ourselves in the position of the German government and solve the complex mathematical optimization to meet the national supply objectives, both with *ex ante* options open before the 2022 Ukraine war and the 2024 options after the initial investments, while keeping the common decarbonization objectives in 2050.

As an initial scenario, we model the Brownfield scenarios as the future path when taking the already decided investments in FSRU leases and port infrastructure for given. Our results for this scenario confirm the German decisions, both in terms of capacity (number of FSRUs) and locations (ports fitted with LNG terminals). Although short-term costs may seem excessive, the alternative costs resulting from curtailing industrial and commercial load and the social costs of price increases are surely even more discouraging and less politically manageable. One may therefore see the first scenario as a sign of confidence in the rationality and unprecedented rapidity of the decisions made to maintain the energy balance through legal, financial, and regulatory means.

To compare the Brownfield solutions, we calculate the investment trajectory under three unrestricted (Greenfield) scenarios to design the supply network, using the German government’s demand estimates (DEG) ([BMWK, 2023a](#)), the Net Zero Emission (NZE) study ([David et al., 2023](#)) and a linear reduction of demand (LIN). Whereas the latter two respect the Green Deal commitments for a phase-out in 2050, we extrapolate the DEG demand curve to a mere 50% reduction in the gas demand for 2050. Our results for the Greenfield scenarios LIN and NZE are similar and robust to a series of assumptions for cost and structural parameters. Both scenarios invest in eight ports and deploy FSRU until 2036 and 2037, gradually reducing the intensity from 2029 and 2030, respectively. The DEG scenario shows significant differences in terms of the depth of the FSRU deployment. However, the locations, capacities, and costs in the NZE and LIN models are close to those decided by the German government. The main differences result from a longer and more intensive use of FSRUs for LNG import to cover the large residual gas demand. Interestingly, even in a somewhat pessimistic DEG scenario, falling short of EU objectives, the existing infrastructure without FSRUs and Russian gas imports satisfies the forecasted gas demand by the end of the period.

Contrasting scenarios in the form of No-FSRU policy and a Peace scenario with resumed Russian low-cost import of pipeline gas provide additional information about the robustness of the policy. Without FSRUs, Germany would have to rely on three times as much LNG imports from neighboring states at a higher cost and lower supply security. A hypothetical reactivated gas import from Russia at HH prices from 2027 would bring economic advantages but with significant political and energy supply security risks. Our findings are confirmatory and positive to the extent that given equal demand assumptions, the German government’s Brownfield scenario and our Greenfield scenarios validate the same infrastructure investments in ports and similar FSRU deployment policies at almost the same cost (LIN) or at most 6% lower (NZE). Compared to earlier estimates for investments in port and gas infrastructure, the actual outcome of the Brownfield scenario shows that permits, construction, and commissioning are being carried out faster than expected. We note that the German authorities foresee a slower-than-projected phase-out of natural gas in the official projections and, consequently, an increased supply reserve capacity compared to the optimized scenario. Likely, the economic shocks to competitiveness and the socio-economic tensions that would result from the previously projected decarbonization of the German energy sector have gotten a second thought. So far, the idea of a common European energy policy and market is still a necessary, but not sufficient, condition for environmental and economic sustainable growth. Germany is no unique case in pursuing a radical LNG policy, other countries such as Spain, Greece, France, and Italy have increased their use of LNG terminals, invested in more infrastructure, or leased FSRUs. Potentially, the use of flexible resources such as FSRUs does enable redeployment to other countries and areas if the local demand reduction is stronger than the forecast, that is, closer to the European commitments.

8.1. Input on current policy discourse

Summarizing, the current policy discussion has expressed concern about four important economic and energy policy issues: (i) how much extra import capacity is needed to ensure supply security until 2050, (ii) what proportion of the future gas imports should be flexible (FSRU and/or LNG), (iii) for how long do we need the extra LNG import capacity, and finally, (iv) are the German government actions compatible with the European Green Deal? Our paper provides clear answers to all questions: (i) the capacity ramp-up will require the installation of eight ports for FSRU and LNG import as early as possible, with the associated minimal investments in gas infrastructure to connect the new ports, (ii) about 38% of the expected gas demand during the period 2023-2050 will be covered by flexible import from FSRUs and LNG

in regasification plants, decreasing over time, and (iii) the scale-down of the FSRU capacity is planned already from 2030 and fully dismantled in 2037. Indeed, (iv) the initiated decisions in port investments, FSRU deployment versus fixed regasification assets, and network reinforcements are close to the optimal decisions under the Green Deal demand trajectory.

8.2. Lessons for policy makers

The analysis of the initial narrative, the actual decisions made, and the model findings provide several insights for policymakers in the sector. First, in terms of crisis preparedness and mitigation, the actual response by the German government is an example of how a serious supply crisis can catalyze faster-than-expected permitting, construction, and commissioning of critical infrastructure. The strategic investments should be designed with built-in flexibility to respond rapidly to geopolitical disruptions without derailing long-term climate commitments. Second, while national energy security is paramount for individual member states, its pursuit must not overshadow broader decarbonization efforts. Policymakers should prioritize mechanisms that harmonize short-term national actions with collective EU objectives, ensuring that the Green Deal's long-term goals remain achievable. Our model findings (that were developed without connections to the German government) show general consistency between the investment profile and the Green Deal assumptions that we imposed. However, the official demand predictions and storage requirements signal a discrepancy between the European decarbonization objectives and the actual supply planning for Germany, an issue that merits attention in the future. Third, strategic investments under the European energy transition policy should already anticipate the future hydrogen infrastructure planning to avoid lock-ins and costly conversions of stranded prime-age assets. Here, the use of FSRU rather than stationary regasification facilities or gas pipeline investments to other transit countries or LNG ports is a flexible and pragmatic choice, considering the analysis limitations discussed below.

8.3. Limitations

Some caveats must be applied to extrapolate the findings. Our models are stylized in the sense that supply and demand are deterministic and linearly decreasing according to the policy objectives, although it is not likely to change the qualitative findings or the policy comparison. However, actual decisions may involve explicit or implicit risk analyses on supply, demand, or market developments resulting from national and European infrastructure choices. Although our sensitivity analyses for economic parameters such as capital, leasing and investment costs confirm the qualitative robustness of the

greenfield findings, the critical assumption in our calculations has been the 2050 phase-out of fossil fuels. The exact shape of the demand curve to this endpoint is not critical to the conclusions for the gas infrastructure, FSRU deployment would naturally adapt to the rate of change. The regasification dimensioning may also partially be explained by seasonality in demand, which is not considered in our model where annual demand is used and storage is assumed covering for seasonal differences. Another important limitation concerns the conversion of the gas transmission network for hydrogen transport. We do not model any refitting or expansion of the gas network for hydrogen use, locations or volumes. The German National Hydrogen Strategy [BMWK \(2020\)](#) hardly mentions the existing gas infrastructure, but later updates in [BMWK \(2023b\)](#) after the gas crisis outline the hydrogen core network, which is further detailed in the Hydrogen Acceleration Act [BMWK \(2024b\)](#). The current plans for the network foresee a network of 9,700 km to be ready by 2032, of around 5,800 km of refitted gas pipelines and 3,900 km of new installations, 15 interconnectors and generalized hydrogen import capacities for LNG ports. The Import Strategy for Hydrogen [BMWK \(2024a\)](#) explicitly supports the German government permitting for the port of Wilhelmshaven, mentioned also by investors in the case of port upgrades in Mukran and Lubmin. In addition, the national strategy also contains provisions for tendered investments in hydrogen-powered plants for electricity generation. The horizon impact of such plants is not clear, as the commissioning probably will involve a transition period using natural gas, given the very low worldwide production of hydrogen at the outset. In summary, the roll-out of the hydrogen core network could likely change the load, the geographical location of the load, and the transport capacity of the residual gas network, which may have an impact on the optimality of our solutions. Fundamental work is needed to formulate greenfield and brown-field models for hydrogen conversion of gas infrastructure in scenarios like the Green Deal with existing asset bases and sites. Future research on the cost of asset conversion and the optimal transition for fuel switching in Europe will be needed to fully answer these questions.

References

- Abrell, J., Chavaz, L., Weigt, H., 2016. Pathways for the european natural gas market, in: 2016 13th International Conference on the European Energy Market (EEM), pp. 1–6. doi:[10.1109/EEM.2016.7521360](https://doi.org/10.1109/EEM.2016.7521360).
- ACER, 2023. Acer price assessments. URL: https://aegis.acer.europa.eu/terminal/price_assessments.

- Agrell, P.J., Bogetoft, P., Gautier, A., 2024. Model Specification GAS, CEER Project TCB21. Technical Report. Sumicsid. URL: www.sumicsid.com.
- Agrell, P.J., Bogetoft, P., Gautier, A., Petrov, K., 2023. Note on Environmental Modelling, CEER Project TCB21. Technical Report. Sumicsid. URL: www.sumicsid.com.
- Ah-Voun, D., Chyong, C.K., Li, C., 2024. Europe's energy security: From russian dependence to renewable reliance. Energy Policy 184. doi:[10.1016/j.enpol.2023.113856](https://doi.org/10.1016/j.enpol.2023.113856).
- BMWK, 2020. The National Hydrogen Strategy. Technical Report. Bundesministerium für Wirtschaft und Klimaschutz. URL: <https://www.bmwk.de/Redaktion/EN/Publikationen/Energie/the-national-hydrogen-strategy.pdf>.
- BMWK, 2023a. Bericht des Bundeswirtschafts- und Klimaschutzministeriums zu Planungen und Kapazitäten der schwimmenden und festen Flüssigerdgasterminals. Technical Report. Bundesministerium für Wirtschaft und Klimaschutz. URL: <https://www.bmwk.de/Redaktion/DE/Pressemitteilungen/2023/03/20230303-bmwk-legt-bericht-zu-planungen-und-kapazitaeten-der-schwimmenden-und.html>.
- BMWK, 2023b. National Hydrogen Strategy: Update. Technical Report. Bundesministerium für Wirtschaft und Klimaschutz. URL: <https://www.bmwk.de/Redaktion/EN/Publikationen/Energie/national-hydrogen-strategy-update.pdf>.
- BMWK, 2024a. Import Strategy for hydrogen and hydrogen derivatives. Technical Report. Bundesministerium für Wirtschaft und Klimaschutz. URL: <https://www.bmwk.de/Redaktion/EN/Publikationen/Energie/importstrategy-hydrogen.pdf>.
- BMWK, 2024b. Wasserstoffbeschleunigungsgesetz. Technical Report. Bundesministerium für Wirtschaft und Klimaschutz. URL: <https://www.bmwk.de/Redaktion/DE/Downloads/W/wasserstoffbeschleunigungsgesetz.pdf>.
- Brauers, H., Braunger, I., Jewell, J., 2021. Liquefied natural gas expansion plans in Germany: The risk of gas lock-in under energy transitions. Energy Research and Social Science 76. URL: <https://doi.org/10.1016/j.erss.2021.102059>, doi:[10.1016/j.erss.2021.102059](https://doi.org/10.1016/j.erss.2021.102059).

- Bundesnetzagentur, 2023. Aktuelle Lage Gasversorgung - Gasimporte in GWh/Tag. URL: https://www.bundesnetzagentur.de/DE/Gasversorgung/aktuelle_gasversorgung/_svg/Gasimporte/Gasimporte.html?nn=1077982.
- Chyong, C.K., Henderson, J., 2024. Quantifying the economic value of russian gas in europe in the aftermath of the 2022 war in ukraine. *Energy* 292. doi:[10.1016/j.energy.2024.130604](https://doi.org/10.1016/j.energy.2024.130604).
- David, S., Max, G., Michael, M., Jan, K., Jakob, J., Hendrik, D., Meike, V., 2023. Analysis of the global gas markets until 2035. Technical Report. EWI, Institute of Energy Economics, University of Cologne. URL: <https://www.ewi.uni-koeln.de/en/publications/analysis-of-the-global-gas-markets-until-2035/>.
- Derse, O., Göçmen, E., Yılmaz, E., Erol, R., 2020. A mathematical programming model for facility location optimization of hydrogen production from renewable energy sources. *Energy Sources, Part A: Recovery, Utilization and Environmental Effects* 44, 6648–6659. URL: <https://www.tandfonline.com/doi/abs/10.1080/15567036.2020.1812769>, doi:[10.1080/15567036.2020.1812769](https://doi.org/10.1080/15567036.2020.1812769).
- Diettrich, J., Pluta, A., Medjroubi, W., 2021. SciGRID gas IGGIELGN Data Model of the European Gas Transport Network. Technical Report. Zenodo. URL: <https://zenodo.org/records/4767098>, doi:[10.5281/ZENODO.4767098](https://doi.org/10.5281/ZENODO.4767098).
- Durakovic, G., del Granado, P.C., Tomasgard, A., 2023. Are green and blue hydrogen competitive or complementary? Insights from a decarbonized European power system analysis. *Energy* 282, 128282. doi:[10.1016/J.ENERGY.2023.128282](https://doi.org/10.1016/J.ENERGY.2023.128282).
- E-Control, 2024. Entwicklung der großhandelspreise. URL: <https://www.e-control.at/industrie/gas/gaspreis/grosshandelspreise>.
- EConnect, 2024. FSRU Wilhelmshaven and EConnect have initiated installation of DET'S 2nd Terminal in Wilhelmshaven. URL: <https://www.econnectenergy.com/articles/fsru-wilhelmshaven-and-econnect-have-initiated-installation-of-dets-2nd-terminal>.
- EIA, 2023. Henry Hub Natural Gas Spot Price (Dollars per Million Btu). URL: <https://www.eia.gov/dnav/ng/hist/rngwhhdm.htm>.

- Emiliozzi, S., Ferriani, F., Gazzani, A., 2023. The European Energy Crisis and the Consequences for the Global Natural Gas Market. Bank of Italy Occasional paper URL: https://www.bancaditalia.it/pubblicazioni/qef/2023-0824/QEF_824_23.pdf, doi:10.2139/ssrn.4849472.
- Enerdata, 2023. Germany's gas consumption and imports declined in 2022 — Enerdata. URL: <https://www.enerdata.net/publications/daily-energy-news/germanys-gas-consumption-and-imports-declined-2022.html>.
- Energy, O., 2024. Germany's Mukran LNG terminal starts trial operations - Offshore Energy. URL: <https://www.offshore-energy.biz/germanys-mukran-lng-terminal-starts-trial-operations/>.
- ENTSO-G, 2024. The european network of transmission system operators for gas, members. URL: <https://www.entsog.eu/members>.
- Eser, P., Chokani, N., Abhari, R., 2019. Impact of Nord Stream 2 and LNG on gas trade and security of supply in the European gas network of 2030. Applied Energy 238, 816–830. doi:10.1016/J.APENERGY.2019.01.068.
- European Commission, 2019. Communication From the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. The European Green Deal. EUR-Lex , 1–43URL: <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2019%3A640%3AFIN>.
- European Commission, 2022. Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions. RE-PowerEU Plan. URL: <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2022%3A230%3AFIN&qid=1653033742483https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2022%3A230%3AFIN>.
- European Commission, 2023. Report from The Commission to The European Parliament, The Council, The European Economic and Social Committee and The Committee of the Regions. State of the Energy Union Report 2023. Technical Report. European Commission. URL: <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52023DC0650>.
- European Parliament, 2018. Regulation (EU) 2018/1999 of the European Parliament and of the Council of 11 December 2018 on the Governance of

- the Energy Union and Climate Action. URL: <https://eur-lex.europa.eu/eli/reg/2018/1999/oj>.
- Eurostat, 2023a. Population structure indicators by nuts 2 region. URL: https://ec.europa.eu/eurostat/databrowser/view/demo_r_pjanind2/default/table?lang=en.
- Eurostat, 2023b. Regional gross domestic product (pps per inhabitant) by nuts 2 regions. URL: https://ec.europa.eu/eurostat/databrowser/view/TGS00005/default/table?lang=en&category=na10.nama10.nama_10reg.nama_10r_gdp.
- Federal Statistical Office Germany, 2024. Gas production, network injection, own consumption, storage level: Germany. URL: <https://www-genesis.destatis.de/genesis/online?operation=abruftabelleBearbeiten&levelindex=2&levelid=1727270050497&auswahloperation=abruftabelleAuspraegungAuswaehlen&auswahlverzeichnis=ordnungsstruktur&auswahlziel=werteabruf&code=43321-0001&auswahltext=&werteabruf=Value+retrieval#abreadcrumb>.
- Floyd, R.W., 1962. Algorithm 97: Shortest path. Communications of the ACM 5, 345. URL: <https://dl.acm.org/doi/10.1145/367766.368168>, doi:10.1145/367766.368168.
- Global-LNG, 2024. Fid nears for german lng terminals. URL: <https://globallnghub.com/fid-nears-for-german-lng-terminals.html>.
- Gritz, A., Wolff, G., 2024. Gas and energy security in Germany and central and Eastern Europe. Energy Policy 184, 113885. URL: https://www.sciencedirect.com/science/article/pii/S0301421523004706?casa_token=EOXBvB8ygz0AAAAA:1b3FXeErk2ndIO2UCBemw7VemV2ymbJPiNXjPCWjC99Ni1S2lMfjf10Zl9B8UTUfB0p4sdA3cQhttp://linkinghub.elsevier.com/retrieve/pii/S0301421523004706, doi:10.1016/j.enpol.2023.113885.
- Gürsan, C., de Gooyert, V., 2021. The systemic impact of a transition fuel: Does natural gas help or hinder the energy transition? Renewable and Sustainable Energy Reviews 138. doi:10.1016/j.rser.2020.110552.
- Halser, C., Paraschiv, F., 2022. Pathways to Overcoming Natural Gas Dependency on Russia—The German Case. Energies 15. URL: <https://doi.org/10.3390/en15144939>, doi:10.3390/en15144939.

- Hamed, M., Zanjirani Farahani, R., Husseini, M.M., Esmaeilian, G.R., 2009. A distribution planning model for natural gas supply chain: A case study. *Energy Policy* 37, 799–812. doi:[10.1016/j.enpol.2008.10.030](https://doi.org/10.1016/j.enpol.2008.10.030).
- Heather, P., 2024. European Traded Gas Hubs: the markets have rebalanced. Technical Report. The Oxford Institute for Energy Studies. URL: <https://www.oxfordenergy.org/publications/european-traded-gas-hubs-the-markets-have-rebalanced/>.
- Huangfu, Q., Hall, J.A.J., 2018. Parallelizing the dual revised simplex method. *Math. Prog. Comp* 10, 119–142. URL: <https://doi.org/10.1007/s12532-017-0130-5>, doi:[10.1007/s12532-017-0130-5](https://doi.org/10.1007/s12532-017-0130-5).
- IEA, 2021. Gas market report Q1 2021. URL: <https://www.iea.org/reports/gas-market-report-q1-2021>.
- IEA, 2023. International Energy Agency. URL: <https://www.iea.org/data-and-statistics>.
- Jaller-Makarewicz, A.M., 2024. European LNG Tracker. URL: <https://ieefa.org/european-lng-tracker-september-2024-update>.
- Jirušek, M., 2022. Step Up or Perish: The EU’s Struggle With Russian Energy Imports and Its Role in the New Geopolitical Reality. *Russian Analytical Digest* 284, 5–8. URL: <https://www.ssoar.info/ssoar/handle/document/86981>, doi:[10.3929/ethz-b-000550755](https://doi.org/10.3929/ethz-b-000550755).
- Kędzierski, M., 2023. Germany: how the gas sector changed in the crisis year of 2022. URL: [www.osw.waw.plhttps://www.ceeol.com/search/gray-literature-detail?id=1163179](https://www.osw.waw.pl/en/publications/rad.html).
- Khatiwada, D., Vasudevan, R.A., Santos, B.H., 2022. Decarbonization of natural gas systems in the EU – Costs, barriers, and constraints of hydrogen production with a case study in Portugal. *Renewable and Sustainable Energy Reviews* 168, 112775. doi:[10.1016/j.rser.2022.112775](https://doi.org/10.1016/j.rser.2022.112775).
- Khoiriyah, L., Buda Artana, K., Dinariyana, A.A.B., Turbaningsih, O., Nur, W., Nisa, H., Mustakim, A., 2023. Conceptual design of floating storage and regasification unit (FSRU) for Eastern Part Indonesia. *IOP Conference Series: Earth and Environmental Science* 1239, 012015. URL: <https://iopscience.iop.org/article/10.1088/1755-1315/1239/1/012015>, doi:[10.1088/1755-1315/1239/1/012015](https://doi.org/10.1088/1755-1315/1239/1/012015).

- Kuzemko, C., Blondeel, M., Dupont, C., Brisbois, M.C., 2022. Russia's war on Ukraine, European energy policy responses & implications for sustainable transformations. doi:[10.1016/j.erss.2022.102842](https://doi.org/10.1016/j.erss.2022.102842).
- LNG Prime, 2024. German FSRU terminal operator offers regas capacity for first time - LNG Prime. URL: <https://lngprime.com/europe/german-fsru-terminal-operator-offers-regas-capacity-for-first-time/92348/>.
- Masudin, I., 2013. Facility Location Modeling in Multi-Echelon Distribution System: A Case Study of Indonesian Liquefied Petroleum Gas Supply Chain. Aceh International Journal of Science and Technology 2, 37–43. URL: <https://jurnal.usk.ac.id/AIJST/article/view/595>, doi:[10.13170/aijst.2.1.595](https://doi.org/10.13170/aijst.2.1.595).
- Melkote, S., Daskin, M.S., 2001. Capacitated facility location/network design problems. European Journal of Operational Research 129, 481–495. doi:[10.1016/S0377-2217\(99\)00464-6](https://doi.org/10.1016/S0377-2217(99)00464-6).
- Molnar, G., 2022. Economics of gas transportation by pipeline and LNG, in: The Palgrave handbook of international energy economics. Springer International Publishing Cham, pp. 23–57.
- Overland, I., 2022. Russia's invasion of Ukraine: Consequences for global decarbonization. Russian Analytical Digest 284, 2–5. URL: <https://www.ssoar.info/ssoar/handle/document/86980https://doi.org/10.3929/ethz-b-000550755>.
- Pluta, A., Medjroubi, W., Diettrich, J.C., Dasenbrock, J., Tetens, H.P., Sandoval, J.E., Lunsdorf, O., 2022. Data Model of the European Gas Transport Network, in: 2022 Open Source Modelling and Simulation of Energy Systems (OSMSES), Institute of Electrical and Electronics Engineers Inc.. pp. 1–7. doi:[10.1109/OSMSES54027.2022.9769122](https://doi.org/10.1109/OSMSES54027.2022.9769122).
- Reuters, 2022. Finland leases floating lng terminal for 10 years to break free from russian gas. URL: <https://www.reuters.com/business/finland-agrees-10-year-charter-fsru-us-firm-excelerate-2022-05-20/>.
- Riepin, I., Schmidt, M., Baringo, L., Müsgens, F., 2022. Adaptive robust optimization for European strategic gas infrastructure planning. Applied Energy 324, 119686. doi:[10.1016/j.apenergy.2022.119686](https://doi.org/10.1016/j.apenergy.2022.119686).

- Ríos-Mercado, R.Z., Borraz-Sánchez, C., 2015. Optimization problems in natural gas transportation systems: A state-of-the-art review. *Applied Energy* 147, 536–555. doi:[10.1016/J.APENERGY.2015.03.017](https://doi.org/10.1016/J.APENERGY.2015.03.017).
- Sarker, B.R., Wu, B., Paudel, K.P., 2022. Optimal Location for Renewable Gas Production and Distribution Facilities: Resource Planning and Management. *Bioenergy Research* 15, 650–666. doi:[10.1007/s12155-021-10278-0](https://doi.org/10.1007/s12155-021-10278-0).
- Sesini, M., Giarola, S., Hawkes, A.D., 2020. The impact of liquefied natural gas and storage on the EU natural gas infrastructure resilience. *Energy* 209. URL: <https://doi.org/10.1016/j.energy.2020.118367>, doi:[10.1016/j.energy.2020.118367](https://doi.org/10.1016/j.energy.2020.118367).
- Songhurst, B., 2017. The outlook for floating storage and regasification units (FSRUs). *Oxford Institute for Energy Studies* 12, 1–54. URL: <https://www.oxfordenergy.org/publications/outlook-floating-storage-regasification-units-fsrus/>.
- Sumicsid, 2019. Norm Grid Development, revision V1.3, CEER Project TCB18. Technical Report. Sumicsid. doi:[10.13140/RG.2.2.19134.09289](https://doi.org/10.13140/RG.2.2.19134.09289).
- Zwickl-Bernhard, S., Rodgarkia-Dara, A., Gatzen, C., Sonnen, L., Lane, A., Otti, M., Golab, A., Auer, H., 2024. Modeling insights from the Austrian national gas grid under declining natural gas demand and increasing domestic renewable gas generation by 2040. *Energy Reports* 11, 1302–1317. doi:[10.1016/J.EGYR.2023.12.064](https://doi.org/10.1016/J.EGYR.2023.12.064).

Appendix

8.4. Summary of sources

Table 7: Summary of sources used for parameter estimation.

Symbol	Parameter	Sources
V and its subsets	Nodes	Diettrich et al. (2021) ; Pluta et al. (2022)
E	Arcs	Diettrich et al. (2021) ; Pluta et al. (2022)
C and its subsets	Countries	Diettrich et al. (2021) ; Pluta et al. (2022)
b_p	Pipeline construction cost	Khoiriyah et al. (2023) ; Sumicsid (2019)
capex_p	Net Present Value of capital expenditures	Songhurst (2017)
$d_{n,t}$	Nodal demand	Enerdata (2023) ; Pluta et al. (2022) ; Eurostat (2023a) ; Eurostat (2023b) ; BMWK (2023a) ; David et al. (2023)
h_n	Domestic production capacity	Diettrich et al. (2021) ; Pluta et al. (2022) ; Federal Statistical Office Germany (2024)
k_e	Flow capacity in pipeline	Diettrich et al. (2021) ; Pluta et al. (2022)
l_e	Losses and compression gas usage	Abrell et al. (2016) ; Molnar (2022)
$m_{c,t}$	Import demand	Bundesnetzagentur (2023)
opex_p	Operational expenditures per FSRU	Songhurst (2017) ; Reuters (2022)
$p_{c,t}$	Prices of exports	ACER (2023) ; EIA (2023) ; E-Control (2024)
$\hat{p}$	Price of LNG imported via FSRU	ACER (2023)
q_p	Berthing capacity	(ECONnect, 2024)
s_c	Export capacity	Bundesnetzagentur (2023)
w_f	Processing capacity of FSRUs	(LNG Prime, 2024)
r	Yearly discount factor	Agrell et al. (2024) .