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Liquefied natural gas expansion plans in Germany: The risk of gas lock-in under energy transitions

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ABSTRACT

The German energy transition has been hailed as a role model for climate action. However, plans for the construction of three large-scale Liquefied Natural Gas (LNG) import terminals are receiving strong state support. This is inconsistent with Germany's climate targets, which require a reduction rather than expansion of natural gas consumption. In our paper, we aim to unpack the connection between the risk of natural gas lock-in and the energy transition. We analyse the co-evolution of the techno-economic, socio-technical and political realms of the German natural gas sector and influence of actors within that process. We use a combination of energy system and interview data, and introduce a new approach to triangulate material and actor analysis. We show that four natural gas lock-in mechanisms cause the support for LNG in Germany: (A) the geopolitical influence from the United States, combined with (B) security of supply concerns due to the planned coal and nuclear phase-out, (C) pressure from a wide variety of state and private sector actors, and (D) sunk investments in existing gas infrastructure. Two additional mechanisms supporting the strong position of natural gas are (E) the strength of the emerging synthetic gas niche, and (F) weak opposition against LNG and natural gas. We highlight the severely overlooked lock-in potential and related emissions, which could complicate and decelerate energy transitions as more countries reach a more advanced phase of the energy transition.

1. Introduction

Natural gas use is the most rapidly growing among all fossil fuels, and was responsible for about 35% of growth in global CO_2 emissions since 2009 [1]. While some present natural gas as a 'bridge technology' [2,3],[2] others argue that this is an ambiguous narrative to influence expectations and visions regarding natural gas [6]. In fact, using natural gas as a substitute for coal can lead to negative climate consequences due to so far underestimated life cycle emissions [7-10] and a delay of a climate neutral energy system [11]. Here, we highlight a third risk of natural gas as a bridge fuel: locking-in large-scale carbon-intensive infrastructure, which could undermine long-term climate goals.

The current rise in natural gas use is also reflected in the dawn of new infrastructure for trading Liquefied Natural Gas (LNG): Global LNG export infrastructure grew to 442 million tons per annum (MTPA) in May 2020, and LNG import infrastructure currently stands at 844 MTPA [12].[3] This compares to an LNG trade of 355 MT in 2019 [13], an increase of ~45% compared to 2015 [14].[4] The existing oversupply on the global market – especially due to new supplies from Australia, the United States and Russia – has led suppliers to search for new export possibilities, and Europe is becoming an attractive import market for LNG, as today's low LNG prices converge to the continent's pipeline

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[2] They mostly base this assumption on the fact that natural gas can emit up to 60% less CO_2 emissions compared to coal, when one accounts only for the burning process [4]. However, when accounting for life cycle emissions the outcome is less positive [5].

[3] Another 122 MTPA of export capacities and 144 MTPA of import capacities are currently under construction [12].

[4] Shipping natural gas as LNG additionally increases the greenhouse gas footprint, due to cooling and pressurising.

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prices.

We thus examine the growing tension between the expansion of LNG infrastructure and climate protection goals. We use Germany as an ideal case to examine this tension because the country is widely recognised as a climate leader with impressive progress in its energy transition and ambitious decarbonisation plans while at the same time offering strong state support to three new LNG terminals (Table 1). We also believe that Germany is a particularly instructive case for a challenge, which other states may face as they enter the 'next phase' of the energy transition – when renewables reach a larger share of the electricity sector and the decline of existing technologies begins [15]. Like many other states, Germany has pledged to phase-out coal[5], and additionally nuclear energy, but the pathway of the remaining energy transition to reach its emission reductions target is still unclear.

In our paper, we answer the following research questions: How do the material conditions around natural gas consumption and LNG infrastructure relate to and interact with actors' perceptions of these conditions? And how do these interactions shape systemic changes and create lock-ins for the German energy transition?

We do this by analysing the co-evolution of key energy technologies and markets, the related socio-technical system and the political system, and analyse how actors' perceptions shape and are shaped by each of these realms. Our methodological innovation is the further development of a meta-theoretical framework on energy transitions [16] (see Section 4). More specifically, we use the meta-theoretical framework [16] as a map to identify relevant questions and actors to probe through a series of interviews and workshops.

As a result, we are able to identify the role of structural developments regarding the energy market as well as the role of actors and their interests and perceptions in the respective decision-making process. We show that (A) support for the planned LNG terminals in Germany arises from geopolitical influence from the US, combined with (B) concerns over security of supply mainly due to the coal phase-out and reliance on Russian natural gas imports, (C) pressure from a wide variety of actors benefiting from high levels of natural gas consumption, (D) sunk investments in existing gas infrastructure, (E) the support of the arising synthetic gas niche, as well as (F) a weak opposition against LNG and natural gas in general. These findings are particularly relevant for other EU countries phasing-out coal, which may face similar concerns and pressure and may also consider natural gas as a bridge fuel within the energy transition.

2. Case description

Fig. 1 depicts all existing and planned LNG terminals in the EU. As of January 2021, there were three potential locations for large-scale LNG terminals in Germany.[6] All locations are in the North of the country: Brunsbüttel in the state of Schleswig-Holstein, and Wilhelmshaven and Stade in Lower Saxony. Together the three terminals would account for ~ 30 billion cubic meters (bcm) of natural gas (Table 1). Jointly, they represent the case of LNG in Germany, which we analyse in this paper.

None of the projects have a final investment decision or construction permit. Proposals for the terminal in Wilhelmshaven have been made and withdrawn repeatedly since the 1970s. The approval for a land-based terminal was granted in 2007. However, the plan changed to build a Floating Storage Regasification Unit (FSRU), for which no approval exists (as of February 2021). The consortium to build the Brunsbüttel terminal – German LNG Terminal – was founded in 2018, and the terminal in Stade was announced the same year. All of the terminals are supposed to be connected to the existing natural gas grid, which requires the construction of connecting pipelines, resulting in further major investment costs (see Table 1 and Section 6).

Schleswig-Holstein's and Lower Saxony's licencing authorities decide on the permits for the respective terminals. Those scoping, regional planning as well as zoning procedures[7] – including e.g. the environmental impact assessment – typically take several years from the initial proposal to the approval, procedural handling, construction, and commissioning. The responsible agencies differ depending on the federal states and are subordinate to different federal state ministries.[8] In the official approval processes, anyone can submit a position statement, voicing support or criticism. The respective offices of the state governments are also subject to lobbying efforts, making the political level as important as the planning and economic level.

Approval needs to be granted both for the terminals themselves and the respective connecting pipelines. Generally, the agencies responsible for the approval processes are only dependent on the existing law. However, included information in the processes depend also on the position of the federal state governments and the respective ministries, where especially Lower Saxony is very supportive of LNG, founding its own LNG agency.[9]

Responsible for the financing of the terminals are the respective private companies. However, the respective state governments of Lower Saxony and Schleswig-Holstein actively support the projects by including them in their coalition agreements[10] and by providing funding, in addition to support by the national government. The Joint Task for the Improvement of Regional Economic Structures (GRW) promised funds for the Brunsbüttel and Wilhelmshaven sites. The state of Schleswig-Holstein had already earmarked €50 million for the Brunsbüttel LNG terminal in its 2020 budget. As these are GRW funds[11], the federal government would match the €50 million budget, as part of complementary financing, in the event of a final allocation. In addition, funding opportunities for alternative fuel infrastructure exist as part of the national mobility and fuel strategy, and according to the national government, construction cost subsidies for the development of an LNG port infrastructure are to be provided as well. Lastly, a letter from finance minister Scholz in August 2020 promised €1 billion in German subsidies for the Wilhelmshaven and Brunsbüttel terminals, if the US would "allow for the unhindered construction and operation of Nord Stream 2".[12]

Nevertheless, the investment decisions of the LNG project companies have been delayed for some time. In November 2020, Uniper announced that it would review its plans to build an LNG terminal in Wilhelmshaven, after not receiving enough binding capacity bookings from

[5] Clean Energy Wire, Spelling out the coal exit – Germany's phase-out plan (2020). https://t1p.de/lq0v.

[6] One additional small-scale terminal has been proposed in Rostock (also in a Northern state of Germany - Mecklenburg-Western Pomerania). As the Rostock terminal is much smaller in scale than the other three terminals, and it would not become connected to the gas grid in case of construction, we exclude it from the further analysis.

[7] In German "Raumordnungsverfahren" and "Planfeststellungsverfahren".

[8] See e.g. Schleswig Holstein Ministerium für Wirtschaft, Verkehr, Arbeit, Technologie und Tourismus, German LNG-Terminal in Brunsbüttel. Unterrichtung gemäß § 15 UVPG über den Untersuchungsrahmen (2019) https://t1p.de/xmdg; Ministerium für Wirtschaft, Verkehr, Arbeit, Technologie und Tourismus Amt für Planfeststellung Verkehr, German LNG-Terminal Brunsbüttel – Beginn Planfeststellungsverfahren (2020). https://t1p.de/o3ks; Landesbüro Naturschutz Niedersachsen GbR, Beteiligung in Umweltfragen (2021). https://umwelt-beteiligung-niedersachsen.de/faq-page#n16; LabüN Gbr (2019). https://t1p.de/h1gk.

[9] LNG Agentur Niedersachsen, LNG-Entwicklung an der niedersächsischen Nordsee (2020) https://t1p.de/jszx.

[10] Coalition agreements from 2017 in Lower-Saxony https://t1p.de/9xex and Schleswig-Holstein https://t1p.de/4202.

[11] For an explanation of this concept of Regional Development Policy in Germany see OECD, Regional Development Policy in Germany (2019). https://www.oecd.org/cfe/_Germany.pdf.

[12] Federal Ministry of Finance, Non Paper Germany Nord Stream 2/U.S. LNG (2020). https://t1p.de/s7cq.

Table 1
Short profile of planned large-scale import LNG terminals in Germany.

	Wilhelmshaven Lower Saxony	**Brunsbüttel** Schleswig-Holstein	**Stade** Lower Saxony
Operators/ Investors	uniper; MOL Mitsui O.S.K. Lines	German LNG Terminal; Gasunie; Vopak; Oiltanking	Dow; Hanseatic Energy Hub; HEC 中国港湾工程有限责任公司; Macquarie
Storage capacity	263,000 cm	480,000 cm	480,000 cm
Annual capacity	10 bcm (incl. FSRU)	8 bcm	4-12 bcm
Connection to grid	Yes	Yes	Yes
Investment costs	~ €1.5 billion (shore-side terminal) ~ €130 million (FSRU)	~€500 million	~€850 million
Construction/ operating costs of connecting pipeline	~ €86 million for connecting pipeline and ~ €690,000 for annual operating costs	~ €87 million for connecting pipeline and ~ €700,000 for annual operating costs	~ €31 million for connecting pipeline and ~ €245,000 for annual operating costs
Status (January 2021)	• No permit for construction for FSRU • No final investment decision (FID)	• No permit for construction • No FID	• No permit for construction • No FID

Sources: [17–32].
Note: An FSRU is a Floating Storage Regasification Unit.

market participants in the pre-tender process. German LNG Terminal, the investor for the terminal in Brunsbüttel, already had to ask for an extension until June 2022 for the final investment decision. The project in Stade plans to take the investment decision in 2021 and to commission the LNG terminal by 2026.

The LNG terminal in Wilhelmshaven is meant to create around ~50–60 long-term jobs.[13] The terminal in Brunsbüttel is expected to create ~70 long-term employees directly by the terminal, and ~1000 for the construction time of around three years.[14] More generally, in Brunsbüttel the operators of the terminals suggest that the local constituencies can expect a durable increase in employment, regional value added and taxes.[15]

3. Theoretical approach

Here, we consider LNG terminals as part of the energy transition in Germany. Energy transitions are long-term structural changes of energy systems [33], which evolve along specific pathways [34]. As such, they exhibit path-dependence, or inertia to large-scale change. The entrenchment of existing systems, which underpin the fossil-fuel intensive energy system, is commonly referred to as 'carbon lock-in' [35]. Unpacking the connection between lock-in and the energy transition is key to understanding what has been called the 'next phase of the energy transition' [15]: This next phase begins when the growth of new technologies accelerates to an extent that challenges established technologies, business models, practices and actors. Here, the key question is no longer concerned with understanding the emergence of new technologies but understanding the inertia of a system – a lock-in.

In order to disentangle this connection, we follow a meta-theoretical framework [16,36], which conceptualises energy transitions as unfolding in three autonomous but co-evolving systems: a) policy system (composed of political actions and policies), b) techno-economic system (composed of energy flows and markets), and c) socio-technical system (composed of energy technologies and artefacts, businesses and practices).[16] The development and interaction of each of the three systems – or realms as we refer to them as of now in this paper – can explain the course of energy transitions. With reference to Elinor Ostrom's research [43], all three realms are described as semi-autonomous with e.g. their own elements, boundaries and dynamics. While all three realms can develop independently of each other, they also interact, and hence co-evolve. The framework makes it possible to identify mechanisms affecting one or several of the three realms, explaining course of change – or lock-in. These dynamics are shaped by both *material realities* and *actor perceptions* [16],[17] with lock-in playing a distinct role in each of these realms.

We consider all three co-evolving realms and their developments as well as the international context to explain the political support for the construction of LNG terminals in Germany and explore whether this fosters lock-in during the next phase of the energy transition (see Table 2):

a) Political realm: The political realm covers how policies shape the

[13] GRÜNE Wilhelmshaven, Positionspapier zum LNG-Terminal in Wilhelmshaven (2021). https://t1p.de/rz45.

[14] CPL Competence in Ports and Logistics GmbH, Regionalökonomische Effekte eines LNG-Terminals (2019). https://t1p.de/kd17. For Stade, no explicit numbers of expected jobs were available to us.

[15] Ibid.

[16] Various other frameworks have been developed within the transition research community to explain energy transitions and to identify relevant variables, most prominently [37,38]: transition management [39], strategic niche management [40], the multi-level perspective [41], and technological innovation systems [42]. Rooted in evolutionary economics and Science and Technology Studies (STS), all these frameworks share the concepts of a socio-technical system, a socio-technical regime as well as a niche and thus primarily can explain the development of the socio-technical system. In contrast, the approach we use here [16] can account for important political economy aspects shaping energy transitions, such as how techno-economic developments shape and constrain choices, and how the policy system co-evolves with the socio-technical system.

[17] By material realities we mean the concrete challenges and constraints energy policies face, such as meeting rising energy demand with secure supply [44], technology availability as well as existing regulations, whereas by perceptions we mean how these realities are seen.

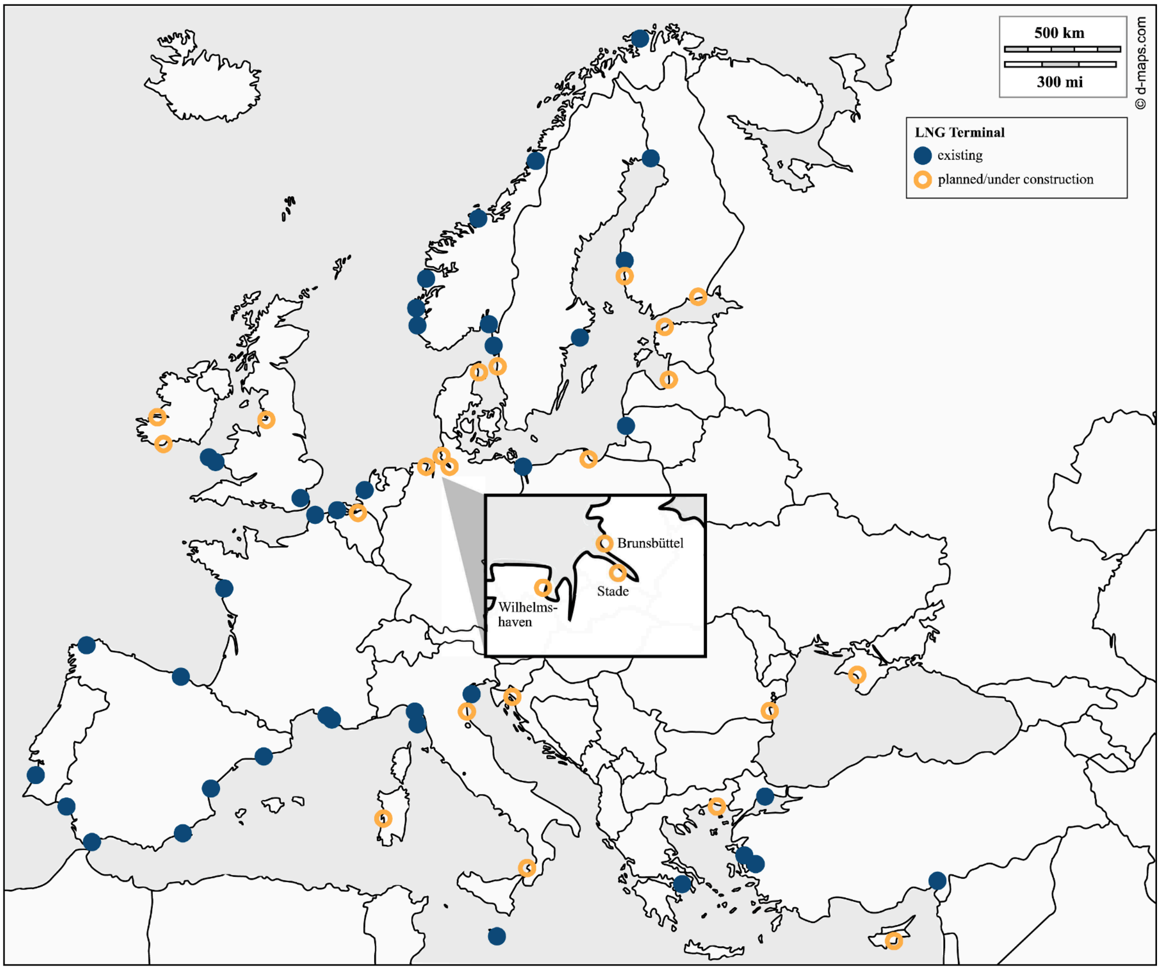

Fig. 1. Existing and planned LNG terminals in Germany and the EU. Source: Authors' illustration based on d-maps and the Global Energy Monitor. (d-maps, Map Europe (2021), https://d-maps.com/carte.php?num_car=2233&lang=en and Global Energy Monitor, Europe Gas Tracker (2021), https://globalenergymonitor.org/projects/europe-gas-tracker/tracker-map/.)

Table 2
Systemic focus, key concepts and role of lock-in in each realm.

Realm	Systemic focus (based on [16])	Key concepts for the next phase of the energy transition	The role of lock-in in this realm (developed from [35])
Political realm	Policy systems – political actions and energy policies	State balancing supply and demand and competing interests	Institutional lock-in, particularly vested interests, and discursive lock-in, particularly from incumbents
Techno-economic realm	Energy flows and markets	Managing stable energy provision and transition of a larger portion of the energy system to low-carbon	Infrastructural and technological lock-in, particularly stranded assets
Socio-technical realm	Energy technologies and artefacts, businesses and practices embedded in socio-technical systems	Understanding regime resilience particularly amidst increased pressure from new(ish) entrants	Behavioural lock-in, or the continuation of suboptimal technology use, regime resistance in the form of combined instrumental, discursive, material and institutional forms of power

energy system and how special interests shape policies [36]. Thus, the focus is on policy systems – encompassing political actions and energy policies. Most relevant to the next phase of the energy transition is how the state, as an actor, navigates the supply–demand balance [44], particularly in the face of growing variable renewable sources. Also of interest is how different interests are mediated by political processes and institutions [45,46]. We understand institutions as formal and informal structures, which shape society (e.g. policies, standards, rules, values) [38].

Thus, the political realm is characterised by what Seto et al. [35] refer to as *institutional lock-in*, whereby various interests and actors benefit from the status quo. Institutional lock-in exists as institutions strongly discourage and impede change once they are established, and institutions get defended by (a powerful network of) beneficiaries [47]. To what extent policy-makers are able to break the lock-in may be to a large extent mediated by the state's overall capacity to balance diffuse with concentrated interests [48,49]. The agency of actors can determine the direction and extent of institutional change [50]. Additionally, we include *discursive lock-in* in our analysis of the political realm: "A discourse assigns meaning, defines power relations and creates subjects and objects through practices. A discourse is always in competition with other discourses and is struggling for its reproduction (by practices) and for dominance in a field" [51]. Therefore, dominant discourses in the political realm can constitute and justify technologies, institutions and behaviours [51], and deserve particular attention in understanding energy transitions (see also [52,53]). Here, the discursive debate with regards to gas [54] is mainly about whether it perpetuates carbon lock-in or creates a bridge to low-carbon sources.

b) Techno-economic realm: The techno-economic realm covers energy flows and markets [16]. Most relevant to the next phase of the energy transition is how to manage base load demand and how to transition a larger portion of the energy system to low-carbon, mostly variable electricity sources. Here, the focus is on the infrastructure itself and quantifying the value investors lose under different climate policies [55]. Stranded assets – either unpaid capital costs or lost profits due to climate policies – is thus a concept closely related to lock-in, known in the framework of Seto et al. [35] as *infrastructural and technological lock-in*. The theory is that the investment in a given infrastructure leads to increased inertia and lock-in to preserve the profits from that infrastructure [56–58]. The infrastructure lock-in consists of a lock-in directly by existing infrastructure emitting GHGs (e.g. power plants), supporting infrastructure (such as pipelines or LNG terminals), and built infrastructures of human societies (e.g. gas heating in homes) [51,59–61].

c) Socio-technical realm: The socio-technical realm covers the emergence and diffusion of new technologies as well as their struggle with existing ones. In the socio-technical realm, the systemic focus is on energy technologies, artefacts, businesses and practices embedded in socio-technical systems. Most relevant to the next phase of the energy transition using socio-technical transition analysis [62–64] is to understand regime resilience [41,65], particularly amidst growing pressure from new(ish) entrants. This connects to what Seto et al. [35] call *behavioural lock-in,* which is the continuation of current practices through individual decisions and choices, influenced also by social norms and cultural values. However, behavioural lock-in is a much less mature scientific concept than institutional lock-in or infrastructure lock-in [66]. Behavioural lock-in could be gauged by the technology-specific strength and pervasiveness of consumer habits [67].

One form of a lock-in in the socio-technical realm has previously been termed *regime resistance* [68]. Regime resistance combines instrumental, discursive, material and institutional forms of power. Instrumental forms of power thereby refer to strategies of actors using their resources and cooperation with others to fulfil their interests. Discursive strategies aim to shape which and how issues are publicly and politically discussed. Material strategies target the technical dimension and focus especially on technical capabilities and financial resources, e.g. to attract further funding or to prevent regulation. The broader institutional power of actors is embedded in political cultures, ideology and governance structures, and this context can support regime resistance [68]. The deployment of such structural power depends on how interests and ideas are promoted and used and how they rely on institutional opportunities [69].

One key theoretical question is how these relatively autonomous realms interact. Policies, artefacts and actors all connect and influence the three realms (grey boxes in Fig. 2). A policy, such as a feed-in-tariff, is born out of a given political climate in the political realm, changes the profitability of different generation sources in the energy realm, and empowers a niche in the socio-technical realm. An artefact, such as a new technology can make certain pathways possible in the techno-economic realm but may also destabilise a regime in the socio-technical realm. Here, we focus on how key actors walk across realms, play different roles in different realms and thus facilitate their co-evolution. This has important implications because it is actors who have agency and can shape the unfolding energy transition and have the capacity to slow it down or speed it up [70].

Actors have different abilities to "mobilize resources to achieve a certain goal" [71]. Resources can be e.g. human capacity, and mental or capital assets. To achieve their goals, actors need – besides access to resources – strategies to mobilise and skills to apply them, as well as the willingness to do so [71]. The more resources an actor has, and the better the strategies he/she uses to mobilise the resources, the more powerful an actor is. For our analysis, it is particularly interesting which strategies actors use to assert their interests and how this leads to potential carbon lock-ins. Strategies include e.g. actors forming alliances and networks [72,73], conventional lobbying [73], or influencing expectations through discourses [50,69,72]. At the same time, actors are constrained by the realms within which they operate [50,72,74–76].

Our analysis introduces a new approach to marrying material and perception analysis. While an analysis of material realities describes the context within which actors operate, it does not address how their agency depends on their perceptions of a specific situation (e.g. the systems' status quo or likely future developments). Thus, our approach provides the foundation for identifying the space for agency in shaping the energy transition by providing a roadmap for identifying the connection between material realities and actors' interests and strategies. Thereby, we gain a deeper understanding of the underlying lock-in mechanisms influencing the course of energy transitions.

4. Methodological approach

In order to unpack the connections between the LNG terminals and a potential risk of a gas lock-in in the next phase of Germany's energy transition, we developed a methodological approach based on the theoretical foundation of Section 3. We thus identify the relevant developments in the three co-evolving realms through material analysis focused on the techno-economic, political, and socio-technical developments within each realm, complemented with an actor analysis focused on their interests, perceptions and interactions.

4.1. Material analysis

Our material analysis is based on the aforementioned meta-theoretical framework [16]. In the following, we introduce the relevant variables of each realm (what is referred to as system in the original framework [16]), we explain which variables were excluded due to a lack of relevance for our empirical case and how we covered the remaining ones in our analysis (also summarised in Table 3).

The **political realm** covers actors and power. The main variables explaining the realm are *state goals, state capacities, political interests and institutions* [16]. We have a special focus on *state goals* (energy security and climate change) and *political interests* of state, private and civil society actors. We neglect *state capacity* as a constraining variable in the German context, as Germany has a high state capacity with strong institutions and a high level of political stability. We also refrain from conducting an in-depth analysis of *institutions* ourselves, however, a coordinated market economy like Germany with federal states, politically stable and relatively wealthy, implies close interactions between the government and a strongly engaged civil society as well as powerful incumbents [62,77,78]. In policy issues regarding gas, the close state-industry interaction consists of a wide network between different private and public sector actors, e.g. lobby and industry associations, and the affected larger companies, such as the utilities and network operators. Official consultation processes, conferences and lobbying behind closed doors enable exchange.

Existing technologies and the related infrastructure as well as energy markets form the **techno-economic realm**. The main variables in this realm are *supply, demand and infrastructure*. We therefore analyse factors that influence the development of natural gas demand and supply in Germany, the existing natural gas infrastructure in Germany and the EU, and the resulting supply–demand balance. We base our analysis on collected primary data on existing natural gas infrastructure as well as expansion plans, gas consumption and relations with exporters. Additionally, we include scenarios as estimates for future supply and demand balance developments, so that interactions with other energy carriers, such as coal, nuclear energy and renewables are included as well.

The **socio-technical realm** comprises technological developments and social practices, summarised by the main variables *regime and niche, technology diffusion, and innovation systems*. The *technology diffusion* of

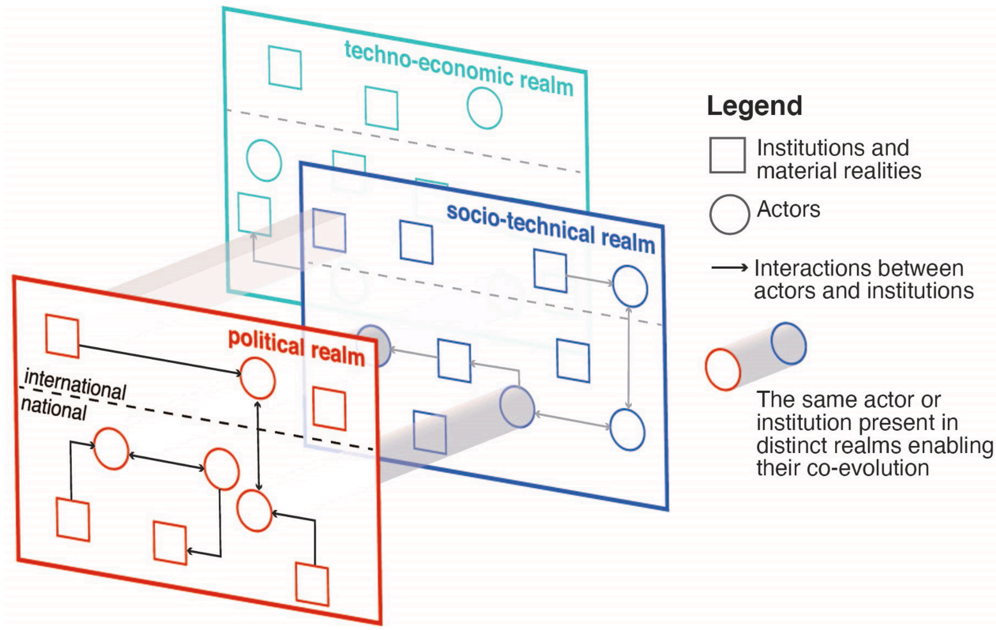

Fig. 2. Actors influence the realms while the realms define the space for actors' perceptions and related strategic actions. Source: Developed based on [16].

Table 3
Main variables covered in respective realms.

Political	Techno-economic	Socio-technical
State goals	Resources	Innovation systems
Political interests	Demand	Regimes and niches
Institutions and capacities	Infrastructure	Technology diffusion

Note: See [16] for more detailed explanation of those variables.

LNG in Germany is characteristic of *regime* development but has interesting interlinkages with the *synthetic gas niche*, and their respective rules, practices, and meanings. LNG has been used for decades in other (EU) countries [79] and the maturity of the relevant technologies is high [80]. Regasified LNG fed into the grid is no different from conventional pipeline natural gas, which is why no behaviour change is necessary and there is compatibility of actors along the value chain. The major innovation in LNG is at the global level within the *global innovation system* [81].[18] We hence focus our analysis of the socio-technical system on *regime dynamics* as characterised by the interlinkages of the *(liquefied) natural gas regime* and the influence of the *global innovation system* on national developments.

Our data collection for the material analysis includes (1) informational interviews with scientific experts and NGO representatives, (2) the participation in information and dialogue events on the local and national level throughout 2019 and 2020, (3) hosting a stakeholder workshop with 15 participants from the private sector and civil society (e.g. companies involved in gas distribution, LNG terminal planning, energy consultants and environmental NGOs) in May 2019 and (4) a desk study of current literature. So far, there is limited scientific literature on the LNG terminals in Germany, so we also considered grey literature (e.g. company reports, newspaper articles, and protocols from political debates).

4.2. Actor analysis

In order to identify the relevant actors in our case and to understand their interests, we conducted an actor analysis following Brugha and Varvasovsky [82].[19] Our methodological procedure can be divided into five steps. In the first three iterative steps, we identified and clustered the relevant actors (based on the material analysis) who exercise power and/or have a substantial interest in German natural gas developments. In the last two steps, we obtained the actors' interests and perceptions, and analysed them. In the following, all steps are described in detail.[20]

1. **Identifying and clustering actors:** We have used the results of the material analysis to identify all relevant actors. From this extensive list, the authors and two additional scientific experts in the German and international natural gas market selected the most relevant actors, clustered them into actor groups, identified their position (supportive, non-mobilised or opposed), the strength of their interest in the project (low, medium, high), and their possibility to influence the process (low, medium, high). In our case, this process resulted in an actor matrix that included 23 actor groups.
2. **Narrowing down the field:** From that list, we excluded actor groups with only moderate or low interest and low or medium influence. In our case, this resulted in a matrix with no opposed actors. In order to avoid a bias in the investigation and to analyse the controversy around the terminals we included opposed actor groups.
3. **Categorising actor groups:** We categorised the actor groups into state, private sector and civil society actors and relevant subgroups (see Fig. 3).
4. **Interviewing the relevant actor groups:** We conducted 14 semi-structured interviews with actors from each of those three actor groups. The interviews took place between July and October 2019.

[18] Generally, technological innovation processes take place and are influenced on various levels, such as regional, national and international, and those levels interrelate [81]. This conceptualisation of technological innovation as multi-locational and with structural couplings (termed global innovation system) is helpful in our case to analyse the influence of global developments on the diffusion of LNG technology in Germany.

[19] While the term 'stakeholder' is used mostly in management literature, 'actor' is more common in the literature strand regarding energy transitions. To avoid confusion by using different terms, we always use 'actor' and therefore 'actor analysis' instead of 'stakeholder analysis'.

[20] Actor analysis as a methodology has been criticized for a lack of rigid criteria according to which actors are included or excluded from the analysis [83]. Therefore, we aim to present our approach as detailed and transparent as possible.

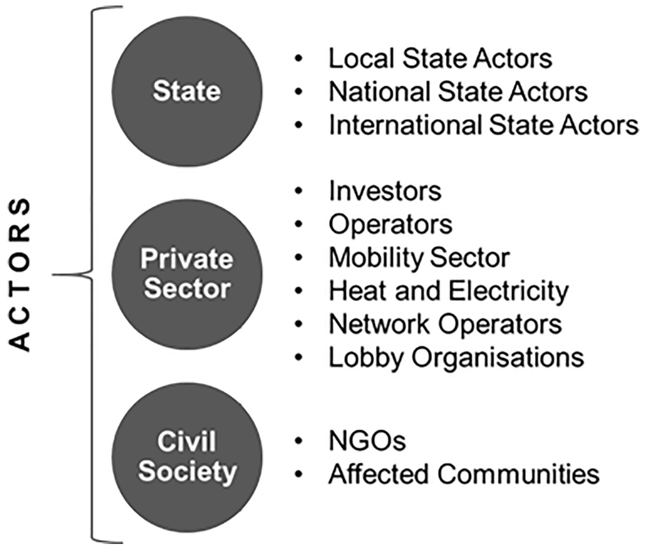

Fig. 3. Main actor groups involved in the political processes surrounding LNG Terminal construction in Germany.

The interview guideline was structured in two parts, to identify both (1) the actors' interests with regard to the LNG terminals and (2) their perception on the material developments affecting German natural gas markets in general. In our analysis, we can thus establish linkages between actor interests and their perceptions of developments. In order to preserve the anonymity of the interviewees we have assigned acronyms to the interviewees, which will be used in the further text when quoting (see Table 4).

5. **Analysing the interview results:** We processed the interview data using qualitative content analysis [84]. We coded for the following 8 categories to identify the main aspects regarding the actors' interests and perceptions of the LNG terminals touching upon all three realms that could not be answered (solely) via a desktop research: 1) Actors' interests in the specific LNG terminal proposals, as well as LNG and natural gas in general; 2) benefits and negative impacts of the terminals; 3) barriers to terminal construction; 4) collaboration and connections between actors; 5) position towards terminals; 6) effect of synthetic gases and 7) natural gas market trends' influence on LNG terminals; 8) possibilities and strategies of actors to influence political decisions regarding the terminals.

4.3. *Triangulation of actor and material analysis*

Our methodological contribution is this 5-step approach on how to combine a material analysis with an interview-based actor analysis. Through this, we can use a wide variety of data (documents and interview data) and cover both the realms and actors' perceptions to analyse the resulting mechanisms influencing energy transitions. We link actors' perceptions and interests with the material systems analysis (Section 5) and derive the most relevant mechanisms (Section 6), and are thereby able to answer the following questions: How do the material conditions around natural gas consumption and LNG infrastructure relate to and interact with relevant actors' perceptions and interests? How do these interactions shape systemic changes and create lock-ins for the German energy transition?

5. Results of realms and actor analysis

The results are structured by realm: Section 5.1 presents the political realm with its competing state goals as well as actors' perceptions of these state goals and political interests of key actors. Section 5.2 contrasts the natural gas supply and demand analysis with actors' perceptions of techno-economic developments regarding LNG and natural gas markets in the techno-economic realm. Finally, Section 5.3 describes the socio-technical realm by comparing the LNG and synthetic gas technology diffusion with actor perspectives on innovation. For each realm, we reflect on the role lock-in plays.

Table 4
Summary of conducted interviews with acronyms.

Number of interviews	Interviewees	Acronym*	Position**
4	State Actors (government, opposition, local and national)	Interview_SA	1 supportive/1 non-mobilised/2 opposed
2	Academic experts	Interview_AE	1 opposed/1 supportive
2	Community Actor and NGO	Interview_CA	Opposed
6	Private Sector Actors	Interview_PSA	3 supportive/1 opposed/2 non-mobilised

* We identify the information used from the interviews by using the acronyms.
** The position of the actors was not always known beforehand but determined through the analysis of the interviews.

5.1. *The political realm*

5.1.1. *Competing state goals*

Gas infrastructure and the economics of LNG projects cannot be disentangled from the political environment. Politics here means two main things: the pursuit of state goals by political actors and the way in which private actors influence policy making.

One important state goal for a country that signed the Paris Agreement are greenhouse gas (GHG) emission reductions. If Germany's natural gas consumption stays at the 2018 level, emissions from natural gas alone (166 Mt CO_2-eq) would account for more than a quarter of Germany's total GHG emission target for 2030 (563 Mt CO_2-eq), or almost all emissions available to the energy sector in 2030 (183 Mt CO_2-eq), even without considering life-cycle emissions [8–11] (see Fig. 4). If Germany is to meet its climate targets, natural gas would need to be reduced in the final energy consumption already before 2030 (as other energy carriers such as coal will be responsible for a share of the emission target as well), and to almost zero by 2050 [85].

The main national state goal competing with climate protection is to balance energy demand with secure supply [44]. Following Cherp and Jewell [89], we define energy security as "low vulnerability of vital energy systems". We operationalise this definition looking at how LNG terminal construction would affect risks from *a)* political and *b)* technological/natural origin, as well as *c)* resilience of the energy system.

a) Risks of political origin can be diminished by reducing foreign control over energy systems.[21] As Germany only produces a small share of its gas domestically, it will not obtain full sovereignty over its natural gas supply. In 2017, Germany's energy import dependence was 64% overall, and 91% for natural gas [90]. An LNG terminal would not contribute to increasing energy sovereignty.
b) The increase of the *robustness* of an energy system helps to minimise technological or natural (resource depletion) risks. The Federal Ministry for Economic Affairs and Energy (henceforth Economics Ministry) states in its monitoring report on energy security and

[21] Commonly known in energy security literature as sovereignty [89].

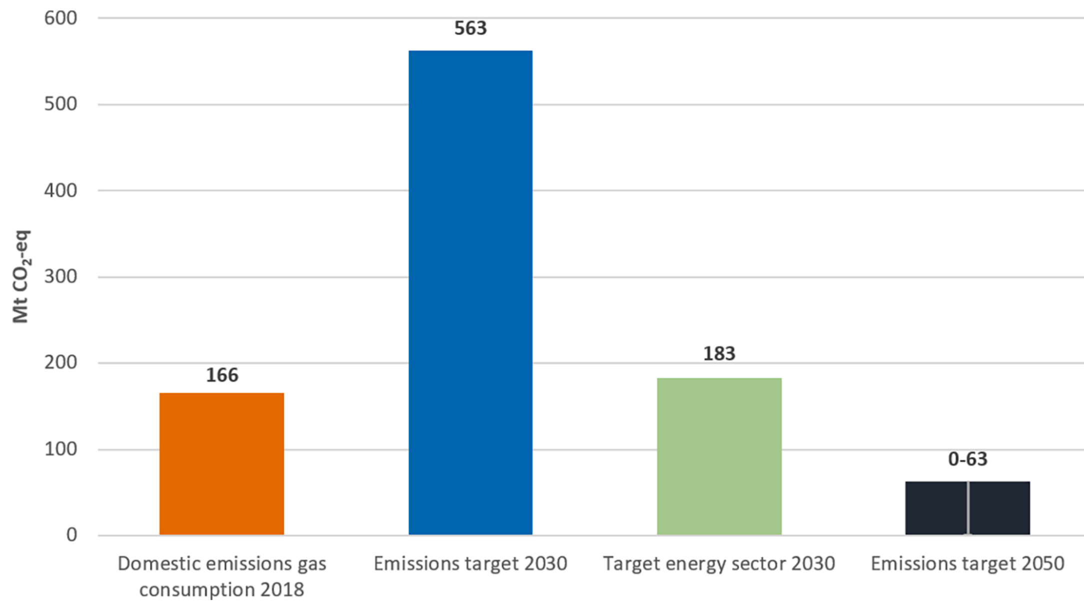

Fig. 4. Comparison of current emissions from gas consumption and emission reduction targets for Germany. Source: Authors' illustration based on [86–88].

natural gas that supply of natural gas for Germany is "very secure" [91] and that even without German LNG Terminal import infrastructure, via the EU internal market the worldwide LNG supply has a positive impact on German gas supply [91]. Nevertheless, the construction of the terminals can lead to a potential increase in robustness of gas supply security due to an increase of import capacities.

c) *Resilience* aims to create the ability of energy systems to respond to disruptions. The major supply security concern is related to Russia [79,92]. Especially since 2006, due to Russian disputes with the transit countries Ukraine and Belarus, and annexation of Crimea, public and political concerns about potential supply disruptions were high [93–97]. To increase short-term resilience, LNG is unsuitable as contracting a new shipment and actual delivery would take in most cases several days. Only in the case of longer interruptions would the additional capacity of a terminal be useful.

Thus, while LNG could increase reliance on foreign sources, and therefore decreasing the sovereignty of the German energy system, it could slightly increase its robustness and resilience by installing a young infrastructure, diversifying imported sources and providing a buffer against import shocks. Energy security is shaped not only by material realities but also by perceptions of key actors.

One additional state goal, both on the national and the local level, is economic growth, which includes the provision of jobs as well as generation of revenues.

5.1.2. Perceptions of state goals and political interests

Central actors in the political system shaping LNG decisions are German national and local level state actors, natural gas interest associations as well as other states. Among these actors, the Economics Ministry and the US Government are the most dominant in the public discourse. Non-state actors such as NGOs and community actors are also trying to influence the process but from a far less powerful position.

The **Economics Ministry** is strongly supportive of LNG terminal construction in Germany, especially to reduce import dependency from Russia. However, the ministry also supports the construction of Nord Stream 2 and states that gas supply security is already high and can be guaranteed without the terminals. It sees synthetic gases and hydrogen imports as a possibility to bring LNG terminals in accordance with German climate protection targets [Interview_SA]. It also started the "Dialogue Process Gas 2030", that reiterated the importance of LNG for diversification, and a resulting gas grid expansion [98].[22] The **Ministry of Environment** has not positioned itself publicly for or against the terminals, although concerns have been voiced during the interview about negative environmental and climate impacts [Interview_SA].

Local state actors from the federal states, where the three potential terminals are located, are interested in the projects as they might lead to employment opportunities, improve the regions attractiveness for new corporations potentially related improvements in street, railway and gas grid infrastructures. In addition, regional and local politicians have an interest in private sector investment that might reduce the needed amount of public investment in structurally weak regions [Interview_SA].[23]

The political support for the LNG Terminals is also influenced, both directly and indirectly, by **other states**, in particular the United States, Russia and the EU. Direct pressure to increase LNG imports comes from the US government, which aims to increase natural gas deliveries from the US to the EU (as part of the general strategy to keep their position as a natural gas exporter, which resulted from the shale gas fracking boom, see also 5.2.2). Several interviewees [Interview_SA × 3; Interview_AE; Interview_PSA; Interview_CA] alluded to the diplomatic pressure for the German government to follow the **US government**'s push to deliver gas to Germany, going so far as calling German state support for LNG a "friendship service" to the US [Interview_SA].[24] On the other hand, interviewees also mentioned concerns about a strong influence of **Russia** on the German natural gas market. Natural gas supplier diversification is often mentioned in the context of Russia being the largest gas supplier for Germany, and related vulnerability to natural gas price increases [Interview_SA; Interview_PSA].

Interest associations connect actors of the entire gas value chain in

[22] Interestingly, despite being called a stakeholder dialogue process, throughout the process mostly industry, energy sector and consulting representatives were part of it, while environmental NGOs were only included towards the end.

[23] We interviewed a local representative from the Green Party, who positions himself against the terminals. He gave us an overview of reasons why other local politicians support the terminals.

[24] In a public statement the Economics minister also called it "a gesture towards the US administration"; Reuters, Germany to build LNG plant in 'gesture' to U.S. drive to sell more (2018). https://t1p.de/067b.

Germany, the EU and globally. Their general aim is to create business opportunities for firms in the gas industry, and to establish favourable political conditions for that. In Germany there are well-organised umbrella interest associations representing the natural gas industry, e.g. the German Technical and Scientific Association for Gas and Water (DVGW) or Zukunft Erdgas ('Future Natural Gas'). They are generally in favour of the construction of LNG terminals in Germany, but are not directly (or at least not visibly) involved in lobbying for the terminals. In the case of the Brunsbüttel terminal, the interest organisation 'Maritime LNG Platform', is actively lobbying for its construction. The platform unites different actors, to create a larger negotiating power. They include industry actors (e.g., Shell, Vopak, MAN, Gasunie, FLUXYS) as well as harbour and shipping companies (Brunsbüttel Ports GmbH, AIDA Cruiser, Hapak-Lloyd). The interest of the association is to establish LNG as a fuel for both shipping and heavy-load road transport and to remove regulative barriers for LNG use [Interview_PSA; Interview_AE].

Opposition to the current LNG terminals comes from several **Non-Governmental Organisations (NGOs)**, mostly due to climate change, but also general environmental and security concerns. A prominent example is DUH (Deutsche Umwelthilfe, Environmental Action Germany), which conducted legal reports, publicly raising security and environmental concerns regarding the construction of the LNG terminals. As a result, the operators in Wilhelmshaven need to find a different location for their FSRU, and in Brunsbüttel they are obliged to address the security concerns raised by the DUH as part of the approval process. Their overarching interest is to prevent the permission of investments that endanger local environments and negatively affect the climate [Interview_CA].

Local community actors are mostly indifferent to the realisation of the projects [Interview_SA; Interview_CA]. Several local actors are open to the project in the hope that additional jobs and an improvement of the local infrastructure will have a positive impact on them. However, some local citizen associations are actively against the terminals for environmental reasons and security concerns [Interview_CA].

An institutional gas lock-in exists, as both private and political actors and institutions profit from existing and additional natural gas projects and their role for energy provision and security. Political and market actors have therefore jointly advanced further regulations which benefit natural gas, such as the change of the gas network regulation and bonus payments when natural gas replaces coal (see Section 6). Such intentional choices further stabilise existing institutions, strengthening both national and international institutional connections.

The discursive debate is between LNG and natural gas being a "bridge fuel" and a "partner of renewable energy" versus a "barrier to the energy transition" and an "environmental risk" [Interview_SA; Interview_CA; Interview_PSA; Interview_AE] [99]. It is part of the prevalent German energy transition and energy mix discourse since the 2000s [51].

5.2. *The techno-economic realm*

5.2.1. *The German gas market and its European context*

Germany is the largest natural gas consumer in the EU. In 2018, the German gas consumption was 92 bcm [100]. This represents 23% of the primary energy consumption [100,101], while for example renewable energy sources contributed around 14% [101]. In 2018, natural gas accounted for 8% of electricity, 45% of the heating sector and 0.2% in the transport sector [102].[25] In total, natural gas accounts for 24% of Germany's CO_2-eq emissions.[26]

Importantly, Germany's gas supply depends on other countries, as the country imports more than 90% of its natural gas consumption: In 2018, 44 bcm came from Russia, 34 bcm from the Netherlands and 22 bcm from Norway (3 bcm unspecified, 33 bcm re-exports) [100,103,104]. Germany has an extensive gas infrastructure, which includes more than 515,000 km of gas pipelines, cross border connections to all its neighbours, as well as Russia and Norway, as well as the largest gas storage capacities in the EU (~23 bcm, corresponding to around a quarter of annual German consumption) [85,105]. Several planned gas infrastructure investments include a second pipeline to Russia (Nord Stream 2), a second pipeline from the Baltic Coast to the Czech Republic (EUGAL), and converting pipelines and appliances running on low-calorific gas to high-calorific gas (due to decreasing imports from the Netherlands). The gas grids are highly regulated and managed by gas transmission system operators (16 companies) and gas distribution network operators (greater than700 different companies). Due to its geographical location and existing storage facilities, Germany acts as a "gas hub" for Europe [106].

In contrast to Germany, the EU as a whole already has considerable LNG import capacities – sufficient to cover around 43% of its current gas demand (as of 2015) [107]. The largest import capacities are in Spain, followed by the UK and France [108].[27] The average utilisation rate of EU LNG terminals varies over time – in 2011 the utilisation rate was only around 50% and it decreased to less than 25% in 2017 before rising in 2019 to the 2011 level [109–111]. LNG imported via a terminal can then be used either in its liquid form, or it can be regasified and put into the gas grid.

5.2.2. *Natural gas supply and demand analysis*

Current security of *supply* concerns stem from the fact that continental European natural gas production is declining. The Netherlands plan to phase-out gas production from the Groningen field in 2022 [112] and there is a widespread belief that the Norwegian gas fields are in decline [113,114] (however, the Norwegian Petroleum Directorate argues that production from currently undeveloped fields could lead to an increase in Norwegian exports [115,116]).

The growing global LNG market has attracted more actors in recent years, among them the US [117] driven by the fracking boom, which resulted in an in a ten-fold increase in exports in only four years [118]. Support for LNG originates in the aim to decrease imports from Russia. Yet, in 2019, Russia was the second largest LNG supplier to the EU (with Qatar being the largest supplier).[28] Hence, it is possible that in case of LNG terminal construction, Germany would also buy more LNG from Russia than the US, which would prevent the desired supplier diversification.

For LNG consumption economic prospects have improved, however not enough to make investments in LNG terminals profitable enough for quick private sector investments in Germany. Final investment decisions have been repeatedly postponed for Brunsbüttel as well as Wilhelmshaven. Concerns about demand for natural gas are exacerbated by COVID-19 [119].

In 2018, 45% of heat production in Germany came from natural gas [102]. Expansion of renewable energy use for heating has stalled since 2012 [120]. Since the German coal phase-out law from July 2020 financially incentivises the conversion from coal-fired power plants not only to renewable energies but also to natural gas, it is unlikely that the overall demand for natural gas in heat provision will fall. Gas use in the electricity sector depends on whether renewable energy and efficiency

[25] Umweltbundesamt, Energieverbrauch nach Energieträgern und Sektoren (2021). https://www.umweltbundesamt.de/daten/energie/energieverbrauch-nach-energietraegern-sektoren.

[26] Statista, Energiebedingte CO2-Emissionen in Deutschland nach Energieträger im Jahresvergleich 2000 und 2018, (2020). https://t1p.de/84q6.

[27] Terminals exist also in Italy, the Netherlands, Belgium, Portugal, Greece, Poland, Lithuania, and Malta.

[28] In 2019, Russia exported 16 Mt of LNG to the EU, while the US exported 12 Mt (Qatar as largest supplier delivered 21 Mt to the EU) (according to S&P Global Platts data, for quarterly data see EC [110]); Petroleum Economist, Russia beating US in LNG price war (2020). https://t1p.de/7mb5.

improvements will compensate for the phase-out of coal and nuclear energy. The transport sector in Germany is under pressure to achieve its emission reduction targets. LNG would provide several actors of the mobility sector with the chance to change towards a fuel, which is similar to their old business model from a technology perspective, while being able to reduce emissions of several pollutants. For this reason, there is currently a trend to use more LNG in transport (especially heavy-duty traffic and shipping; the absolute amounts of natural gas use are nevertheless still very small, see Section 5.2.1). Subsidies and other beneficial regulations implemented for LNG in the transport sector include e.g. a reduction in energy taxation for natural gas for vehicles [121,122], the exemption of LNG trucks from toll charges, and the creation an official "LNG-Taskforce".[29] However, studies show that switching to LNG in the transport sector does not necessarily lead to a reduction of GHGs [123].[30] Other countries, such as the UK, have decided in their mobility strategy not to consider LNG as a climate friendly fuel option.[31]

In contrast to some actors' expectations of an increasing natural gas demand, a multi-model comparison shows that in modelling results in line with the Paris Agreement (or merely an 80% GHG emission reduction by 2050) natural gas demand decreases, even before 2030 [85,124]. A study by the German Environmental Agency shows that ambitious climate protection would render unnecessary up to 74% of all gas distribution grids due to a reduction in gas consumption [125].

5.2.3. Economic interests of key actors

In general, gas market actors, such as gas traders, pipeline operators and utilities, have an interest in increasing gas consumption in Germany. An expansion of the gas infrastructure and additional natural gas imports can strengthen their business and increase the value of their asset, whereas a strong decline of gas consumption would negatively affect their business models. **Gas traders** have an interest in the flexibility provided by LNG in contrast to pipeline gas, as one terminal can be used to import gas from a variety of suppliers and offers the possibility of short term contracting in case of a changing gas demand or prices [Interview_PSA]. **Utilities** experience pressure due to the nuclear and coal phase-out and the need to find dispatchable sources. Gas is close to their old business model and therefore a convenient substitute.

The **industry sector** was responsible for 40% of Germany's total gas and 47% of its electricity consumption in 2018. Industrial actors have, hence, a particular interest in low gas prices, for cheap electricity and heat provision, as well as feedstock [Interview_PSA x2; Interview_AE]. **International suppliers** have an interest to access the largest European gas market to sell their LNG.

Gas grid operators' business model is threatened by a potential reduction in gas demand. They could benefit from an increase in gas throughput in case of LNG deliveries, especially the ones connecting pipelines and the ones close by. Another option are synthetic gases, which is why some gas grid operators start investing in "hydrogen ready" infrastructure.

For actors in the **mobility sector**, LNG is an opportunity to meet short-term emission reduction targets (e.g. CO_2, NO_x, SO_x), opening investment opportunities for trucks, long-distance shipping and inland vessels and related infrastructure, such as filling stations [Interview_AE, Interview_PSA].

Relatively **few** of the gas market actors are **opposed** to the LNG terminal construction in Germany. One example is an association of municipal utilities, which opposes the allocation of the access pipelines' costs to gas customers, but not the terminals themselves [126].

Germany has a well-developed natural gas infrastructure that many actors are interested to continue to avoid stranded assets. An infrastructural natural gas lock-in exists due to the long lifetime and large sunk costs of existing infrastructure. Additional investments would reinforce the infrastructural lock-in. Especially in the heat sector, a strong technological lock-in exists, as renewable heating alternatives are not yet widespread and would require a different infrastructure, rendering e.g. the natural gas distribution network unnecessary [61].

5.3. The socio-technical realm

5.3.1. Gas regime technology diffusion and synthetic gas niche

The *natural gas regime* is influential. It is dominant and well connected across different sectors (electricity, heat, industry, and to an increasing extent transport) and actors (gas network operators, corporations of various industries using gas as input for heat or as feedstock, manufacturers of gas appliances, municipal and nationwide utilities, gas storage operators, traders, several political actors, etc.), through, for example, joint interest associations. LNG is a part of the highly institutionalised natural gas regime, as the actors and formal and informal rules are mostly the same, and one of the shared beliefs is that natural gas should play an important role in the energy transition.

There is an emerging *synthetic gas niche*, to utilise (renewable) electricity to produce hydrogen with electrolysers [127].[32] Hydrogen has long been promoted as an alternative (see e.g. IEA [128] for "previous waves of enthusiasm for hydrogen" since the 1970 s) and this trend has re-emerged now in connection with increasing pressure on the natural gas regime [54,129].[33] To produce renewable synthetic gases domestically, Germany would need to substantially expand the capacity of electrolysers, but also additional renewable energy capacities to produce the needed electricity [127,130,131]. Due to space constraints for additional renewable capacities and related societal opposition, imports of synthetic gases would need to play a substantial role [130,131]. The assumptions about imports are made without actual existing projects in other countries on the required scale to provide those import possibilities, and partnerships are in an early stage.

In the debate about the LNG terminals, the possibility to use the planned terminals for hydrogen imports is often mentioned, despite the fact that the technical requirements are very different for hydrogen and not fulfilled by the terminal (see [132] for a comparison of LNG and liquid hydrogen properties). Synthetic methane could potentially be imported via the terminals, but the costs and available supplies are still highly uncertain.

In general, the high level of natural gas use in various sectors facilitates support for LNG. The *(liquefied) natural gas regime* also shares many rules, values and goals with the *synthetic gas niche*, creating in many instances a further alliance instead of competition.

5.3.2. Actor perceptions of innovation

Various private sector actors and state actors referred to the possibility of importing *synthetic gases* (i.e. hydrogen) via the terminals [Interview_PSA x2; Interview_SA]. However, there is not a large market for synthetic gases and market actors stated that they had no concrete plans for those imports, as the uncertainty about price developments and

[29] Dena, Liquefied natural gas: LNG Task force defines work priorities (2016). https://t1p.de/kgc2. Dena, LNG-Taskforce und Initiative Erdgasmobilität (2021). https://t1p.de/6fhc.

[30] The reduction of GHGs depends on various factors, such as the origin of the fuel, the engine design and the associated methane leakage. Depending on how these factors interact, a possible reduction of GHG is between −20% and +3%.

[31] GOV.UK, Written statement to Parliament Clean maritime plan (2019). https://t1p.de/0k95.

[32] In a second step – the methanisation – hydrogen can be converted into methane.

[33] One example for the pressure is the company 'Total' complaining about the European Investment Bank stopping to finance investments in unabated gas projects, from 2021 onwards, stating that "Gas has never been so much criticised in Europe"; Reuters, UPDATE 1-Energy group Total criticises EIB's decision not to finance gas (2019). https://t1p.de/1cz7.

possible suppliers is too high. Nevertheless, synthetic gases are strongly present in the discourse on the energy transition. One important actor in this context is the "Power to X Alliance". Among the members of this association are car manufacturers, transmission grid operators and natural gas traders.[34] The alliance demands the construction of 5 GW electrolyser capacity[35] by 2025 and changes to regulation to facilitate the market entry of 'Power to X' technologies.[36] Central actors from the renewable industry, like the umbrella association of renewable energy[37], are not part of it.

Hydrogen does influence the debate in the socio-technical realm and could encourage some actors to support the construction of the terminals. However, given the still immature technological development and incompatibility of hydrogen with LNG import terminal technology, it is unlikely that there will be any actual synergies.

The natural gas regime is well connected to political actors. Regime actors use their resources to promote their technological preferences, create strong networks, achieve beneficial regulation, a supportive public discourse, and mobilise public funding for their projects.[38] The combination of the efforts of regime actors creates effective regime resistance.

Generally, LNG and synthetic gases relate to a behavioural lock-in of natural gas, as utilities and other companies are used to large-scale energy infrastructure and trade, and customers are familiar and satisfied with gas boilers and district heating grids. Regasified LNG requires no change of standards or any change in behaviour of consumers or companies along the value chain, enabling the continuation of the status quo.

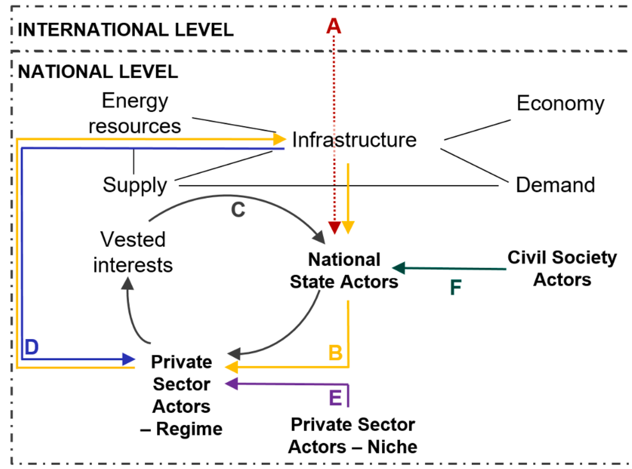

Fig. 5. Explanatory mechanisms for political support for LNG investments in Germany. Notes: Each mechanism is designated by a specific colour and letter. A – International diplomacy pressures German state actors to support LNG; B – State actors support incumbents to ensure a secure supply–demand balance; C – Regimes enable beneficial regulation through promoting the alignment of their vested interests with political interests; D - Sunk investments reduce willingness for change; E - Niche innovations strengthen the gas regime; F – Weak opposition of actors outside the regime poses no counterweight. Source: Adopted from [36].

6. Mechanisms explaining LNG support in Germany

The main mechanisms to explain political support for LNG terminals are summarised in Fig. 5. The three realms are linked through the relevant actors, which enhance co-evolution via their actions. The mechanisms can explain the observed reciprocal developments of the three realms as well as perceptions and actions by the actors. The mechanisms are explained in detail in the following and can be divided in those that represent one form of lock-in (defined in Section 3), and those that more generally support natural gas as a technology.

A – Pressure on German state actors to support LNG through international diplomacy: Institutional lock-in

One of the general mechanisms that creates political support for LNG terminals is international diplomacy: Since the shale gas boom turned the US into a natural gas exporter (see Section 5.2.2), the Trump administration was putting increasing pressure on both the EU as a whole and Germany in particular to import more gas from the US. The outcome of national dynamics in other countries is included here, however, a detailed analysis of those dynamics – e.g. what is leading US politicians to act the way they do – is beyond the boundaries of the analysis and the framework.

Illustrative for this mechanism are for example meetings between US and European state actors regarding the so called "trade war" in July 2018, when EU commissioner Juncker and US President Trump agreed on EU purchases of LNG from the US in the context of the threat of US punitive trade tariffs. Since then, LNG imports from the US to the EU have risen sharply, albeit from a very low level [134,135]. Reasons for the increase are, however, not only the political pressure but also various global LNG market developments (see Introduction and Section 5.2). A conference on US LNG organised by the German Economics Ministry in February 2019 is another illustration for the pressure the US is putting on the German government to support imports of US LNG: Only US politicians and corporations but no actors e.g. from Qatar or Russia were invited. As a preliminary result of the conference, a key-issues paper of the Economics ministry proposed the changes to the network regulation in favour of LNG infrastructure projects [136]. In December 2019, the US officially imposed sanctions on companies involved in the construction of Nord Stream 2, against which the US government has officially positioned itself.[39] Together, the measures taken by the US – trying to stop more infrastructure enabling gas imports from Russia and pushing the EU to import US LNG – are putting the German state in a difficult situation: It needs to respond to this larger geopolitical conflict between Russia and the US, while aiming to guarantee high supply security and low energy prices. In this context, finance minister Scholz proposed in a now publicly available non-paper to the US Secretary of the Treasury that Germany would support the Brunsbüttel and Wilhelmshaven LNG terminals with up to €1 billion, if in return the US would stop sanctions related to Nord Stream 2.[40]

The simultaneously decreasing natural gas production in central Europe (especially in the Netherlands and possibly Norway) reinforces beliefs of various actors that Germany and the EU as a whole are vulnerable to Russian gas supplies, which in turn intensifies mechanism B.

What makes the German gas market particularly attractive to the US is its size and that it acts as a gas hub in Europe. Thus, while other European countries will be subject to similar supply constraints from decreasing continental European gas production, it is not clear if the US

[34] Power to X Allianz, Allianzpartner (2021). https://www.ptx-allianz.de/ueber-uns/allianzpartner/.

[35] Used to generate hydrogen from electricity.

[36] Power to X Allianz, 10-Punkte-Plan zur Nationalen Wasserstoffstrategie – Power to X durch Anwendungsoffenheit zum Erfolg führen. (2021). https://t1p.de/aw16. 'Power to X' refers to the conversion of electricity to gases, heat, or liquids, often used to improve storability of electricity.

[37] German Renewable Energy Federation (BEE).

[38] Next to the support for LNG, the German hydrogen strategy, provides e.g. €7 billion for the creation of a hydrogen industry [133].

[39] SEC. 7503, National Defense Authorization Act for Fiscal Year 2020, https://www.congress.gov/116/bills/s1790/BILLS-116s1790enr.pdf.

[40] Federal Ministry of Finance, Non Paper Germany Nord Stream 2/U.S. LNG (2020). https://t1p.de/s7cq.

would put the same pressure on other European countries.

B – State actors support incumbents to ensure a secure supply–demand balance: Institutional lock-in

In consideration of the decreasing natural gas production within the EU and internationally low LNG prices, the support of private sector investments in LNG terminals can help state actors to create higher supply security levels by facilitating imports from additional supplier states (or at least the perception of higher energy security) (see Section 5.1.1). This mechanism therefore represents an institutional lock-in mechanism. On the international supply side, the aforementioned decreasing European natural gas production increases supply security concerns, and low international LNG prices reduce the barrier for investments and increase the attractiveness of natural gas use.

The extent to which supply security would actually increase through the LNG terminals is contentious for various reasons: (1) LNG might not be contracted and shipped rapidly enough to function as an emergency supply mechanism [Interview_PSA], (2) LNG supplies might come from Russia and therefore may not provide diversification, (3) the Economics Ministry states that supply security would also be guaranteed without the construction [Interview_SA], (4) as well as studies showing that EU gas supply is secure without new investments [92,137].

Despite a rather small increase in supply security and the repeated statement that the LNG terminals are a private sector investment (Interview_SA, Interview_PSA, Deutscher Bundestag [138]), the federal and state governments support the construction in various ways, to close acknowledged "substantial profitability gaps"[41]. The main measure by the government was the change of the Gas Network Access Regulation in March 2019. Thus, the Economics Ministry overturned a previous decision by the German network regulator (BNetzA) from December 2018 that investors would have to bear the cost for pipelines connecting the terminals to the gas grid themselves.[42] Now, 90% of the investment costs and 100% of the operating costs for the connecting pipelines will have to be borne by gas consumers through a rise in network charges.[43] Interestingly, the related entire political process was only several weeks long, which has been evaluated as unusually quick and surprising by different interviewees [Interview_PSA x2]. For these connecting pipelines, additional changes to the rest of the gas grid become necessary, as it would not have sufficient capacities to transfer the additional supplies. These additional grid expansion plans might cause additional costs of €800 million, which would again have to be borne by gas consumers and not the terminal operators [139].

The terminals are also financially supported through direct federal state subsidies for LNG terminal construction[44] and through the common task budget "Improvement of the Regional Economic Structure".[45] Further political support for the terminals consists of general governmental support, such as economics minister Altmaier stating repeatedly that he expects the construction of terminals to go ahead, as it would be good for supply security, and encouraging companies to apply for public funding.[46] The relevance of this becomes starker when compared to the stalling wind energy expansion without increasing political support. The financial as well as discursive governmental support is particularly interesting, as no final investment decision has been made yet by any of the potential project investors. This suggests that the terminals are not necessarily financially viable without supportive measures.

The parallel coal and nuclear phase-outs increase the pressure on private sector and state actors to ensure a stable and affordable energy provision. Besides the technical requirements, especially state actors also need to create public trust in their strategy to achieve this. A well-known and established energy source, such as natural gas, continues to be promoted as a reliable and relatively climate friendly fuel. It is claimed that natural gas can fill this role more easily than renewables and new storage technologies. Effectively, climate concerns and environmental concerns are thereby dominated by short-term economic and energy security concerns (see Sections 5.1.1 and 5.1.2).

The German coal commission and coal phase-out law illustrate political side games regarding natural gas: While the process of negotiating the pathway and related support for affected regions and companies was supposed to focus on coal, natural gas is mentioned repeatedly. New gas power plants are now to be granted a facilitated construction process [140], and the coal phase-out law[47] encourages the conversion of coal-fired power plants to gas via a financial "coal replacement bonus" (Kohleausstiegsgesetz § 7c).

Several elements of this mechanism are likely to be replicated also in other EU countries[48]: That states work with incumbents to ensure a supply–demand balance is a well-known phenomenon, and refers to an institutional lock-in [16]. Like Germany, other countries, such as Spain, Portugal or the United Kingdom, are now in the next phase of their energy transition, where they are phasing out coal, and face an increase in natural gas use.

C – Regimes enable beneficial regulation through promoting the alignment of their vested interests with political interests: Regime resistance

Gas regime actors promote their vested interests as to be aligned with local governments' and communities' interests. For example, when the proposals for the LNG terminal were presented to local politicians in Brunsbüttel (a comparatively structurally weak region), hopes for infrastructure improvements, such as railways and roads, were specifically addressed [Interview_SA]. In addition, potential positive effects, such as local jobs or tax revenues, were used to argue for financial and regulatory support.

Another strategy of private sector regime actors is to threaten state actors with moving their projects abroad. Since this would harm the local economy, politicians are more inclined to create support for their business. For instance, in Brunsbüttel, Yara[49] has mentioned to local policy-makers the possibility to close its production facilities, if the LNG terminal and a resulting better gas grid connection would not be built [Interview_SA].

> *"So the entire area is too poorly connected to the natural gas grid. The industry companies now come and say, if that won't get better […] then we won't invest here in the future. Of course, this also causes fear and*

[41] E.g. by the Federal Government Coordinator for the Maritime Industry Norbert Brackmann or the State Secretary of the Ministry of Economic Affairs, Transport, Employment, Technology and Tourism of Land Schleswig-Holstein Thilo Rohlfs, Handelsblatt, Warum Deutschlands erstes Flüssiggas-Terminal ein Befreiungsschlag wäre (2018). https://t1p.de/txb3.

[42] BMWi, Verordnung zur Verbesserung der Rahmenbedingungen für den Aufbau der LNG-Infrastruktur in Deutschland (2019) https://t1p.de/2jqn. (Ordinance to improve the framework conditions for the development of LNG infrastructure in Germany).

[43] Telepolis, "Erdgas wird die neue Kohle" (2019). https://www.heise.de/tp/features/Erdgas-wird-die-neue-Kohle-4398966.html.

[44] Süddeutsche Zeitung, Finanzausschuss stimmt Investitionspaket zu (2020). https://t1p.de/u4o7.

[45] Besides that, natural gas and LNG consumption are encouraged through a wide variety of different measures, e.g. the mobility and fuel strategy [138], as well as via tax rebates for LNG use, financial benefits for research and development and the development of LNG fuelling infrastructure [153,154].

[46] Telepolis, "Erdgas wird die neue Kohle" (2019). https://www.heise.de/tp/features/Erdgas-wird-die-neue-Kohle-4398966.html.

[47] Bundesregierung. 2020. Gesetz zur Reduzierung und zur Beendigung der Kohleverstromung und zur Änderung weiterer Gesetze (Kohleausstiegsgesetz).

[48] Currently, LNG import terminals are under construction in Finland, Italy, Poland and Spain, while proposals exist in Croatia, Estonia, Finland, France, Ireland, Latvia, Netherlands, Romania, Spain and the United Kingdom [141].

[49] Yara is one of the five single biggest gas consumers in Germany (0.7 bcm in Brunsbüttel; ~1% of German gas consumption). Boyens Medien, Gute Ernte: Yara in Brunsbüttel (2018). https://t1p.de/ftxs.

panic. There's no question about that. Of course, they pursue their own interests […], and we as the little volunteer councillors here, get told so. And then you are confronted with a responsibility. […] You can't just dismiss it and say it's shenanigans, what they say, it is definitely not. There is a good bit of truth in it somehow. But it's hard for us to judge whether they won't invest more in the future or whether it's just one of those threatening backdrops that are being built up." [Interview_SA].

This direct lobbying works especially well through strong existing networks between the natural gas industry, interest associations and politicians. For example, companies involved in the LNG terminal payed political lobby institutions, such as the von Beust & Coll consulting, to advocate for the terminals[50] [Interview_PSA]. The consulting firm created the "Maritime LNG Plattform e.V." (see Section 5.1.2), which unites various actors along the value chain. Jointly they benefit from a more advantageous position to lobby state actors for political support. The consulting firm directly advertises their influence through using different party contacts, known from former political work [Interview_PSA x2] (e.g. from Ole von Beust, the former mayor from Hamburg from 2001 to 2010).[51]

A main strategy from larger gas interest associations is to present natural gas as a benefit for supply security, affordable energy, and as necessary for economic growth. The gas industry also advocates for the "partnership" between renewables and gas [142], again managing to create at least the perception of complementarity instead of competition.

This is also the case when LNG terminals are framed as a means to import "green gases". Noteworthy is the presentation of plans to use the terminals in the long run for hydrogen, despite the different technical requirements that would need a different terminal design and substantial reconstructing with high costs [132] (see also Section 5.3).

In general, the gas regime managed to introduce the narrative of gas being 'climate and environmentally friendly' and a 'bridge fuel' in the public discourse (see also [6]). These cognitive frames have not been significantly challenged yet by opposition, which is why they contribute to reinforcing misguided public beliefs and facilitate gaining public and political support [143].

This strategy is a well-observed phenomenon in many countries. On the European level, since 2010, the five main oil and gas corporations and their lobby groups have spent at least €250 million to influence European decision-making.[52] Together these different strategies represent a form of lock-in termed regime resistance, used by the regime to shape ideas about problems and solutions, to advance their own interests, and to prevent stronger regulation. While the strategy has oftentimes proven successful, it is worth noting that in some EU countries, such as Sweden, natural gas has not been strengthened substantially despite an advanced, next phase [15] of the energy transition.

D – Sunk investments reduce willingness for change: Infrastructural lock-in

An important barrier to using less natural gas are past investments: The related sunk costs push actors to keep using that infrastructure, as they cannot recover the already incurred costs. This mechanism is, hence, a form of infrastructural lock-in. Incumbents have an incentive to frame gas infrastructure as a valuable asset that should be used long-term. However, almost two-thirds of all gas distribution grids would not be needed anymore for natural gas distribution, if climate targets were to be fulfilled (see Section 5.2.2). One relatively small change for distribution grid operators or power plants is to invest in so-called "hydrogen ready" infrastructure.[53] This vague term encompasses infrastructure with varying capabilities to integrate hydrogen (between single-digit percentage levels and 100%), mostly creating a further lock-in but no systemic changes. Additional investments in gas infrastructure lead to an increase of an already existing gas lock-in. The scale is, among other factors, dependent on the expected lifetime of investments and the financial barrier to switch to renewable alternatives as well as system-wide institutional effects [67,144]. Most gas infrastructure has relatively long expected lifetimes, e.g. LNG terminals at least 20–40 years, new ships equipped with LNG as power unit ~ 65 years, and gas-fired power plants at least 20–30 years. The quantitative analysis of the additional lock-in's extent is beyond the scope of this analysis and remains a proposal for future research.

E – Niche innovations strengthen the gas regime

States often nurture niches in parallel with working with incumbents, and do not choose either or (as e.g. shown in [36]). The German state supports the strengthening of the niche by financially supporting domestic synthetic gas production (e.g. electrolysers for hydrogen production). Additionally, imports of synthetic gases (i.e. renewable methane and hydrogen) are discussed and cooperation with other states is planned [133].

However, the gas case is special, as the natural gas regime builds a network with the gas niche: The synthetic gas niche, including diverse synthetic and renewable gases (see [145,146] for a typology), poses no competition to natural gas yet, but actually supports the natural gas regime (of which the LNG regime is a part), as it consists of very similar infrastructure and actors. Even strong growth of synthetic gases (via domestic production or imports) would not constitute a competition for the gas regime but mostly a useful new element to it (e.g. increased supply for the gas grid and power plants, new investment opportunities for equipment suitable for a high hydrogen share, etc.). It would also not imply major changes of rules or routines. Therefore, we find that the synthetic gas niche (e.g. hydrogen) is not a threat but a complement to the existing natural gas regime.

Despite the slow development of the various synthetic and biogenic gases (little investment, high costs, limited space and partly missing technological readiness), political debates are prominent and (financial) political support has already been promised (see e.g. Germany's hydrogen strategy [133]).

This mechanism may also be replicated at the EU level and in other European countries, as the new prominence of synthetic gases in policy debates is increasing rapidly.

F – Weak opposition of actors outside the regime poses no counterweight

Opposition to natural gas in Germany is now slowly emerging. The most visible one is DUH, which commissioned legal reports on the Brunsbüttel, Stade and Wilhelmshaven terminals, raising concerns about the legal feasibility of approval for the terminals. For Brunsbüttel, feasibility is disputed especially on grounds of security risks, e.g. due to the immediate vicinity of a nuclear power plant and an interim storage facility for radioactive waste [147]. For the FSRU in Wilhelmshaven, environmental and safety concerns evolve especially around extensive waterway construction, continuous maintenance dredging works, and the location being close to several nature protection zones [148]. The legal reports see the construction of the terminals as incompatible with the existing major accident laws in all three locations, as well as the existing climate law [147–149]. The aspects mentioned in the legal

[50] In this case especially the Brunsbüttel terminal.

[51] They themselves call the platform the "joint" between economy and politics and "partners" of the economics and transport ministries. von Beust & Coll; https://www.vbcoll.de/.

[52] CEO, Food and Water Watch and Friends of the Earth Europe: Big Oil and gas buying influence in Brussels (2019). https://t1p.de/lxnb.

[53] Another possible response strategy would be to stop new investments in a coordinated way to avoid stranded investments. This happens in the Netherlands, where gas distribution operators pushed the government to introduce policies ending natural gas grid connections in new build homes, as they would not have been able to recover those costs when the Netherlands phase-out natural gas by 2050 [personal conversation with Dutch energy expert].

reports need to be included in the approval processes of the terminals, such as the related planning permission hearings and the environmental impact assessments. This might have complicated or slowed down the approval [Interview_PSA]. Despite attempts by political actors at the state level to undermine the legitimacy of the legal report, the approval process for none of the terminals has been completed yet. Additionally, some local opposition by citizen initiatives exists. Those actors opposed to the terminals describe presswork as difficult, since e.g. the local newspapers benefit financially from advertisements by the terminal operators [Interview_CA].

In general, opposition by these few actors is small compared to the strong support by a wide variety of political and private actors in favour. NGOs and citizen initiatives are more fragmented and additionally their involvement targeting natural gas is much lower than e.g. compared to nuclear energy and coal, where they exerted strong opposition [150,151]. Opposition to LNG terminals is being organised in other constituencies than those of the LNG terminal locations, and jointly across countries. How German NGOs strategies (especially regarding the legal reports) influence LNG terminal construction might be used as lessons learned by other organisations.

Together, those six mechanisms can explain political support for LNG in Germany. Four mechanisms (A, B, C & D) represent the institutional and infrastructure lock-in, as well as regime resistance. Additionally, two other mechanisms are not directly lock-in mechanisms, but still facilitate the development of LNG terminals and use of natural gas (E & F). Together, they illustrate the stable lock-in of natural gas in Germany:

(1) An institutional lock-in of gas results from the pressure of international state actors and domestic incumbents. The course of political decisions is shifted due to the influence of special interests to the expansion of natural gas use, and therefore the support of LNG. As the opposition has so far been weak, and the personal and institutional connections are not nearly as strong as the ones of the existing regime, it could not break up the existing institutional lock-ins. However, due to legal interference in the projects, the opposition might still have a large impact by at least delaying and potentially preventing the construction of the terminals.

(2) An infrastructure lock-in is particularly related to potentially stranded assets of long-lived natural gas infrastructure, such as LNG terminals, but also pipelines and power plants. The fear of lost profits or destruction of values already prevents stronger regulation on natural gas, and would increase with additional infrastructure investments. As the synthetic gas niche does not pose an actual competition to the existing natural gas regime and would use the same infrastructure, the continuation or an even higher infrastructure lock-in is likely.

(3) The behavioural lock-in is more important on the consumer side and the heating sector, but the LNG terminals nevertheless also illustrate a behavioural lock-in, as the natural gas industry can continue and potentially even strengthen the status quo of their business with additional LNG supplies. A behaviour change is unnecessary, as regasified LNG fed into the grid is no different from conventional pipeline gas. Regime resistance fostered political support and beneficial regulation and advances the interests of the natural gas regime.

(4) A discursive lock-in exists, as the narrative of gas being a 'climate friendly' 'bridge fuel' is still dominant in the public discourse. It prevents a necessary debate about the barriers natural gas poses to advanced energy transitions and the change towards renewable energies by justifying natural gas use.

7. Conclusion

In this paper, we analysed the case of LNG terminal investment plans and related state support in Germany. This is particularly interesting because Germany promotes an energy transition towards renewable energies, but risks an increasing lock-in of the fossil fuel natural gas, contradicting GHG emission reduction targets. We analysed the material conditions around natural gas consumption and LNG infrastructure, and the interaction with relevant actors' perceptions and interests. This enabled us to identify the main lock-in mechanisms of LNG and natural gas, as well as other mechanisms generally supporting the role of natural gas in Germany. Together they can explain the political support for LNG terminal construction.

By linking the lock-in concept with the meta-theoretical energy transitions framework by Cherp et al. [16] as well as an actor analysis, we make a theoretical contribution to the energy transitions literature: In particular, we showed how actors walk between different realms, which shape energy transitions to enable or block change. This relationship with lock-ins will become increasingly important as they are key to understanding inertia and change in accelerating energy transitions. Our methodological contribution lies in a 5-step approach on how to combine a material analysis with an interview-based actor analysis.

This comprehensive approach enabled us to identify six mechanisms creating state support for LNG terminals. Two mechanisms represent institutional lock-in: A) pressure on German state actors to support LNG through international diplomacy and B) state actors supporting incumbents to ensure a secure supply–demand balance. Mechanism C) finding that regimes enable beneficial regulation through promoting the alignment of their vested interests with political interests is a form of regime resistance, while mechanism D) is a case of infrastructural lock-in, as sunk investments reduce the willingness for change. Two other mechanisms benefit natural gas's position in general: E) niche innovations strengthening the natural gas regime, and F) a weak opposition posing no counterweight to the regime.

In general, the strength of a well-anchored gas regime would be threatened by an ambitious climate policy. Thus, political lobbying tries to increase gas consumption in various sectors and construct new gas import capacities. Germany, despite its relatively high climate ambition, is providing strong state support to LNG, which risks leading to an increasing natural gas lock-in, even as natural gas consumption today is already inconsistent with future climate targets.

The development of German gas is interesting from a climate perspective, given that the country represents almost 25% of EU-27 natural gas consumption in 2019 [152]. Additionally, we deem the German case to hold lessons for the development of LNG in other European countries as they reach the 'next phase' of the energy transition. Many European countries already use natural gas, and now face similar challenges to Germany of managing a coal phase-out along with growing variable shares of renewables. We hold that our findings are particularly relevant to those countries in a similar energy situation and with a coastline to possibly install more LNG terminals, such as Spain, Portugal, or the United Kingdom.[54] How the international and national factors we identified play out in different states will shape to what extent the insights from the German LNG case are transferrable. All EU countries have closely linked energy markets. Diplomatic pressure from exporting countries could be a major challenge for the next phase of the energy transition. However, the degree of pressure they receive from international actors may differ due to the relative size and importance of their markets in the EU gas markets.

The perception of natural gas as a comparatively clean fuel and its link to synthetic gas will likely shape the development of LNG in all states. The discourse on and optimism about synthetic gases strengthens the natural gas regime generally, as they open a window of opportunity for political inertia in the sense that no unpopular decisions on a demand reduction have to be taken. Instead, the status quo can be prolonged with the promise that natural gas will be replaced by synthetic gases at a

[54] In Spain, two further terminals are currently under construction, while in the UK a proposal for an addition terminal exists.

later stage of the transition process. With the current immaturity of these technologies, this is a risky path. The relative importance of this lock-in mechanism will be shaped by the role of natural gas and synthetic gases in the countries' decarbonisation strategies. Finally, the well-observed phenomenon of states working with incumbents will likely be replicated. However, the strength of the natural gas regimes varies as well as the perception of the importance of natural gas for energy security.

As this is a case study on only one country, preliminary conclusions for other countries need to interpreted with caution. Also, more aspects of the natural gas sector besides LNG need to be analysed to understand the full lock-in. Another limitation of this research is that actors might have had incentives not to share all of their actual interests and plans in the interviews, which in turn might have altered the findings. As further research, we deem valuable a quantification of the GHG lock-in, and further qualitative analyses of natural gas lock-ins in other countries and sectors.

The main resulting recommendation for policy-makers would be to include lock-in risks in calculations for their decision-making: Especially when planning the ongoing energy transition, the risks for an accelerated transition posed by stranded asset, but also institutional, infrastructural, behavioural and discursive lock-ins need to be accounted for. To avoid an increasing natural gas lock-in and resulting negative economic and ecological impacts, natural gas infrastructure investments would need to be aligned with climate policy targets, and not only seen in a security of supply context. Otherwise, natural gas could crowd out investments in renewables and thereby slow down the shift to low-carbon energy sources. In addition, measurements of methane emissions and targets for methane emission reductions could help to reduce the climate impact. We also want to encourage further research on the role of natural gas in energy transitions, and the question how an increasing lock-in can be prevented.

Declaration of Competing Interest

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

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