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Perspective

Locked in a fossil-centric system paradigm: LNG expansion impedes socio-ecological transition toward a just and renewable energy future

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SUMMARY

The expansion of liquefied natural gas (LNG) infrastructure in Europe significantly impedes the necessary socio-ecological transformation (SET) required to shift toward a decentralized, 100% renewable energy system (RES). By reinforcing a fossil-centric system paradigm, LNG infrastructure deepens Europe's dependence on fossil fuels, thereby delaying climate goals and increasing greenhouse gas emissions. Additionally, "H2-ready" claims and carbon capture and transport technologies (carbon capture, transportation, and storage [CCTS]) serve primarily to prolong fossil pathways rather than support a genuine transition. These developments exacerbate environmental damages and raise critical justice concerns, unfairly burdening future generations and communities affected by resource extraction. The analysis emphasizes that expanding LNG capacity is unnecessary for energy security and poses risks of stranded assets and infrastructure lock-ins incompatible with climate goal objectives. To foster a just transition aligning with sustainable development goals, the study calls for halting further LNG infrastructure expansion and redirecting investments toward 100% RESs.

INTRODUCTION

In response to the climate and geopolitical energy crises, energy supply in Europe and beyond must undergo a profound and prompt transformation toward decarbonization and a fossil fuel exit.[1–3] The growing concerns and awareness about the negative climate and environmental impact of fossil natural gas[4] largely disappeared in the shadow of the energy-economic implications of the Russian invasion of Ukraine starting in February 2022.[5] On the ground, a remarkable restructuring and diversification of the energy imports of Europe took place, mainly affecting countries such as Germany, which were heavily reliant on Russian fossil energy exports.[6] Most countries could cope with the reduction of gas deliveries from Russia. During the winter of 2022/23, energy emergency plans, short-term high energy prices, and energy-saving measures by industries and households[7] ensured a winter without a gas shortage in Germany.[8] However, new and extensive import contracts and infrastructure, particularly for liquefied natural gas (LNG), were established at an unprecedented speed, driving the development of LNG production and export facilities in producing countries.

As a consequence, the fossil gas industry and national policymakers seized on a revival of LNG as a "bridge solution" to the energy crisis. Thus, the United States tried to strengthen its position as one of the world's leading LNG exporters, driven by strong European demand and increased trading activity. As one of the top three LNG exporters globally, alongside Qatar and Australia, the United States increased its total exports by 15% in 2023, largely due to increased shipments to Europe.[9] German energy providers, such as RWE, EnBW, and SEFE, have signed long-term contracts with US LNG exporters to secure LNG supplies produced in the United States.[10–12] US LNG is primarily produced from fracking gas ("liquefied fossil fracking gas"), which is highly damaging to the environment and has severe social and health impacts on communities near extraction, processing, and shipping sites,[13] like Port Arthur and Corpus Christi, Texas.[14] Other large LNG exporters were also active and increased their exports, e.g., Qatar.

The expansion of production has devastating consequences due to its climatic and environmental impact. These concerns lead to the temporary suspension of permits and investigations into the economic and environmental impact of LNG expansions in the US.[15] This development should prompt a global reassessment of LNG use. Politically and socially, the narrative that LNG is "saving" Europe's energy supply is gaining momentum. The narrative's framing addresses Europe's immediate energy

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security concerns and justifies the expansion of LNG export capacities in the US, reinforcing the role of US LNG in global energy markets. Our article demonstrates that the narrative is flawed and based on misconceptions by European importing countries, leading to highly controversial LNG overcapacities, both in exporting and importing countries.

We argue that transitioning from fossil natural gas to fossil LNG is not required for the socio-ecological transformation (SET) toward a just and 100% renewables-based energy system (RES). Consequently, severe negative impacts from LNG expansion on people and the environment are unjustifiable. Furthermore, we argue that expanding LNG infrastructure and usage is unnecessary from an energy-economics perspective, hinders the SET, worsens climate change, and deepens global injustices.

Building on previous research,[4,16–18] this article critically examines new LNG infrastructure developments in the EU, focusing on Germany as a case study. We demonstrate from four multiple dimensions that LNG expansion results in increased greenhouse gas emissions (GHGs) and ecological damage (3.1), fossil infrastructure overcapacities (3.2), and risks of asset stranding and fossil-centric lock-ins (3.3), all of which are misaligned with sustainable (regional) development. As a novelty, we extend classical energy-economic analysis by incorporating insights from transformation and sustainability research, challenging the narrative that LNG expansion is necessary for energy security and sustainable development in Europe (3.4). We expand our analysis to incorporate the sustainable development goals (SDGs) framework and the principle of a just transition, ensuring that social and justice impacts are also considered (4.5). Thereby, we acknowledge the importance of sustainability and justice aspects within safe operating spaces for humanity.[19,20] Hence, our case study offers valuable insights into energy transformation processes and contributes to a broader understanding of the SET processes going beyond climate change. Based on our analysis, we develop policy recommendations for the SET toward an RES within planetary boundaries to facilitate sustainable development.

FRAMEWORK FOR AN RES

We begin by defining our framework for an RES, distinguishing it from the common net-zero scenarios. In contrast to 100% RES scenarios, net-zero or ‘‘climate-neutral’’ scenarios often rely on balancing residual GHG emissions with removals through carbon capture, transportation, and storage (CCTS) technologies.[21] This approach is frequently used to justify the ongoing use of fossil natural gas. Additionally, many scenarios assume nuclear energy expansion to meet climate targets. However, nuclear power plants' continued operation and construction pose substantial safety, economic, and transitional challenges, making them unsuitable for a truly sustainable energy system.[22,23]

An RES relies on solar, wind, hydro, and other renewable sources and emphasizes the full phasing out of fossil fuels and nuclear power.[24,25] Recent research increasingly supports the viability and cost-effectiveness of an RES, demonstrating its superiority in enhancing energy security, achieving climate goals more effectively than net-zero strategies, and fostering citizen participation.[25–29] A decentralized RES is supply-oriented, meaning that demand is organized according to the availability of renewable energy. To ensure supply security, particularly for the industry and economy, and to meet society's needs (housing, mobility, etc.), the expansion of renewable energy should be given first priority. It requires flexibility options such as demand management, digital solutions, smart grids, storage, and Power-to-X and Vehicle-to-X options.[30] In an RES, the concept of baseload, previously provided by large, centralized fossil and nuclear power plants, is replaced by decentralized and intelligently networked RESs. Consequently, the proportion of baseload generation will decrease, and a smart grid will exhibit significantly more volatile load patterns.

The shift from a centralized, fossil fuel- and nuclear-based energy system—here referred to as ‘‘fossil-centric’’—to a decentralized RES has been promoted since the 1970s.[31–33] For Germany, exit, entry, and transitioning processes within the SET of the 21st century have been systematically examined by Präger[34] through the lens of applied transformation research, integrating interdisciplinary and transdisciplinary approaches. Amid the growing body of research on RESs, different national, regional, and global scenarios have been explored. In distinguishing between decentralized and centralized energy supply infrastructures, several technical-economic dimensions can be considered. However, it mainly addresses the spatial arrangement of generation facilities, such as for electricity, gas, or hydrogen. Their supply structures integrate various elements that can be aligned with either centralized or decentralized approaches.

The term ‘‘centralized’’ refers to both the allocation of individual large power plants and the associated ownership and organizational structures of these infrastructures,[35] which private, profit-oriented energy supply companies operate. By contrast, ‘‘decentralized,’’ community-based renewable energy plants are typically owned and operated by citizens or cooperatively organized energy companies.[36] These plants can be either non-profit or profit-oriented, as well as equitably organized, thus competing with traditional energy supply companies.[37] This contrast underscores the broader socio-economic implications of energy supply models, where decentralized systems present alternative governance and ownership structures compared with centralized, corporate-driven models. Decentralized approaches promote local control and community engagement, challenging traditional corporate dominance in energy production and distribution.

To set further context, we define the SET within a socio-technical framework, emphasizing the complex interplay of the energy system's intricately interdependent exit, entry, and transitional processes. In a broader context, recent research highlights that the climate crisis is just one aspect of ecological challenges that can trigger concurrent social crises.[17,38,39] Accordingly, the energy ‘‘transition’’ is not merely a techno-economical shift but a SET toward a just and sustainable (energy) future.[40] Therefore, evaluating energy-related developments like LNG and hydrogen expansion necessitates considering social aspects, including political feasibility[41] and energy justice, to ensure equitable benefits for all stakeholders.[38] Moreover, the SET extends beyond climate concerns to encompass ecological limits such as planetary boundaries.[42] This broader transformation perspective enhances our understanding of the social and environmental consequences of expanding fossil LNG infrastructure within sustainable development. It incorporates the concept of a just energy transition[43] and acknowledges the interconnectedness of social and ecological crises.[44] All these aspects are encapsulated in the concept of a just and renewables-based energy future, which aims to eliminate dependence on fossil fuels. This approach is increasingly regarded as the most viable pathway for social-ecological transformation due to its combination of technological feasibility, environmental sustainability, and cost-effectiveness.[29]

Based on these considerations, the concept of a SET toward an RES within planetary boundaries, combined with a focus on environmental justice, forms the foundation for the further assessment presented in this article. In doing so, we go beyond government-set climate targets and include ambitious sustainable transition criteria. By environmental justice, we refer to the fair distribution of environmental benefits and burdens across different social groups and generations and the inclusive participation of all people in environmental decision-making processes. This includes equitable access to natural resources and protection from environmental harm, regardless of race, income, or other social factors.[45,46]

ASSESSING THE MULTI-DIMENSIONAL IMPACTS OF LNG EXPANSIONS

Section 4 offers a multi-dimensional assessment of LNG infrastructure expansion in the context of the SET and RES. It examines the climate and ecological impacts (4.1), questions energy-economic justifications (4.2), highlights the risk of infrastructure lock-ins (4.3), and critiques the role of hydrogen in perpetuating fossil pathways (4.4). It also addresses justice concerns, including distributional effects, public participation, and conflicts with the SDGs, arguing for a shift toward a SET (4.5).

Climate mitigation and ecological dimension

Replacing fossil natural pipeline gas with fossil LNG means exchanging bad for worse. Nevertheless, this is precisely what is unfolding at present. The transition to LNG perpetuates reliance on fossil fuels and increases overall emissions. The entire LNG life cycle, from extraction to regasification, involves significant emissions. These include not only CO_2 but also methane, which has a far greater impact on global warming in the short term compared with CO_2.[4] The process of liquefying natural gas, transporting it across long distances, and regasifying it at the destination is energy-intensive and increases the emissions footprint.

The 2024 study by Howarth[47] assesses GHG emissions of LNG exported from the US, highlighting significant environmental concerns. Howarth found that in addition to methane emissions, the GHG footprint of LNG is somewhat 33% higher than that of coal. This highlights the significant environmental costs of LNG, especially considering methane's potent short-term impact on global warming. The study finds that despite their higher fuel efficiency, modern LNG tankers produce more emissions than steam-powered vessels due to methane slippage. Upstream and midstream processes, including gas production, liquefaction, and transport, contribute nearly half of the total emissions, while end-use combustion contributes only 34%.

Additional studies confirm significant emissions associated with LNG production, particularly due to the energy-intensive processes involved. The LNG supply chain, especially during the natural gas extraction stage, is a significant source of emissions.[48] Liquefaction, transportation, and regasification also contribute significantly, with emissions increasing as transportation distances grow longer. Liu et al.[49] highlight that LNG infrastructure remains a considerable emission source, particularly offshore gas flaring. Without targeted policies and technologies to reduce flaring, further LNG expansion could undermine efforts to achieve decarbonization goals.

While Burney's[50] study primarily focuses on the downstream air pollution effects of switching from coal to natural gas in the US, its insights extend to LNG. The findings demonstrate that transitioning from coal to natural gas can reduce some CO_2 emissions, but significant pollutants such as methane, particulate matter, and nitrogen oxides remain, impacting local air quality and contributing to regional climate change through alterations in aerosol composition and radiative forcing. Although these findings are based on the US context, they indicate that when natural gas undergoes energy-intensive liquefaction, is transported to Europe, regasified, and ultimately combusted, the initial emissions advantages are likely offset by the additional emissions generated throughout the LNG supply chain. This diminishes the potential environmental benefits of natural gas over other fossil fuels.

Similar findings have been corroborated in previous studies on LNG imports to Europe, mainly focusing on Germany, highlighting their significant contribution to climate change and revealing a higher carbon footprint than pipeline gas.[51] The study also highlighted that methane emissions are a significant issue in LNG imports, as leaks occur at multiple supply chain stages. These leaks could contribute to 14%–33% of the total GHG emissions associated with LNG imports, amplifying the environmental impact of the LNG life cycle.

LNG imports generally have a higher global warming potential compared with pipeline gas, largely due to the additional energy required for liquefaction, transport, and regasification. The climate impact of LNG imports also varies by country of origin. For example, emissions from the USA and Qatar are significantly higher than those from Norway, owing to differences in extraction techniques, infrastructure efficiency, and methane management practices. As fossil natural gas is not environmentally sustainable,[4] using it in its liquefied form as LNG exacerbates the problem, making it even more harmful.[52]

A further deterioration of the emissions balance is associated with LNG that is sourced from unconventional gas extraction methods (such as fracking in the USA), which tend to be higher than those from conventional extraction methods gas.[13] Considering planetary boundaries beyond just climate,[53] such as the contribution of, e.g., fracking techniques[54] and LNG in marine fuel to ocean acidification[55] or the impact of water-intensive processes on freshwater scarcity,[56] enlarge the pictures of the negative environmental impact of fossil LNG.

LNG is neither a climate-friendly alternative to coal nor to Russian pipeline gas. Although evidence indicates that natural gas extraction in Russia results in notably high methane emissions[57] and that methane regulation is relatively ineffective,[58] LNG does not provide a "better" or "cleaner" alternative to Russian pipeline gas in Europe.

We emphasize once again that fossil natural gas is fundamentally the wrong energy carrier for the SET.[4] Its significant climate impact disqualifies it as a "transition fuel," and recent developments regarding dependence on Russian gas, as well as the vulnerability of gas infrastructure to potential sabotage,[59] demonstrate that it is also unsuitable as an energy source for ensuring supply security.

Energy-economic dimension

A fossil gas exit is essential for creating a more sustainable energy system in Europe, whereby the declaration of fossil gas as a "bridge fuel" is a misconception.[55] The Russian invasion of Ukraine on February 24, 2022, strongly highlighted the vulnerabilities in gas supply and dispelled the myth of fossil gas as a secure transitional technology, given its significant climate impact, similar to coal, which constitutes a consequent fossil natural gas exit.[4]

Within Germany, the construction of 11 fossil LNG import terminals is justified as mandatory to attain energy independence from Russian gas supplies and to secure Germany's energy supply during a transitional period. A continuous energy-economic analysis since the Russian invasion, however, reaches divergent conclusions from the political and industrial action that takes place.[60,61]

Following the war, the European Union (EU) significantly reduced its dependency on Russian natural gas. Imports via major pipelines, including Nord Stream and the Ukraine transit route, declined, and by 2023, Germany had completely stopped importing Russian gas through pipelines.

2 years after Russia's war on Ukraine began, Germany's natural gas markets have stabilized.[60,62] A key indicator of this stabilization is the significant decline in natural gas prices, which have returned to pre-war levels across Europe. Market normalization has been supported by diversified supply sources and high storage levels, ensuring uninterrupted supply through the winters of 2022/23 and 2023/24. For example, the EU-wide storage level was at 94% in November 2023 and remained above 60% at the end of winter 2023/24, indicating strong supply security. Forward prices for contracts such as for March 2024 also reflected this trend, with prices dropping to around €25/MWh, compared with peaks of over €300/MWh in 2022.[62]

Importantly, the projected gas shortages that were used to justify the accelerated LNG expansion since mid-2022 did not materialize. Even under a complete Russian supply stop, Barner et al.[62] show that European gas demand can be met through alternative LNG sources—primarily from the US—as well as pipeline imports from Norway and Algeria, combined with moderate demand-side reductions. Their modeling shows that under the transformational zero emissions ("TZEs") scenario, only 27 bcm of LNG imports are needed by 2025, even if Russian gas flows cease entirely. By contrast, the planned and under-construction LNG import capacities across the EU total over 200 bcm, suggesting a severe overcapacity risk.

Given the expected structural decline in gas demand—projected to fall by approximately 35% in Germany by 2030 under current climate targets—and stabilized supply conditions, Barner et al.[62] conclude that it is appropriate to reassess the infrastructure expansion outlined in the German LNG Acceleration Act. In particular, the need for new land-based LNG terminals and the long-term role of floating storage and regasification units (FSRUs) should be critically re-evaluated. From a climate protection perspective, strengthening energy efficiency and accelerating the phase-out of fossil gas remain key priorities for aligning with Germany's and the EU's climate targets.

Despite stable supply and declining demand, the LNG infrastructure expansion in Germany continues. However, the low utilization rates of existing LNG terminals suggest that further expansion, including plans for new terminals like Mukran on Rügen, may not be necessary.[63] The LNG infrastructure expansion, justified initially by fears of a gas shortage, should be reconsidered in light of current market conditions to avoid unnecessary investments and fossil-centric lock-ins.

The existing fossil gas infrastructure is sufficiently developed, making further large-scale expansions unnecessary[4] or even risking stranded assets.[64] This is even confirmed in more fossil gas optimistic studies.[65] Moreover, in terms of supply security, research by Holz et al.[60] indicates that European countries can mitigate disruptions in Russian gas imports across various demand scenarios. Even with high demand projections through 2030, the EU's gas requirements could be met through existing pipeline imports and existing LNG capacities without additional infrastructure expansion. Their analysis suggests that enhancing energy efficiency and a consequent fossil gas exit would decrease reliance on Russian supplies while aligning with the EU's climate objectives. The potential future use of hydrogen and its derivatives remains uncertain, and repurposing fossil gas networks for possible future conversion to hydrogen could perpetuate the fossil-centric system without clear advantages. Considering that, even with moderate climate targets, the phase-out of natural gas is anticipated by the 2040s at the latest, the need for new infrastructure, such as LNG terminals and pipelines, is minimal.[60]

In examining recent LNG expansions in Germany, we assess the energy-economic justifications for these projects. Our findings, based on the latest research, suggest that the expansion of LNG infrastructure will not significantly mitigate gas shortages due to supply-demand imbalances, potential restrictive bottlenecks in the transportation network, and LNG's limited contribution to long-term energy supply security.

Infrastructure dimension

The urgency to mitigate climate change and secure planetary boundaries highlights the need for careful energy infrastructure planning. Given the potential long-term impacts and risks of path dependency, avoiding technology lock-ins and ensuring an alignment with an RES and climate goals is essential.[66,67] It requires a decisive break from the centralized fossil-system paradigm.

Generally, infrastructure serves the economic system, meaning it supports the overarching macroeconomic and energy-related goals through energy infrastructure planning, such as supply security and regional development. Therefore, the quality of the infrastructure, or its ability to efficiently and cost-effectively achieve these goals, is more important than the mere quantity of infrastructure expansion.[68] An excess of infrastructure can lead to inefficient resource allocation and promote environmentally harmful production structures, such as the export of fossil-based electricity.[69,70] Already in the past, European infrastructure development has overestimated network expansion and adhered to fossil-fuel trajectories, leading to technology lock-ins.[71] With the current expansion plans for LNG infrastructure, Germany and the EU risk repeating these mistakes.[61]

Mendelevitch et al.[72] analyzed European energy and climate policies, highlighting the political compromise that prioritizes a mix of fossil fuels (sometimes with CCTS), nuclear, and renewable energy. Holz et al.[71] argue that European infrastructure expansion has been overestimated and largely followed a fossil-centric path shaped by earlier scenarios. Past decisions heavily influence energy systems, leading to technological lock-ins.[73–75] This becomes particularly critical, emphasizing the need to avoid reliance on supposed "bridge technologies" in the EU, such as LNG terminals, that could reinforce carbon lock-ins.[76]

Thus, energy infrastructure development should be a subordinate technical system resulting from a renewables-based target system. Planning, construction, and operation of infrastructure must be system-supportive and not a vehicle to shape the energy system. The construction of LNG terminals, with operating permits and depreciation periods extending until 2045 and beyond, will lead to further lock-in effects within the fossil-centric system paradigm. Simultaneously, incentives and urgency to transform the current system into a primarily electrified RES will diminish. This shifts the transformation dynamic in favor of the fossil natural gas industry, which wants to maintain its capital-intensive infrastructure and the associated business models. We counter this strategy by advocating for a shift in focus from expanding fossil gas infrastructure to prioritizing decommissioning existing fossil gas networks, including local distribution systems and cross-border transmission lines.[77]

Another example is fossil hydrogen production, aimed to be a climate-friendly technology through CCTS,[78] risking extending fossil infrastructure and business practices as a misleading "bridge technology.[4]" Despite decades of research on CCTS as a potential solution for reducing carbon emissions, its impact on decarbonization is limited.[79] For example, while the IEA projected a capture capacity of around 195 Mt CO_2/year for the steel and cement sectors by 2021, actual deployment remained below 1 Mt CO_2/year.[80] Even looking ahead, the IEA's scenarios require 2,000 Mt CO_2/year by 2050—over 2,000 times current capacity and more than 100 times what is planned for 2030 (~19 Mt CO_2/year). This stark gap between projections and reality underscores the high uncertainty and limited contribution of CCTS to industrial decarbonization.

CCTS technologies often focus on maintaining existing fossil-centric infrastructure ("clean-coal") rather than achieving meaningful emissions reductions.[81] Only a small portion of "not-to-abate" emissions necessitate the use of CCTS.[25] Even under optimistic projections,[82] the development and deployment of CCTS infrastructure are progressing too slowly to provide adequate climate protection. Emission reductions are significantly undermined by the persistent upstream emissions associated with fossil fuel extraction, processing, and transportation.[83] Furthermore, the technical, environmental, and economic challenges of CO_2 storage are also largely underexplored, although the challenge is comparable in scope and complexity to the construction of repositories for high-level radioactive waste.[84] Given the high costs of capturing CO_2, preventing emissions at their source is more efficient and effective.

Transformative dimension

The discussion around hydrogen has been misguided from the outset by the strategy of the fossil gas industry, which has an economic interest in preserving fossil-based infrastructure and business models. The paradigm that hydrogen is necessary as a new energy carrier to replace fossil natural gas is misleading. Instead, the role of hydrogen in an RES is primarily limited to its use in some seasonal storage and as a feedstock for three products—methanol, aviation fuel (kerosene), and ammonia—which can primarily be produced in Europe and transported and utilized with existing infrastructure.[85] Hydrogen derivatives, therefore, complement an almost fully electrified energy system, contrasting with the strategy of a comprehensive global hydrogen economy. Emphasizing the direct electrification of final energy demands—particularly in the short term as renewable electricity capacity expands—can significantly reduce the need for liquid and gaseous fuels. In Germany, plans for LNG import infrastructure are often justified by claims that the facilities will be H_2 ready, implying future compatibility with hydrogen. This term refers to the technical ability of natural gas-based infrastructure—like heating systems, turbines, LNG terminals, and pipelines—to transition from fossil natural gas to a blend of natural gas and hydrogen ("blending") and eventually to 100% hydrogen operation.[86] This strategy, mainly promoted by gas turbine manufacturers with the goal of using renewable fuels by 2030, lacks a clear definition. This raises concerns that it might prioritize blending hydrogen with natural gas[87] rather than fully transitioning to 100% renewable hydrogen, risking the perpetuation of fossil natural gas extraction and further fossil lock-ins and climate risks.[88] Moreover, retrofitting combined heat and power plants for district heating with H_2-ready turbines may lead to prolonged fossil gas as affordable renewable hydrogen is rare, enabling CCTS in the energy sector or wasting expensive hydrogen on inefficient heating purposes. Additionally, the necessary dismantling of the natural gas distribution network, ideally coordinating with the development of district heating networks, is often overlooked.[77]

Technically, hydrogen's low volumetric energy density means that blending with fossil natural gas displaces less fossil energy than the volume ratio might suggest, resulting in only marginal emission reduction, supporting concerns about fossil natural gas "greenwashing.[89]" The H_2-ready strategy is significant for the conventional heating industry. Gas sector organizations and heating, ventilation, and air conditioning companies are eager to integrate hydrogen into the building sector. Despite robust contrary evidence,[90] the industry urges the government to support hydrogen in buildings, emphasizing consumer independence from electricity prices and downplaying hydrogen costs and availability. However, if the hydrogen supply falls short, fossil gas may continue to be used directly or for hydrogen production, as the continued focus on hydrogen risks sidelining already available and scalable alternatives—such as electric heating systems like heat pumps, infrared heating, and electric boilers, as well as renewable heating options including solar thermal, biomass-based, and geothermal district heating.

The LNG Acceleration Act in Germany allows for the construction of LNG terminals under the claim that they are H_2 ready.[91] However, the law only requires these terminals to use "climate-neutral hydrogen" or its derivatives starting from 2043, with no current evidence of the technical feasibility or a clear definition for its conversion.

Unlike LNG, the transport, landing, and regasification of liquid hydrogen (LH_2) impose much higher demands on infrastructure, particularly insulation and cooling technologies, making it more akin to new construction rather than retrofitting.[92] It leads to higher costs and uncertainty about the emergence of a seaborne LH_2 market or the use of hydrogen derivatives like ammonia. While the political narrative of reusing LNG terminals for hydrogen justifies expanding fossil-centric infrastructure, recent research shows that existing LNG terminals are not suitable for hydrogen imports,[92] as FSRUs cannot be converted for hydrogen use, and stationary terminals would need expensive retrofits of fundamental components like storage tanks and heat exchangers, essentially requiring new infrastructure.

Despite the initial focus on renewable hydrogen in the European hydrogen strategies, using hydrogen derived from natural gas—primarily fossil-based with CCTS (often referred to as "blue hydrogen")—has become widespread and is integral to most hydrogen strategies. However, this is a misguided, false solution in terms of climate protection technology and transformational aspects. The fossil hydrogen technology is often promoted as a lifeline for the natural gas industry, but it carries significant risks, including another iteration of fossil-centric path dependencies and lock-in effects. Hydrogen production from methane via steam reforming leads to methane leakage and continued CO_2 emissions, as not all CO_2 can be captured and permanently stored in a final repository.[4] Studies show that burning fossil hydrogen with CCTS results in a 20% higher GHG footprint than burning natural gas.[93] At the center of the debate, the cement industry is frequently used as a questionable justification for large CCTS infrastructure, diverting resources from more sustainable alternatives.[80] Alternatives, such as cement recycling[94] or mitigation strategies,[95] which have the potential to completely eliminate CO_2 emissions, are often downplayed or ignored. Lastly, it is essential to address what happens after capturing CO_2. Using captured CO_2 as feedstock for products or synfuels is merely a form of temporary storage, as these products are eventually burned, releasing large amounts of emissions into the atmosphere, or end up unburned in the world's oceans. So, the final storage of CO_2 is the only path to have positive climate effects. Based on these issues, we conclude that only 100% renewable hydrogen is beneficial for the SET—if used in not-to-abate sectors and under strong justice considerations, as even imported renewable hydrogen can bear negative socio-political implications.[38,96,97]

Incorporating justice and resource perspectives at both national and global levels into future hydrogen use necessitates a critical reflection on prevailing consumption patterns as represented in current climate and energy scenarios. A mere substitution of fossil fuels with 100% renewable energy sources risks reinforcing existing extractivist logics if not accompanied by a deeper SET. In this regard, sufficiency-oriented scenarios and a broader sufficiency paradigm must be seriously considered—particularly where a just and sustainable hydrogen use within planetary boundaries cannot be achieved under current conditions.[44] Addressing the socio-political and ecological implications of hydrogen consumption thus requires not only technological innovation but also a fundamental reassessment of what constitutes a desirable and equitable energy future.

In addition to technical challenges, the significant role of non-European imports presents another critical issue. Relying on future hydrogen imports is problematic due to economic constraints, as transportation costs make imported hydrogen expensive, contributing to 30%–60% of the total cost.[98] This economic burden raises concerns about the feasibility of large-scale reliance on imported hydrogen. Another key problem is the inadequate consideration of ecological and social justice aspects in the few initial hydrogen projects.[99] Addressing these issues appropriately will likely result in higher costs, reduced profit margins, and diminished import potential.

A further challenge lies in ensuring the actual sustainability of imported hydrogen. As global supply chains begin to develop, it remains difficult to guarantee that hydrogen reaching Germany and Europe—particularly from non-European countries—meets the criteria for truly renewable hydrogen. In the absence of robust certification and monitoring systems, there is a risk that hydrogen labeled as "clean" may in fact be based on fossil sources, such as so-called "blue hydrogen." This poses similar risks to those already discussed in the context of H_2-ready LNG infrastructure, potentially reinforcing fossil fuel lock-ins under the guise of transition.

Developing the production and availability of renewable hydrogen and its derivatives is highly uncertain. There is first evidence that the extensive expansion plans are excessive and not driven by actual needs, given the minimal progress on the anticipated hydrogen supply in Europe.[95] Renewable hydrogen supply will be less than 1% of final energy in the EU by 2030 and globally by 2035, underlining renewable hydrogen's short-term scarcity and long-term uncertainty.[100] According to a report from the European Court of Auditors (ECA), the European Commission's hydrogen production and import targets for 2030 may be excessively ambitious. The ECA argues that these targets are driven more by political motivations than by thorough and robust analyses.[101]

Just transition dimension

Framing the energy transition within the context of the SET approach highlights its nature as a socio-technical transformation. In that case, it becomes clear that ecological and economic criteria, but also social and justice criteria, should be considered in energy infrastructure expansion.[40,41] Thus, neglecting just transition aspects and fossil-centric lock-ins cannot foster sustainable development and an RES.

There are growing concerns that LNG expansion hinders the SET and exacerbates justice conflicts.[17,39] LNG expansion can raise conflicts with key aspects of a just transition, particularly in terms of procedural justice and public participation for both current and future generations, the Global North and the Global South.

For example, protests at the Mukran LNG terminal in Germany underscore procedural justice issues, as citizens felt their concerns were ignored during planning. This is because the LNG terminal facilities were constructed in an expedited process. Hence, participation procedures were difficult to implement, leading to protests and lawsuits from local communities and environmental organizations.[102]

The absence of participation can erode public trust and acceptance and weaken the shared vision necessary for a successful SET. Fostering procedural justice through inclusive decision-making is essential, not just for fairness but also to maintain the long-term support of communities affected by such developments.[103–105]

LNG expansion also risks delaying the socio-ecological shift toward a renewable energy future, imposing higher costs and risks on future generations as necessary. Technologies like CCTS, often linked with LNG, burden future generations, as the CO_2 literally needs to stay underground forever, and thus longer than the current generation can take care of. From an ethical justice perspective, this poses a disproportionate burden of managing CO_2 storage on future generations, who are already more vulnerable to the escalating impacts of climate change and environmental degradation, which they did not cause.[106]

Furthermore, potential conflicts with the SDGs, which promote sustainable human development, are strong indicators of whether a technology or energy strategy aligns with the principles of a just transition.[17] From an SDG perspective, the expansion of LNG infrastructure brings several conflicts into focus.

First, SDG 7 (affordable and clean energy) might be jeopardized. While renewable energy offers the most cost-effective solution, LNG impedes the transition to an RES. LNG prices, especially during times of crisis, disproportionately affect low-income households, which already bear higher energy costs relative to their income, particularly often living in poorly insulated homes.[107]

There is also a direct conflict with SDG 3 (good health and well-being). Increased use of LNG and associated CCTS technologies brings environmental and health risks, including air pollution from continued fossil fuel use, noise pollution from LNG terminals, and health consequences from the process of fracking.[108] In addition, building LNG infrastructure can degrade coastal environments, which often serve as spaces for recreation and mental well-being.[109] The recent 15-year LNG contract between the German state-owned SEFE and the US-based Delfin LNG project highlights these concerns.[110] Approved just days after a fast-tracked executive order by former President Trump, the deal involves fracked gas and a controversial offshore terminal in the Gulf of Mexico, raising environmental concerns, particularly for marine life and fisheries.

SDG 12 (responsible consumption and production) also is at risk. LNG infrastructure could create a false sense of climate-friendliness, leading to behavioral lock-ins where households continue unsustainable energy consumption patterns.[76] On the production side, responsible production also includes the responsible use of financial resources. Constructing long-lasting infrastructure like pipelines and terminals is incompatible with the necessity of fossil fuel phase-outs required to achieve the 1.5°C climate target and net-zero goals. From a green finance perspective, investments in LNG expansion and all fossil energy facilities hinder progress toward environmental goals and redirect financial resources away from renewable energy technologies.[111] Investments in LNG infrastructure divert capital from renewable energy and innovative technologies—such as renewable hydrogen, grid upgrades, and industrial electrification—thereby undermining sustainable infrastructure development and conflicting with SDG 9 (industry, innovation, and infrastructure) by hindering the advancement of sustainable industrial practices and the innovative infrastructure necessary for the SET.

The expansion of LNG has international ramifications beyond Germany, as the German, European, and global energy systems are interconnected. These interdependencies and energy trade partnerships significantly shape domestic and foreign energy transitions, influencing policy, infrastructure, and market developments across borders. Analyses show that especially resource-rich developing and emerging countries of the Global South focusing on fossil energy and its export are at risk of massive energy asset and resource stranding. Due to their strong dependence on fossil fuel exports and often weak political and social systems, these countries and their populations are particularly vulnerable to the severe and wider socio-economic consequences of declining export revenues—a trend increasingly driven by global energy transition efforts, especially of the Global North.[112] This effect is further exacerbated by LNG partnerships. Hoffart and Holz[38] propose a benefit-sharing framework for energy partnerships, which especially refer to (in)justice issued between the Global South and Global North and refers to SDG 17 (partnerships for the goals). It emphasizes that both exporting and importing countries, especially their population, should profit mutually from these partnerships, which also contributes to SDG 8 (decent work and economic growth). Energy-transition benefit sharing ensures that trade does not hinder a country's energy transition. Country-level benefit sharing means the economy and industry gain advantages, while population-level benefit sharing ensures that local communities face no disadvantages, with opportunities to participate and improve their regional development. Applying the framework to LNG and hydrogen makes the justice conflicts clearer.

CONCLUSIONS FOR ENERGY INFRASTRUCTURE DEVELOPMENT

This multi-dimensional analysis highlights that expanding LNG infrastructure is not only unnecessary for advancing the SET but actively hinders it by exacerbating negative effects on people, the climate, and ecosystems. LNG development reinforces the fossil-centric energy paradigm, delaying the shift toward a decentralized RES. Relying on fossil LNG infrastructure and hydrogen derived from fossil natural gas, especially when justified by H_2-ready claims and CCTS technologies, risks entrenching fossil fuel pathways and may even elevate GHG emissions.

The expansion of LNG infrastructure also raises significant justice concerns, disproportionately burdening future generations with technologies like CCTS and fracking, which could compromise the SDGs related to affordable energy, health, and responsible consumption. Our findings suggest that there is no valid energy-economic necessity for increasing LNG import infrastructure in Europe if the transformation to an RES progresses as planned. Therefore, producing and exporting countries must prioritize fossil-exit strategies and develop just transition frameworks for the affected communities.

The EU has introduced key policy mechanisms—such as the methane regulation, European Union Emissions Trading System (EU ETS) and ETS2, the Energy Efficiency and Renewable Energy Directives, the Gas Market Decarbonization Package, the Sustainable Finance Taxonomy, and the Energy Taxation Directive—to reduce demand for and disincentivize imports of environmentally harmful LNG. These instruments must now be consistently implemented, strictly enforced, and further developed to support a SET aligned with climate justice and sustainability goals.

In conclusion, expanding fossil-centric LNG infrastructure for the false premises of energy security and sustainable development in Europe keeps us trapped in a fossil-centric system paradigm. Breaking away from this paradigm requires a concerted effort toward a SET and the establishment of a decentralized and just 100% RES.

AUTHOR CONTRIBUTIONS

Conceptualization: F.P. and F.M.H.; investigation and analysis: F.P. and F.M.H.; writing – original draft: F.P. and F.M.H.; writing – review and editing: F.P., F.M.H., C.K., and C.v.H.; supervision: C.v.H.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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