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Pathways to Overcoming Natural Gas Dependency on Russia—The German Case

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Abstract: The war in Ukraine has sensitized German policy makers towards the negative economic impact of a curtailment of natural gas flows from Russia. Given its large import dependency, Germany has implemented regulatory measures for mitigating a possible gas shortage and is seeking to diversify from pipeline imports of liquefied natural gas (LNG). In this context, we provide a comprehensive review of the natural gas crisis in Europe and place it in the context of the peculiar role of natural gas in Germany. We critically discuss the economic impact of an embargo, and assess demand and supply factors capable of mitigating a supply shortage. We derive a short-term import substitution potential of 13 bcm, assuming timely installation of Floating Storage and Regasification Units (FSRUs). We discuss the potential for demand reductions in the power sector, in industry consumption, and in households, and estimate a combined maximum of 24.1 bcm. Under decreased industrial demand, the most optimistic scenario indicates an import gap of about 9 bcm for a one-year perspective. Given our findings, we advocate for the delayed phasing out of coal and nuclear power, the accelerated deployment of renewable energy, and caution in the initial execution of storage quotas and restrictions to industrial consumers.

Keywords: natural gas; energy policy; energy security; diversification; import embargo

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1. Introduction

As a result of record prices at European gas hubs and looming supply shocks, European importers of Russian natural gas are laying out strategies for mitigating a gas crisis. In the longer-term view, the German government aims to reduce natural gas imports from Russia to a maximum of 10% by 2024 [1]. The Russian invasion in Ukraine, however, and halting Russian supply to several European countries, call for short-term measures to avoid a natural gas shortage, implying import diversification and demand adjustments. Given constraints to these measures, in the form of limited import alternatives and the feasibility of demand adjustments, pathways for reducing the import dependency on Russian natural gas cannot follow an ideal scenario. Rather, with the goal of avoiding the negative economic consequences of a gas shortage, these pathways are defined by the immediate need to find substitutes for Russian gas in imports and consumption.

Germany has developed a great dependence on natural gas imports from Russia, which had an import share of 55% in 2020 [2] and totaled 46 billion cubic meters (bcm) in 2021 [3]. Despite traditional use cases in households and industry, in Germany, natural gas-fired power plants have been given the additional role of providing a buffer for the intermittency of increasing shares of renewable power, because of their quick switching times compared to those of coal-fired power plants. Furthermore, natural gas offers a cleaner alternative to other fossil fuels, emitting about 45% less CO_2, on average, than coal [4]. Investments in natural gas infrastructure were therefore declared sustainable under the EU taxonomy, if aligning with the EU's decarbonization targets [5].

Having an industry consumption share in 2021 of 37.2% [6], natural gas is applied in various industrial processes, largely for process heat. In addition to a great reliance on natural gas for households (31.2% of consumption in 2021 [6]), the challenge of a gas shortage for the industry sector lies in the use of gas for the manufacturing of base materials. The largest contributors to industrial demand are the chemical industry (29.1%), food industries (15.2%), and the metal work industry (12.5%) [7]. Because of the high specificity of industrial use cases, the potential for a quick substitution of natural gas for other energy sources is limited [8]. Therefore, a sudden curtailment of natural gas flows from Russia to Germany, for which Germany is unprepared, can have detrimental effects on the economy. Critical assessments indicate the cumulative two-year negative GDP effect may be 5.3%, with additional unemployment of 750,000 [9]. Studies using a dynamic model, in which substitution can reduce the negative effects on the German economy, project a substantial but manageable GDP impact between 0.2% and 0.3% [10]. Although the author's most pessimistic assessment yields a negative 3% contribution to GDP, a previous study [10] further advocates an early voluntary gas embargo to trigger necessary adaptation processes.

Inadequate storage build-up over the summer months of 2021 by Gazprom, and its subsidiary Astora, fueled the fear of a European gas shortage and led to a dramatic price increase, with a yearly high of 116 EUR/MWh reached on 5 October 2021 [11]. As a response to the inadequate filling of underground storage, several regulatory measures have been undertaken, such as the declaration of mandatory storage quotas. Because of the historic abundance of pipeline gas from Russia, Germany did not develop domestic LNG import capabilities, restricting the possibilities for import diversification. Facing reduced imports from Russia and threats of a natural gas supply shortage, Germany has therefore taken out options for chartering Floating Storage and Regasification Units (FSRU) to enable the short-term domestic import of LNG.

The crisis regarding natural gas can be framed theoretically with the concept of energy security. Energy security may concern different subsets of risk sources, such as technical, human, or natural risk sources, whereas most definitions focus on the availability of commodity supplies [12]. No universal definition of energy security exists [13] and definitions can be found to be contextual and dynamic [14]. Review studies criticize the isolated focus on individual energy carriers [15], and a widening scope to include environmental sustainability and energy efficiency has been identified [14]. Previous research [16] thus points to the significantly improved energy supply diversity and lower import dependence in the EU, due to increasing renewable energy. Because of the interlinking dynamics of fossil fuels and renewables, a twofold process is called for that recognizes the low-carbon transition and the phase-out of fossil fuels (high-carbon transition) [17].

A distinction can be drawn between short- and long-term energy security [18], in which the former concerns relative shortages (demand and supply mismatch), partial or complete supply disruptions, and their mitigation [19]. A number of indicators for long-term import dependence exist, such as the Shannon index, which calculates the relative concentration of an import source weighted by a country's energy mix [20], and may be extended by factors of political risk ratings [18]. A popular approach for identifying elements of long-term energy security are the four As, comprising the Availability, Accessibility, Acceptability, and Affordability indicators [21]. Although these categories experience a complex interplay and are context-dependent [22], the IEA defines energy security "as the uninterrupted availability of energy sources at an affordable price" [23].

The Russian state company, Gazprom, has long been accused of exploiting the energy dependence of European natural gas importers for political leverage [24], and several studies have critically assessed Russia's use of the "energy weapon" in Europe (e.g., [25,26]). Deteriorating energy security is described as the result of total dependency on one natural gas supplier, such as Russia [13]. Although diversity is a necessary but not sufficient condition for the security of energy flows [27], studies note the harm of the EU's import dependency on energy security [28]. In the context of our study, short-term definitions are most relevant, which define energy security as the low vulnerability of vital energy systems [29], the ability to insure against the risk of import disruption [30], or simply energy system resilience to disruptions [31]. Other applicable definitions frame energy security as the continuity of commodity supplies [12].

Several studies have also constructed theoretical indices for measuring import risk of natural gas (e.g., [32–34]; also see [35] for a review of energy security indices). The need for short-term natural gas import diversification in Germany, however, is acutely driven by diminished energy security, caused by an existing disruption (see [12,30,31]) in the form of reduced flows through the Nord Stream I pipeline from Russia to Germany. Given the practical implications of a gas shortage on consumers and the overall economy, immediate measures are needed to ensure adequate supply of natural gas in the coming months, when ideal scenarios are not available. Motivated by this unique crisis, we undertook a systematic literature review and, in this paper, deliver a short-term outlook for closing the import gap of Russian natural gas via demand adjustments and import substitution (Figure 1). We contribute to the existing literature by providing a joint economic perspective that takes into account technical import constraints and infrastructure developments. Our study offers a comprehensive review of the roles of Germany and Russia in the dynamics surrounding the current gas crisis, and an assessment of pathways for overcoming an acute gas shortage. Unlike other studies, we thereby provide a link between policy measures, the economic impact of a full embargo, and practical suggestions. Our framework follows the necessity for immediate gas savings and import diversification.

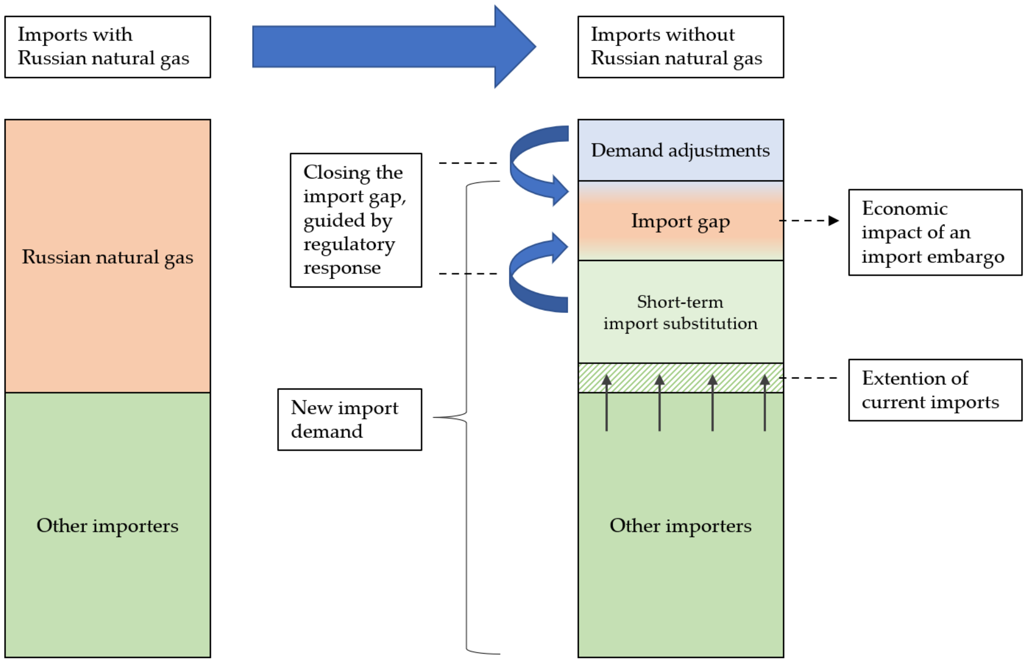

Figure 1. Methodology framework: from an import portfolio with Russian natural gas to an import portfolio without Russian natural gas through import substitution and demand adjustments.

In addition to traditional transport via pipelines, natural gas allows for a flexible transport mode via sea cargoes. Unlike that in crude oil, however, LNG trade requires costly cooling of gas and regasification at a destination terminal. Due to the lack of LNG terminals in Germany, options can be taken for FSRUs, which function as temporary floating terminals to import LNG from the global market and for diversion of seaborne cargoes. We estimate Germany's short-term import substitution capability and merge these with the literature findings to provide feasible demand reductions across various sectors. Even for optimistic estimates, however, our findings indicate a natural gas import gap of about 9 bcm in the coming year.

In addition to providing for the necessary infrastructure for LNG imports via FSRUs, we urge policy makers to accelerate the deployment of renewable energy and to consider the temporary lifetime extension of coal and nuclear power plants. Furthermore, in light of the economic risk of a possible natural gas shortage, we call for flexibility in applying mandatory storage quotas, in addition to caution with regards to restrictions on the industrial sector. The remainder of this paper is organized as follows: Section 2 offers an overview of the use of natural gas in Germany and its role in the economy. Section 3 delivers a comprehensive review of the market developments surrounding the Russian invasion of Ukraine and the regulatory responses undertaken by Germany and the EU. Section 4 reviews the economic impact of an import embargo, after which we provide detailed short-term supply and demand strategies for mitigating the gas crisis in Section 5. Section 6 offers a comparison to the situation in other European countries. This is followed by the discussion in Section 7 and the conclusion in Section 8.

2. Natural Gas in the German Economy

2.1. Energy Mix and Consumption

The latest challenge in mitigating a gas supply crisis for Germany stems from the important role of gas in its energy supply and a great reliance on imports. In 2020, the share of natural gas in the energy mix amounted to 26.4%, being surpassed only by oil consumption (34.3%) and followed by renewable energy (10.4%) [36]. Despite a slight decrease in imported volumes, surging wholesale prices, especially in the latter months of 2021, contributed to a stark rise in import expenses. The monetary value of Germany's natural gas imports thus increased by almost 100%, from EUR 18.3 billion in 2020 to about EUR 35.4 billion in 2021 [37]. The role of natural gas for Germany is further emphasized by a comparatively higher share in the energy mix than that in neighboring countries. In France, for instance, which has a great reliance on nuclear power, the share of gas in the energy mix amounts to only 16% [38]. Because of the intended use of gas as a transit fuel in the country's energy transition (Energiewende), Germany has increased its reliance on natural gas in light of the phase-outs of both coal and nuclear power.

Total German natural gas consumption in 2021 amounted to 93.4 bcm (i.e., equivalent to 1012.2 TWh; throughout this paper, we refer to the gross caloric value when applying conversion factors and, following German convention, this translates to a conversion factor of 1 bcm = 38.988 MJ (see [36])) [39]. Having only a miniscule domestic supply of 4.66 bcm (about 5% of consumption), the vast majority of consumed gas is imported. Net imports in 2021 amounted to 83.17 bcm and increased by about 4.9% compared to the previous year. The remaining supply share of 5.61 bcm originated from net storage withdrawals [39]. Due to its vast pipeline import capacity, especially from Russia, Germany acts as a natural gas distribution hub for other European countries. Total imports transiting Germany in 2021 amounted to 154.46 bcm. Thus, 73.3 bcm of imported gas (46.1% of gross imports) were exported to neighboring European countries. Although BAFA, Germany's Federal Office for Economic Affairs and Export control, stopped publishing the origin of natural gas imports in 2016, BP's statistical energy review offers a widely used benchmark for natural gas flows.

Figure 2 depicts the development of the origin of Germany's natural gas imports between 2010 and 2020. The import share of Russian natural gas increased gradually between 2009 and 2020 from about 30% to 55% [2]. Although Figure 2 indicates a clear trend towards greater imports from Russia, an import share of more than 50% is not unprecedented. The share of imports from the former Soviet Union amounted to 50.4% in 1988 and stayed above 40% in the following years between 1989 and 2008 [37]. The mutual dependency between natural gas imports to Germany and the flow of foreign currency reserves into Russia originates from the substitution of coal with gas in Germany in the 1970s. The first gas imports were recorded in 1973, under a deal commonly referred to as "pipes for gas", which saw the former Soviet Union deliver natural gas in exchange for steel pipelines from Western Germany. As no stoppages in gas flows were experienced during the cold war, the cooperation has long been considered a trust-building mechanism and may partially explain Germany's continued reliance on imports from Russia. The trade relationship intensified during the oil crisis, and initial imports through the extension of the Soyuz and Brotherhood pipelines to Bavaria were soon extended with imports through the Yamal pipeline in the mid-2000s, followed by the Nord Stream pipeline through the Baltic Sea.

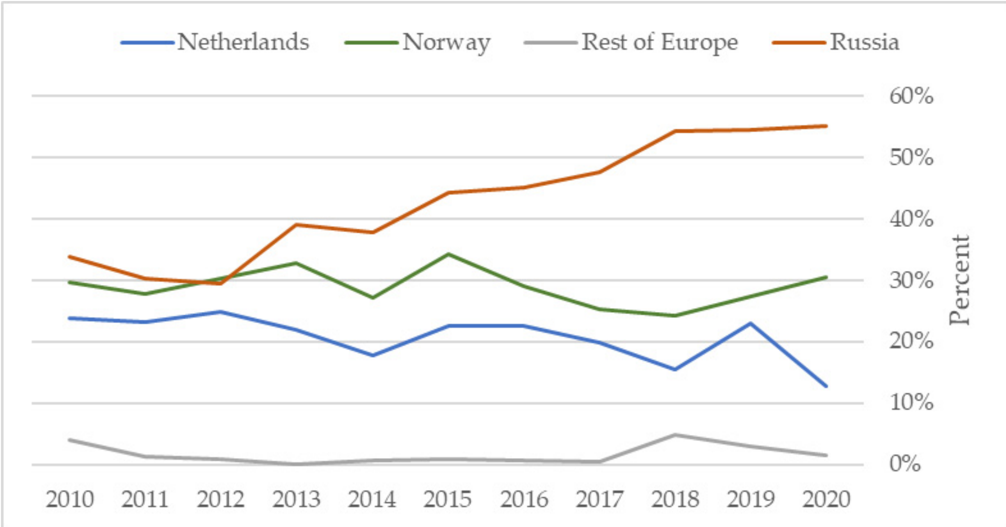

Figure 2. Origin of German natural gas imports: 2010–2020. Source: [2].

Natural gas is traditionally used in industrial processes, and in private households for heating, because it is a cleaner alternative to coal and oil. Thus, the importance of natural gas for the German economy has further been increased due to its role in providing a buffer for the intermittency caused by increasing shares of renewable power. The EU has therefore declared that investments in natural gas infrastructure are sustainable under the EU taxonomy when aligning to the goal of decarbonization. Figure 3 shows the supply origin of Germany's natural gas consumption in 2021 (on the left) and a breakdown of consumption patterns by sector (on the right). We note that most of the gas supply originated from yearly imports, amounting to 83.17 bcm, which in 2021 were supplemented by net storage withdrawals of 4.66 bcm and domestic production of 5.61 bcm [39].

Figure 3 emphasizes the important roles of the industrial sector and households in total natural gas consumption; in 2021, households accounted for 31.2% of total consumption and the share of industry consumption amounted to 37.2% [39]. Figure 3 further indicates that, in 2021, in the wake of the gas crisis, only 9.3% of natural gas was consumed for electricity production, a 30.3% decrease compared to the previous year. In absolute terms, about 29 bcm was consumed by households and 34.7 bcm by the industry sector. District heating and electricity production were responsible for consumption of 8.8 and 8.7 bcm respectively, and consumption in the trade and commerce category amounted to 11.9 bcm [39].

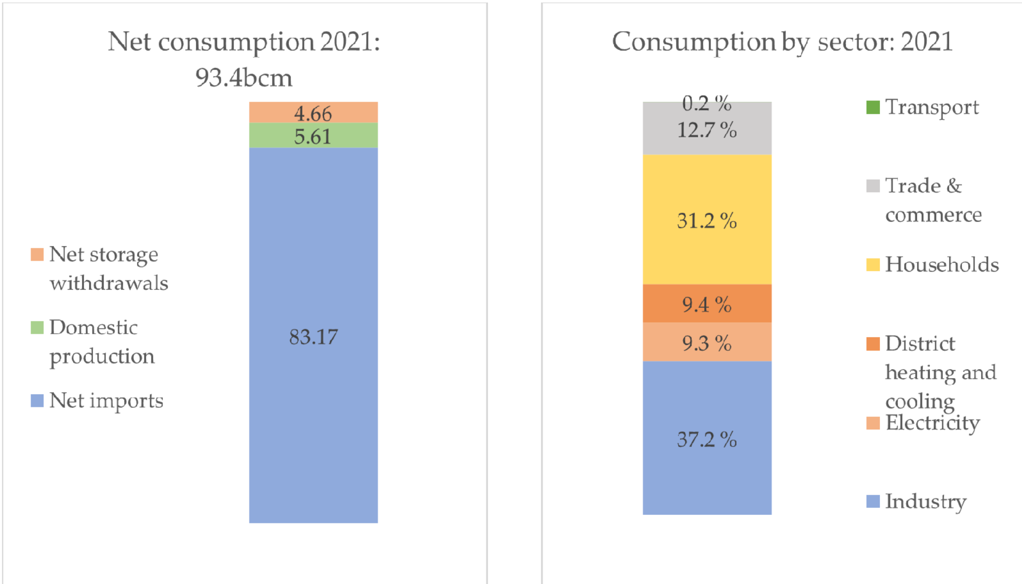

Figure 3. Supply sources of natural gas consumption in Germany in 2021 (**left**) and relative consumption share by sector (**right**). Source: [39]. Note that different publications show slight variations in the consumption share of sectors. For details see: [6,40–42].

2.2. Import Flows and Storage

Although requiring substantial upfront investments for the construction of liquefication and regasification terminals, LNG promises a more flexible trade flow compared to the traditional pipeline flows. Despite a great reliance on imports to meet its natural gas demand (Figure 3), until 2022, Germany had not developed any domestic import capacity for LNG because of the availability of sufficient pipeline import options, especially from Russia. With a 34.3% share in the country's primary energy supply, oil plays an even greater role for the German primary energy supply than gas, which has a share of 26.4% [36]. Diversification of gas imports in comparison to the import of oil, however, faces greater obstacles. These obstacles, despite the lack of alternative pipeline routes, relate to the costly and time-intensive construction of regasification terminals. Whereas crude oil can be transported by ship in its natural liquid form, LNG transport requires gas for high-energy use to be liquefied in specialized plants for export, transported in specialized vessels, and regasified at a destination terminal. In the EU, existing LNG terminals are primarily located in countries having previously significant, yet declining, natural gas production, such as the UK or the Netherlands. Because of its large share of idle LNG regasification capacity, during the current crisis, Spain has moved into focus for EU import diversification. The lack of a connection to France and the central European pipeline network via the Pyrenees, however, prevents the country's idle LNG import capacity from contributing to import diversification.

Russian natural gas reaches Germany and central Europe through three main pipeline systems. Historically, the most significant connection has been the Ukrainian transit (Soyuz and Brotherhood pipeline) with a total capacity of 120 bcm/year [43]. These pipelines merge into Transgas, which reaches Germany through Hungary and the Czech Republic, while also playing a significant role in the supply of other European countries, such as Italy and Austria. The Yamal pipeline delivers natural gas to Germany via Belarus and Poland, and has a capacity of 33 bcm/year. Lastly, the Nord Stream I pipeline directly connects Germany to Russian gas fields via the Baltic Sea and offers a yearly capacity of 55 bcm; this pipeline further extends through Germany into Denmark, the Netherlands, France, and Belgium. Norwegian pipeline capacity via Nordpipe, and Europipe I and II, totals 54 bcm/year [43]. More recently, the Southern Gas Corridor also began to deliver gas from the Caspian Sea and Azerbaijan through Turkey into Greece and Italy, with a capacity of 10 bcm/year.

Natural gas from storage supplements imports during the high demand of the heating season. Total German storage capacity amounts to 21.23 bcm, which is equivalent to about 25% of annual consumption [44]. As expected, the supply share from storage is large, as household consumption accounted for 31.2% of total annual consumption in 2021. In Germany, about half of the underground storage is located in salt caverns, and the other half, including Germany's largest storage facility in Rehden, is situated in depleted gas fields. Figure 4 outlines the market share of the largest underground gas storage operators in Germany. Astora, a 100% subsidiary of Russian Gazprom, operates Germany's single-largest storage facility in Rehden, with a working capacity of about 4.5 bcm. Together with a second unit in Jemgum (0.83 bcm), Astora's joint capacity of 5.3 bcm makes it Germany's second-largest natural gas storage operator, with a total market share of 21.7% (Figure 4).

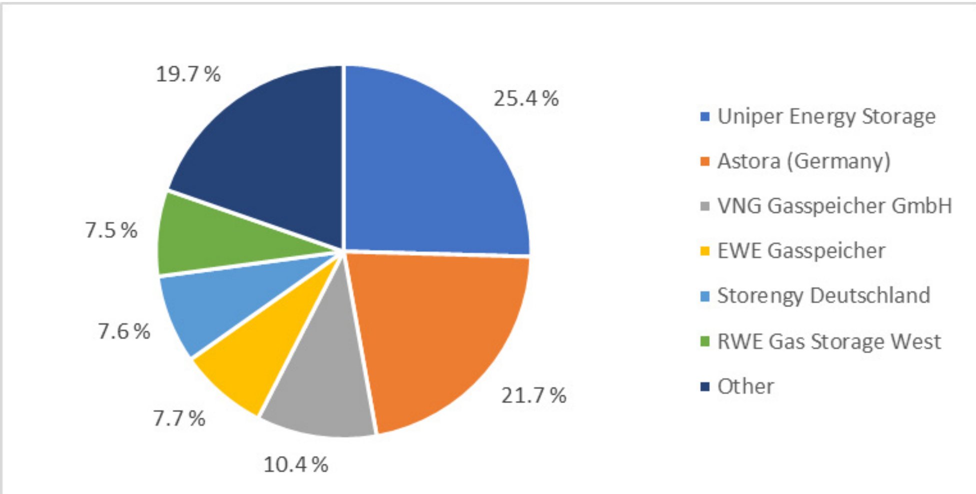

Figure 4. Storage operators' percentage shares of Germany's total working volume of 22 bcm. Source: [44].

3. Developments Surrounding the War in Ukraine

3.1. Market Developments and Gas Flows 2021–2022

The second half of 2021 was characterized by record levels in European gas prices, driven by supply and demand dynamics. The demand shock of the COVID-19 pandemic and the following price declines led to a decrease in exploration and production activity, and underinvestment in fossil energy. In Europe, domestic production between 2020 and 2021 declined by 7.6% to about 45 bcm [45], due to the phase-out of Europe's largest gas field in Groningen, Netherlands. However, domestic production was also affected by environmental concerns and perceived risks of creating stranded assets in light of the energy transition. At the same time, most available LNG was in transit to North-East Asia, where the phasing out of coal for gas, with the aim of lowering carbon emissions, found increasing policy support, thus further reducing the amount of LNG available for Europe [46]. However, this coincided with an increase in the demand for fossil fuels in Europe, due to light winds and, therefore, reduced renewable electricity production; in Germany, this decreased from 244 TWh in 2020 to 226 TWh in 2021 [47]. Because of the phasing out of coal and nuclear power in Germany, natural gas-fired power plants were further intended to act as a buffer for the intermittency of renewable power. Despite record prices of 116 EUR/MWh at the Title Transfer Facility (TTF) gas hub on 5 October 2021 [11], the Gazprom-owned storage operator, Astora, did not fill its storage during the summer of 2021, unlike in previous years, and unlike other storage operators (Figure 5). Because Astora owns about 21.7% of total German storage capacity, record-low storage levels thus further contributed to the gas scarcity of 2021, and the consequential price spikes, while further limiting Germany's flexibility to handle a significant reduction in gas flows.

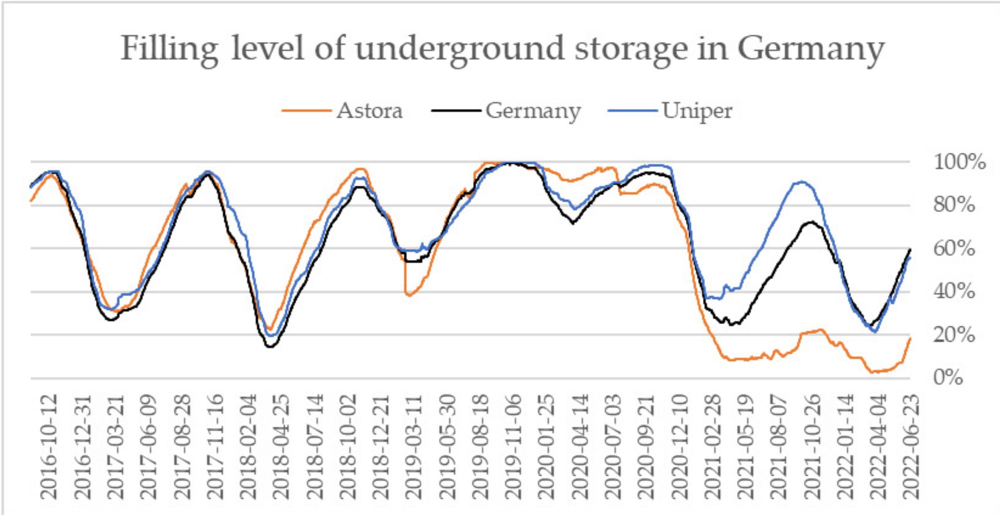

Figure 5. Filling level of Gazprom-owned Astora storage facilities, and those of Uniper, and total German storage capacity, 1 September 2016–23 June 2022. Source: [44].

The absence of storage filling was caused by falling imports from Russia during 2021 via the Ukrainian and Yamal transits, which decreased by about 25% in the last quarter of the year. In contrast to normal practice, Gazprom delivered only gas amounts corresponding to long-term contracts, and delivered no additional volumes via their Electronic Sales Platform. This initially led European buyers to reduce their imports of Russian gas and to buy more LNG for a cheaper price. Quickly rising LNG prices, however, reversed the attractiveness of Gazprom's monthly contracts, which led to full capacity usage of the Ukrainian transit after the invasion on 24 February 2022. The combination of soaring prices for natural gas and continuous deliveries resulted in record Russian natural gas sales, which rose to more than EUR 600 million per day in early March 2022 [48]. In addition, the Russian ruble rebounded and reached a multi-year high against the Euro, of 58.97 RUB/EUR [49], although Russia simultaneously witnessed its highest inflation since 2002, of 17.83%, in April 2022 [50].

Following the invasion of Ukraine, however, the increase in gas flows did not lead to a buildup of storage, with Astora filling levels remaining below 10%. A previous study [41] offers possible explanations for the underutilization of pipeline transits and the avoidance of storage buildup, including the goal of applying pressure on German authorities to grant permits for the controversial Nord Stream II pipeline. Prior to the Russian invasion, another goal for Gazprom may have been forcing importers, who were otherwise faced with record price levels at trading hubs, back into long-term contracts. Following the invasion, however, the European gas shortage served as a bargaining tool for Russia against Germany and other European countries to ensure they did not become involved in the war in Ukraine. The failure to ensure adequate storage of gas is especially noteworthy, as Germany, in contrast to the case of crude oil, does not possess a national strategic reserve. Trusting the economic incentive to fill its storage facilities, German authorities granted the sale of the country's single-largest storage facility in Rehden, by BASF subsidiary Wintershall, to Gazprom in 2015, only months after the 2014 annexation of Crimea.

Threats of a curtailment of gas flows manifested on 14 June 2022, when Gazprom announced reduced flows via the Nord Stream I pipeline, due to technical conditions. Following an initial cut from 167 to 100 million cubic meters per day, flows were further reduced to 67 million cubic meters per day on Wednesday 15 June [51]. Gazprom blamed the export reduction on a lack of equipment, which, according to Siemens Energy, was not able to be returned from its scheduled repair in Canada due to sanctions on Russia [51]. In addition to the halting of deliveries via the Yamal pipeline in mid-May [52], the 60%

reduction affected imports to France, Austria, Italy, and the Czech Republic, in addition to those to Germany. Following the announcement, TTF gas prices rose to 108 EUR/MWh on Wednesday 15 June, an increase of more than 35% compared to the previous week [11] (Figure 6), and the reduction in exports was declared to be politically motivated by Germany's minister for the economy, Robert Habeck [53].

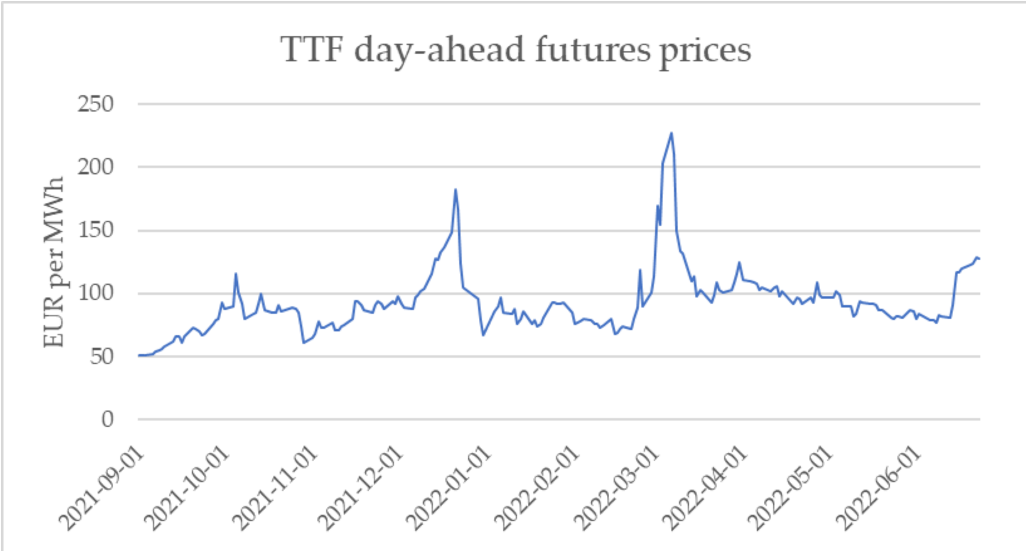

Figure 6. Day-ahead TTF gas price, 1 September 2021–23 June 2022. Source: [11].

3.2. The Regulatory Response of Germany and the EU

In response to the Russian invasion of Ukraine and the weaponization of energy, Germany and the EU have issued several regulative measures to bolster supply security and reduce the import dependence on Russian natural gas. The reduced deliveries via Nord Stream I and, in particular, Gazprom's halting of deliveries to Poland, Bulgaria, and Finland due to Gazprom's demand for payment in the Russian ruble, have sensitized German officials to the consequences of a complete curtailment of gas flows.

Because of the lingering threat of a cessation of supply from Russia, Germany's Economic Affairs Ministry declared the early warning level of the three stage Emergency Plan for Gas on 30 March 2022 [54]. In recognition of the crisis, Germany further declared the second alarm stage on 23 June 2022, because of the severe reductions in gas imports from Gazprom [54,55]. In compliance with the EU security of supply (SoS) regulation, which calls for solidarity among EU member states in the case of local gas emergencies, the first warning step of the emergency plan calls for the use of market mechanisms to mitigate the gas shortage. In addition to an enhanced monitoring of gas flows, these measures include the possible exercise of flexible purchasing options and increased reliance on storage. The second alarm stage further calls market participants into action and is declared in a worsening situation, when no significant substitution from neighboring countries is achieved. It further constitutes the grounds for gas providers to forward higher purchasing costs in wholesale markets to end consumers, which requires the additional declaration of a substantial decline in imports by the Bundesnetzagentur, Germany's federal energy regulator [56]. The alarm stage also enables the ramping up of older coal-fired power plants to reduce the demand for gas for power and heat, while also bringing forward an auction model that incentivizes industrial consumers to reduce natural gas consumption. The final emergency stage allows the grid operator to reduce or cut supply of nonprotected customer groups, such as that of gas power plants, because their contribution, in addition to a required flexible minimum, can be replaced easily with coal power. Only when previous measures remain insufficient will protected groups, including household consumers or social services, such as hospitals, be affected [54]. The feasibility of prioritizing household consumers in a gas shortage, however, is questioned, because the requirement for minimum pipeline pressure does not allow for selective stoppages in the supply to smaller industrial consumers, but only to large-scale industrial complexes.

To combat the supply crisis, the European Commission encourages demand pooling and the establishment of a "joint purchasing mechanism" for natural gas, in addition to energy partnerships with key LNG and hydrogen suppliers as part of the wider REPowerEU plan [57]. The initiative further provides for EUR 72 billion in grants and EUR 225 billion in loans for the development of renewable energy to achieve the EU goal of reducing net emissions by 55% by 2030. The plans also include financing of up to EUR 10 billion for the construction of missing links for gas and LNG, in addition to plans for doubling the deployment rate of heat pumps to a cumulative 10 million units over the next 5 years. Aiming to reduce the vulnerability to import disruptions, the EU has further proposed a legal obligation for natural gas storage [58]. In line with the mandatory storage quotas proposed by the European Commission, Germany passed the gas storage act on 26 March 2022 [59], which stipulates mandatory gas filling levels of 65% by 1 August, 80% by 1 October, and 90% by 1 November. At its final escalation point of inadequate filling, the regulation further allows privately owned storage to be filled by the regulator (the "use it or lose it" principle) [1]. The regulation passed by the Bundestag further allows for the dispossession of energy infrastructure in the case of an emergency in energy supply [60]. In addition to requiring storage operators to declare the halting of gas fillings to the Bundesnetzagentur, it allows storage operators to be placed in escrow if they do not deliver on their mandate of storing natural gas, as already implemented in the example of Gazprom Germania. As Gazprom planned to pass ownership to other Russian companies outside of Gazprom, German regulators stepped in, temporarily holding all voting rights in the company until 30 September. In this role, the Bundesnetzagentur has already taken control of the storage facilities of Astora and is in the process of refilling storage. Similarly, Austria, who hosts Europe's third-largest storage facility, which has a capacity of 2.9 bcm and is critically important for Southern Germany, is opening the filling of the Haidach facility to other market participants because of the inadequate storage filling by Gazprom [61].

Russia, in contrast, issued sanctions, mandating Gazprom to halt business with 31 former trading and storage subsidiaries, including the storage operator Astora in Germany [62]. Russia issued a decree demanding buyers to settle their import contracts in the Russian ruble; however, the EU commission opposes the idea of settling purchases in the ruble and urged its member states to remain compliant with EU sanctions. In order to ensure compliance without risking further curtailment of deliveries from Russia, the European Commission guided its members by issuing a statement noting that their payment obligations would be met after payment in euros or dollars, while not preventing importers from opening an account with Gazprombank [63].

In order to achieve its target of reducing natural gas imports from Russia to a maximum of 10% by 2024 [1], the German government has already implemented measures for supply diversification. These include the delivery of one additional bcm of LNG through the Netherlands, and up to one additional bcm from Norway, which became possible due to a delay in maintenance work [64]. The German government further enabled the purchase of 0.95 bcm via the market operator Trading Hub Europe (THE) for storage injection at the end of May 2022 [1], and is making a further EUR 15 billion in credit lines available for additional purchases [56]. The targeted filling led to an increase in the filling level of Germany's largest underground storage facility in Rehden to 11.87% by 20 June [65].

A cornerstone for future diversification is the development of domestic LNG import capabilities that allow for flexible import substitution. Because the planning and construction of large onshore LNG terminals takes several years, the government has made EUR 3 billion available [66] and, in collaboration with RWE and Uniper, taken out options for the charter of four Floating Storage and Regasification Units (FSRUs) [1]. The first of two units operated by Hoegh, having a capacity of at least 5 bcm/year, is scheduled for operation in Wilhelmshaven by the end of 2023, with the second unit planned to be in operation at the beginning of 2023. The plan further foresees the deployment of two additional FSRUs, of Dyngas, between 2023 and 2024, with possible locations in Rostock, Hamburg, or the Netherlands. Jointly, these measures are expected to boost import capacity from 7.5 bcm/year in the winter of 2022/2023, to up to 33 bcm by the summer of 2024 [67]. To ensure timely availability of gas from FSRUs, Germany has further adopted the LNG acceleration law (LNG Beschleunigungsgesetz) [68], under which authorities may, under certain criteria, temporarily halt or circumvent checks for environmental compliance during the construction of critical infrastructure. The adoption of this law has become necessary because of the large requirements for infrastructure development, which include the need for a 30 km long pipeline to be built in Friesland, Wilhelmshaven, and a 60 km pipeline in Brunsbüttel, to connect these FSRU sites to the larger gas grid. In addition to temporarily boosting the import capacity through FSRUs, the planning of a total of three large onshore LNG terminals is underway. The first of these terminals, having a yearly import capacity of 16–20 bcm/year, is planned for Wilhelmshaven and is being developed by Tree Energy Solutions and EON [69]. Uniper, in Wilhelmshaven, requires all new LNG terminals to be adaptable to the import of clean fuels such as hydrogen, and is planning an import terminal for ammonia, which can be decomposed into green hydrogen, in addition to a hydrogen storage plant. Current plans foresee the development of another two onshore regasification units in Brunsbüttel (KfW/Gasunie, 8–10 bcm/year) and Stade (Hanseatic Energy Hub, 12 bcm/year), which are expected to be operational by 2026 [69,70].

Because Germany acts as a transit hub for neighboring countries, such as Austria, imports must exceed German demand, resulting in the necessary replacement of about 150 bcm in pipelines, and 14 to 18 bcm in LNG imports from Russia. Therefore, the US and the EU have signed a memorandum for the delivery of 15 bcm via LNG in 2022, which, jointly with Qatar, includes the diversion of existing orders [71]. The EU's plan of diversifying 50 bcm of Russian EU imports to new supplier sources in 2022 faces challenges, as existing LNG facilities are at their theoretical maximum use capacity, and allow for the diversification of only half of Russian pipeline gas. Furthermore, efficient use of existing facilities requires the construction of new network interconnectors, such as those from Spain to France via the Pyrenees. Because most supply is tied to long-term contract commitments, significantly larger contributions from North America are not expected before 2025, when new liquefication capacity goes online [72]. Therefore, with nearly 75% of all US LNG deliveries being sent to Europe in early 2022, a further increase of an additional 15 bcm in 2022 has been dubbed symbolic, because the increase in shipments has largely been achieved by diversion of US shipments to Asia [73].

4. Economic Impact of an Import Embargo

Due to the great importance of natural gas for the German economy, many scholars agree that a cessation in imports would have a substantial negative impact. Because diversification from Russian natural gas is unattainable in the near future (see Section 3), many policy makers object to the idea of an early voluntary import embargo. In contrast to coal, because of the lack of sufficient LNG import capacity for import diversification, a natural gas embargo has not found support from all EU member states. Germany, which has a great reliance on natural gas, especially in industrial processes, favors a gradual phasing out of Russian natural gas to 10% by 2024. A slower pace would enable the development of critical infrastructure, thus allowing for domestic LNG imports. Although a voluntary import embargo can be prepared and planned for, European economies are vulnerable to a sudden shortage of natural gas.

Several studies have discussed the potential impact of this scenario for the German economy, resulting in varying estimates of its consequences. For example, a previous study [10] applied a multi-sectoral open economy model that accounts for substitution and input reallocation [74]. Allowing for trade and interlinkages across 30 sectors in 40 countries, this study [10] projected a GDP impact of only 0.2 to 0.3%. While assuming inelastic substitution of natural gas, the authors acknowledge a considerable degree of uncertainty regarding the choice of elasticities. In a more simplified model that assumes a 30% input shock in the natural gas supply, equivalent to a Russian embargo, the study [10] derives an economic loss of 2.2% GDP, and the author's worst-case scenario does not exceed a GDP loss of 3%. Furthermore, contrary to the short-term continued import of Russian natural gas, the study [10] argues for an early voluntary embargo, in order to trigger necessary substitution and reallocation dynamics, which, if self-induced, can reduce the economic cost of a hostile import ban. Another study [75] similarly applies an existing multi-sector multi-country model [74] and, in the same manner as the estimation of [10], the authors derive an economic loss of only 0.3% GDP. In this study, trade is argued to largely diffuse the shock, as Germany would be able to substitute intermediated goods with imports from France, and the authors argue for a European-wide tariff instead of a boycott of Russian natural gas.

Similar to the extreme scenario of [10], ref. [76] also argues for a 3% GDP reduction in Germany, in addition to similar GDP reductions in Southern European countries such as Italy. This reduction, however, is estimated to manifest after six quarters, because of the long-term negative effect of an embargo on the means of production, which renders parts of the capital stock unusable. The authors further project an additional inflation increase of 2.3%, driven by the combination of the supply shock, and only a slow reduction in demand [76]. Ref. [77] criticizes the main finding of a 0.2% to 0.3% GDP impact, as proposed by [10], due to the overestimation of the short-term substitutability of natural gas in industrial use and the central role of natural gas-intense industries in the value chain of the German economy. By comparison, ref. [77] applied a macroeconomic network model theoretically based on another study [78], and estimated the total GDP loss of an embargo of natural gas from Russia to be up to 8%. These calculations originate from first-round effects of a 1.6% loss, after which the initial shock through network effects cascades to second-round effects. The author assumes a multiplier for second-round effects of 5, following the findings by [79] for the second-round effects of the Fukushima crisis. The lower bound of the basis scenario by [77] was defined to be 3.2%, and the second-round multiplier used was 2. The economic impact of a Russian gas embargo, however, is largely driven by the availability of alternative import sources. Therefore, ref. [77] offers an alternative scenario with less problematic availability and derives a GDP reduction of 1.2–3%.

Similarly, using a multiplier of 2 for second-round effects, ref. [80] offers two estimates for GDP effects in 2022, relating to higher energy prices (a deduction of 2%) and a rationing of natural gas imports (3.25%). The derived cumulative GDP deduction was up to 5.25% for 2022, compared to a "do-nothing" scenario. Fiscal policies, however, may limit the economic effect by half a percent. Applying a NiGEM model, as used in [80], ref. [81] delivered a more severe estimate for the economic effect of an unexpected curtailment of gas flows. Assuming a dramatic price increase of up to 900 EUR/MWh, the estimation derived a 6% impact on GDP. Moreover, the joint analysis of Germany's largest economic research institutes [9] discussed the effect of a gas embargo for the economic development of Germany. For 2022 and 2023, the authors foresee a combined loss in economic productivity of EUR 220 billion, or 6.5% of GDP. According to [9], a sudden EU oil and gas embargo would lead to a sharp recession in Germany and an increase in unemployment of 750,000, which equates to an unemployment rate of 6%, compared to a baseline level of 5.2% in 2022. In particular, from January to April 2023, after the hypothesized depletion of storage, shortages for industrial consumers may occur, because of the prioritization of households in Germany's natural gas emergency plan. Finally, against a baseline GDP growth forecast of 0.6% for the euro area, ref. [82] estimated a 3.4% GDP decline for Germany if Russian natural gas imports are halted.

Thus, the presented literature varies in its estimation of the economic effect of a Russian natural gas embargo. Some of the presented studies, such as [9] or [81], suggest a severe economic impact from a Russian export ban of natural gas. The mild effects presented by [10,75], although complex in their approach and assumed substitution elasticities, are surprisingly low. Although natural gas accounted for 35% of total energy consumption in the industrial sector of Germany in 2020 [36], both authors delivered a negative GDP effect of only 0.3% in their full models, following a curtailment of all Russian gas imports. The results of [10,75] should therefore be considered the lower limit of the economic consequence of a gas shortage. By comparison, severely negative effects on GDP and employment, as hypothesized by [9], should be considered possible outcomes of an import ban that has not been prepared for.

5. Strategies to Replace Natural Gas from Russia

Ref. [41] calculated the amount of Russian gas according to import statistics for 2021; this amount was 45.7 bcm (495 TWh). By comparison, ref. [42] derived a replacement need calculated by adjusting European imports from Russia (155 bcm in 2021) for Germany's import share in the EU of 28%; this amounted to 43.4 bcm. According to [3], however, Germany's natural gas net imports from Russia in 2021 amounted to 46 bcm. Arguably, a curtailment of gas flows may lead to negative economic effects that, in turn, may lower the demand for gas. In addition, as outlined in Figure 3, net storage withdrawals contributed 4.66 bcm to total consumption in 2021 [6], largely due to the inadequate storage filling of the Gazprom subsidiary, Astora. A long-term sustainable replacement of Russian natural gas, which assumes no reductions in demand, would include the demand of adequate storage filling. Therefore, to accommodate both an overall demand reduction and the necessary filling of underground storage, we assume the need to replace 46 bcm of imports for our one-year short-term assessment. An estimation of a possible import gap in natural gas supply needs to include both possible substitutes for Russian imports on the supply side, and the demand-side adjustments in consuming sectors. In the following section, we discuss the diversification potential and the relevant research findings for reducing gas demand.

5.1. Short-Term Supply Substitution Potential

Germany lacks alternative pipeline routes to other suppliers and available natural gas resources are scarce. Furthermore, new pipelines, although more cost efficient in the long term, are inflexible and require a long construction time. LNG offers a more flexible trading mode, allowing for a broad diversification of imports. Although nearly half of the existing regasification capacity in Europe is idle [83], much of this capacity, e.g., in Spain, is unavailable due to missing interconnectors. Furthermore, a curtailment of natural gas flows from Russia to Germany would also increase the LNG demand of other European countries. Moreover, new large onshore regasification terminals, which are required to be hydrogen-ready [84], may not be available before 2025, because of their lengthy development and construction times. Therefore, as outlined in Section 3, in the short term, substitution of Russian natural gas can only be achieved with FSRUs. In addition, due to the construction of necessary connectors to the gas grid in a "national effort" [85], these FSRUs can be served by the diversion of LNG deliveries without a destination clause. These may include LNG deliveries from the US, which, due to soaring prices, delivered nearly 75% of its available exports to Europe during the first months of 2022 [73]. According to [1], the two FSRUs operated by Höegh offer an annual capacity of at least 5 bcm. With start-up times planned for the end of 2022 for Wilhelmshaven and early 2023 for Brunsbüttel, at least 10 bcm of import capacity is available in the short-term. However, in our analysis, we do not account for the two FSRUs of Dynagas, because of unspecified start-up times between 2023 and 2024. In addition to the possible LNG import capacity of 10 bcm, Germany purchased 1 bcm via Trading Hub Europe (THE), and entered agreements for the additional delivery of 1 bcm from the Netherlands and 1 bcm from Norway. Together with the development of floating import capacity of 10 bcm, these commitments bring the short-term natural gas availability to 13 bcm.

5.2. Potential of Short-Term Demand Reductions

Several studies and think tank reports that examined the demand-side potential for reducing natural gas consumption over the course of the next year are contrasted in this section ([8,41,42,86–88]). Because households and the industry sector contribute to the majority of natural gas consumption, having shares of 31.2% and 37.2%, respectively [39], we assume that the literature finds the largest savings potential in these sectors. However, Refs. ([8,41,42,86–88] identify that the largest contribution to a demand reduction can be made by the power and heat sector. Because coal- and oil-fired power generation is implemented easily but hampers the decarbonization targets of the EU, ref. [86] only lists these forms of generation as additional options to its main suggestions, and derives a possible contribution for Germany of 6.4 bcm. Jointly with the installation of new renewable power and generation (1.4 bcm), and an increasing contribution from bioenergy and nuclear generation (3 bcm), the study's total estimate of demand reduction is 10.8 bcm. Similarly, [87] implies savings potential of 10.8 bcm in the power and heat category, including 5.7 bcm from coal-fired power plants and a contribution of about 2.5 bcm from the lifetime extension of nuclear power. For [42], the switch to coal, increases in renewable power, and temporary use of heating oil when possible, also deliver the largest contributions to reducing natural gas demand. In a conservative estimate, the total contribution amounts to 6.6 bcm, whereas, in the optimistic scenario, a contribution of 9.7 bcm is achievable. Exceptionally high prices for natural gas in Europe are thereby expected to make coal temporarily more attractive compared to gas-fired generation. The accelerated development of renewables is considered a key measure in Germany's energy transition towards an independent energy supply [85]. The potential of accelerated installment of wind and PV capacity is therefore included in the savings contribution for the power and heat category. Although [88] similarly derived reduction potentials of 7 and 9 bcm, respectively, for the medium and optimistic scenarios, ref. [41] derived a more conservative savings potential for increasing coal power. Because gas is largely used in combined heat and power (CHP) plants, not all gas use in the power and heat category can be substituted for. Ref. [41] estimates the potential of using coal-fired generation to be only 3.5 bcm. Although accounting for lifetime extensions, higher loads of current plants, and reactivation of those already decommissioned, this estimate does not include the potential for new renewable power or oil-fired generation. Lastly, ref. [8] also estimated the second-largest potential for reducing gas demand in the power and heat category. Assuming a full replacement of gas in pure power plants, and partial replacement in CHP (including in industrial power plants), ref. [8] estimated potential savings of 10.4 bcm.

The industrial sector, which is responsible for the largest gas consumption share in Germany, shows the second-largest potential for reducing gas demand in many of the reviewed studies. Natural gas consumption in the industry sector, however, is not homogenous. A share of 11% of the demand of the industry sector—that is, 4% of total German natural gas consumption—is used as a direct input, for instance, for the production of methanol and hydrogen, and for ammonia synthesis [42]. The use of gas as a direct input can only be substituted for by imports, and the largest potential for decreasing industrial gas demand lies within its use for process heat, which accounts for 84% of consumed gas in primary industry consumption [7]. We found similarities between the potentials estimated by [42,88], who, in their conservative estimates, proposed savings potentials of 5 and 4.5 bcm, respectively. The main driver in both studies is the substitution with alternative energy sources, such as electricity, coal, and biomass, in which the switch is deemed challenging if processes require very high temperatures [88]. Nevertheless, the optimistic scenarios of both studies, which are based on the assumption of an economic downturn and, therefore, lower industrial demand, yield larger reduction potentials of 9 bcm [88] and 9.2 bcm [42]. Refs. [8,41] suggest far lower potentials for reducing gas consumption in industrial processes, of 2.3 and 1.8 bcm, respectively. Ref. [8] points to the specificity of production processes, especially in the chemical industry, in which challenging fuel switches become feasible only due to investment in a new technology. By comparison, ref. [88] assume greater flexibility in imports of the chemical industry; however, this study also implies a temporary but significant reduction in industrial output. In contrast, rather than the chemical industry, ref. [8] finds the greatest potential for demand decreases in the food industry, where a fuel switch to electricity and oil for heating and drying applications can be achieved. In its rather conservative estimate, ref. [41] attributes the largest potential for demand reduction to the installation of flow heaters and heat pumps, and to the reduction in room temperature. Lastly, ref. [86], in its suggested measures for the EU, does not offer suggestions for industrial demand reductions, likely due to the peculiarity of industrial gas use in Germany compared to that in other European countries.

Reducing gas demand in households is straightforward, as the majority of gas consumption can be attributed to the use of water boilers and heating. Although, in the short term, the accelerated installation of heat pumps can contribute up to 0.46 [86] and 0.22 bcm in both scenarios of [42], a larger impact can only be expected in the long term. However, in addition to efficiency improvements, the installation of heat pumps, and a 1 °C reduction in room temperature, ref. [86] estimated reduction potentials in buildings of 2.8 bcm. According to [41], reductions in room temperature of 1–2 °C and the switch to electric flow heaters may reduce gas consumption of households by 3.7 bcm, which translates to 8% of the overall gas consumption. Ref. [8] points out that one degree of temperature reduction during the heating period relates to a demand reduction of between 5% and 6% [8]. Using efficient room ventilation and smart thermostats, ref. [8] estimates the potential for demand reductions in households to be 4.3 bcm, and, using similar measures, to be 1.8 bcm for buildings in the trade and commerce sector; these values translate to 15% and 10% reductions in these sectors, respectively. Ref. [42] indicates a potential of 3.5 bcm in the baseline and 5.2 bcm in the optimistic scenario. In addition to reductions in room temperature, the estimates also include potentials ranging from 0.5 to 0.9 bcm for the use of boilers, a smaller contribution from improved building insulation, and up to 1 bcm from the short-term use of wood and propane for heating. Ref. [88] similarly projects a potential of 4 bcm for the reduction in temperature in households, and 2 bcm for that in buildings of the trade and commerce category. In addition to the stated potentials for demand decreases, smaller less-effective measures exist, such as a possible ban of natural gas-fueled cars, which has the potential of cutting 0.18 bcm of demand in Germany [8]. Although alternative gases, such as biogas or biomethane, and hydrogen, play an integral part in the EU decarbonization strategy, they are not available in sufficient quantities as a short-term solution and require necessary investments and facilities, such as in the case of electrolysis.

Figure 7 summarizes the assessment of the remaining import gap for natural gas in Germany. Note that, although these studies may use their own assumptions about short-term import alternatives, we only refer to their stated potentials for demand decreases and incorporate our own findings for the import substitution potential. Figure 7 indicates that, with slightly less than half of Russian imports of 2021, the largest remaining import gap is estimated by [41], which amounts to 22.2 bcm. In particular, the small contributions for heat and power (3.5 bcm) and the industry sector (3.7 bcm) are noticeable. Similarly, ref. [8] also estimates a small contribution of the industry sector, due to difficulties in fuel switching in specialized applications. However, with a sizable contribution in heat and power (10.4 bcm), Refs. [8,87] equally estimate a remaining import gap of 15.3 bcm. Refs. [42,88] show great similarity in their optimistic scenarios, leaving import gaps of only 9 and 8.9 bcm, respectively. Both studies identify great potential for demand reductions of around 9 bcm in both the heat and power category, and for industry consumption. By comparison, the studies' more conservative estimates yield import gaps of 15 bcm [88] and 18.4 bcm [42]. We identified the smallest potential for demand reductions and, therefore, the largest import gap, in [86], in which no contribution from the industry sector is suggested.

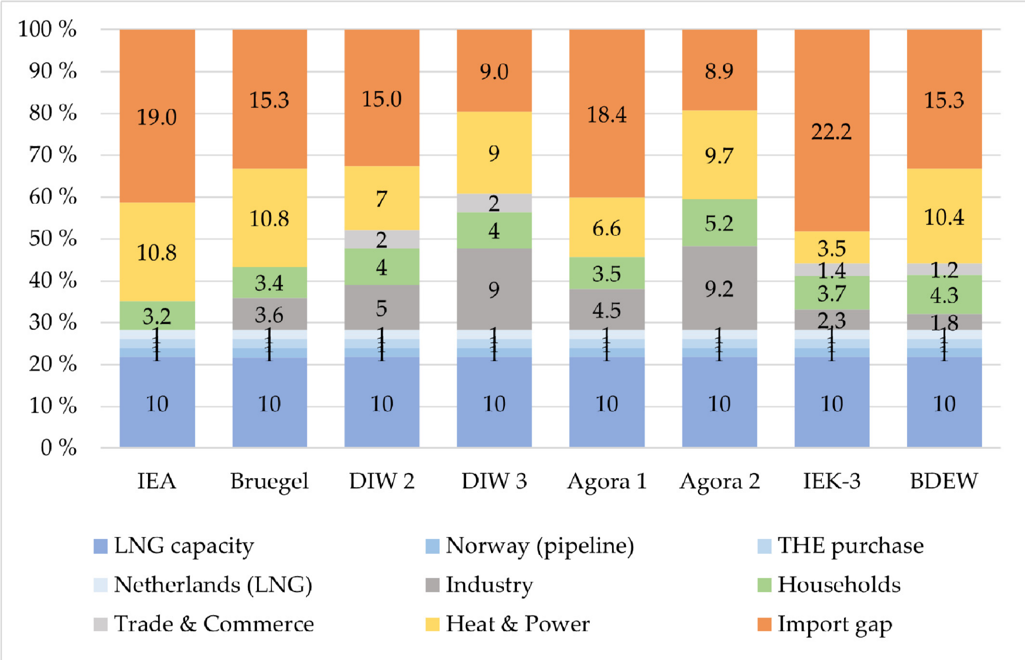

Figure 7. Import gap accounting for short-term gas availability (blue) and potentials for a demand decrease in consumption sectors. IEA refers to [86], Bruegel to [87], and DIW 2 and 3 refer to the medium and optimistic scenarios of [88], respectively. Agora 1 and 2 refer to the two scenarios of [42], IEK-3 refers to [41], and BDEW refers to [8]. Note that the contribution for households in [42] includes reductions for trade and commerce, while also [86,87] provide joint estimates for residential and commercial energy conservation, included in the household category above. Estimates by [86,87] are approximated by relating published contributions for the EU to Germany's consumption share of 23%. Smaller contributions, such as from a ban of natural gas-fired cars, are not included.

6. Lessons for Other European Countries

6.1. Differences in Dependence and Market Structure

The impact of the current gas crisis on other European countries varies depending on the role of natural gas in each country's energy mix and their import dependency on Russia. Compared to the 26.4% share of natural gas in the energy mix of Germany [36], France exhibits less reliance on gas, with a share of natural gas in the country's energy mix of only 16% [38]. Furthermore, without significant domestic natural gas production, the import share of Russian natural gas to France in 2021 amounted to only 17%, whereas Norwegian natural gas had an import share of 36%, followed by 8% from Algeria and 7.5% each from the Netherlands and Nigeria [89]. The continued use of nuclear power further sets France apart from Germany. Although being phased out in Germany, the share of nuclear power in electricity production in France amounted to 69% in 2021, or 36% of primary energy, whereas the share of natural gas in electricity production was only 6% [90]. Some European countries, however, have a greater dependence on natural gas than Germany, including in electricity production. In Italy, for instance, the share of natural gas in the energy mix is 40%; imports account for 94% of this gas, of which, 40% is sourced from Russia [45]. The contribution of fossil fuels, which mainly comprise gas, to electricity production, is 59% [90]. In the Netherlands, which has a historically large domestic production, natural gas contributed 38% of the energy mix in 2020 and 63% of electricity production. The import share in 2021, however, amounted to only 33% [45], and only 15% of consumed gas was imported from Russia [90,91]. In addition, the country experienced an accelerated deployment of renewable energy capacity, which contributed to 34% of electricity production in 2020 and 9.5% of primary energy consumption [90]. Spain, as the EU's fourth-largest country, showed complete import dependency in 2021, and natural gas accounted for 24% of all energy consumed [45]. Of the above-mentioned countries, Spain has the largest share of renewable energy in primary energy consumption, of 20%, and the share of nuclear power amounts to 10% [91].

6.2. Crisis Responses and Challenges

Arguably, countries having a smaller share of natural gas in primary energy consumption and fewer imports from Russia would be less affected by a curtailment in gas flows and face fewer challenges for import diversification. In response to the current crisis, France increased its imports of LNG by 66% in early 2022, and has further sought to raise the import capacity of an existing regasification terminal in Marseille, while also seeking to establish new capacity in its northern area [92]. Furthermore, the French government cut subsidies for gas-fired heaters, and currently supports household heat pump installation by up to EUR 1000. Facing a far greater dependence on Russian imports, Italy signed a new deal with Algeria for the import of an additional 9 bcm per year by 2023/24, and also formed an agreement with Egypt regarding additional LNG cargoes [93]. Furthermore, the country's state oil and gas company, Eni, is seeking to secure future supply by developing an LNG project, having a yearly capacity of 4.5 bcm, in the Republic of Congo. Although natural gas plays an equally important role in the Netherlands, the ability of all European countries to diversify LNG imports in the short term is limited by their existing regasification capacity. Whereas idle LNG regasification capacity in Italy between November 2021 and February 2022 was 50%, Dutch import utilization was 93%, leaving only 7% idle for new imports [87]. Having a relatively small import share from Russia, of 15%, however, the Netherlands faces an easier diversification task. Furthermore, in addition to the development of new LNG import capacity, the Netherlands is seeking to increase domestic production via the development of a new field in the North Sea in conjunction with Germany, promising 60 bcm of total reserves [94]. In addition, facing the phasing out of Europe's largest field in Groningen, the Netherlands has reduced fossil fuel use in electricity production from 80% in 2018 to 63% in 2021, while the share of renewables rose from 16.6% to 34% [90]. Although only 32% of France's LNG import capacity lay idle in March 2022 [52], diversification from Russian gas in France is attainable, as gas contributed to only 16% of primary energy consumption, with a Russian supply share of 17%. Similarly, in Spain, who possesses Europe's largest LNG import capacity, of 60 bcm [70], the majority of capacity (55%) lays idle [52]. Taking advantage of this capacity, Spanish LNG imports increased 16% year-on-year in March 2022, in an effort to provide a substitute for the Russian LNG supply share of 8.7%; this also halved pipeline imports from Algeria [95].

The comparison to other European countries further emphasizes the short-term diversification dilemma for natural gas imports to Germany. Countries having idle LNG capacity, such as Spain, can flexibly diversify their imports with LNG shipments from other countries. In addition to the lack of LNG terminals, the phasing out of both coal and nuclear power in Germany impedes the short-term substitutability of natural gas in electricity. In France, the use of nuclear power instead of gas in electricity provides for additional resilience against short-term gas supply shocks. Furthermore, countries having a large share of renewable power are also better equipped to substitute electricity for falling gas deliveries. Germany, like other European countries, has grown the share of renewable electricity production; in Germany, Italy, and Spain, this amounts to more than 40% of total production [90]. The past deployment of renewable capacity has strengthened the energy autarky of all countries. Germany, however, in addition to contending with the unique role of gas in the country's Energiewende, lacks alternative pipeline import routes, available LNG import capacity, and nuclear power options.

7. Discussion

Because of reduced natural gas imports from Russia and a possible complete embargo, Germany faces a unique challenge in mitigating a supply shortage for the next year. The threat to Germany's energy security formerly manifests in an inadequate resilience to disruptions [31] and a discontinuation of commodity supplies [12]. Given the need for the establishment of adequate natural gas storage before the next winter, short-term solutions for import substitution and demand reductions are needed, with few choices available for an optimal solution. The triggering of the alarm stage of Germany's national emergency plan equips policy makers with a rich set of measures for tackling an evolving natural gas crisis and, in principle, allows utility companies to forward their higher replacement cost of Russian gas at wholesale markets (Figure 6) to end consumers. Although this measure requires further legislative approval, in addition to policy-driven measures, higher prices can contribute substantially to demand reductions, because of the negative price elasticity for gas demand [96]. Although the own-price elasticity for the household sector in Germany is significantly larger than that in France, the short-run price elasticity has been found to be very inelastic [97]. To avoid a supply shortage in the winter, German regulators hope for a contribution from demand reductions, motivated by surveys indicating that, due to the effect of record prices, 48% of Germans are more conscious about their energy consumption, and are using less electricity, heating less, and switching to green power [98]. Behavioral changes, such as the lowering of the room temperature in households, should further receive public support in the form of an information campaign.

Emergency planning tools, such as the temporary extension of coal burning for electricity and heat, in addition to an incentive mechanism to save gas in industrial consumption, can help close the import gap. The historic dependence on Russian gas, which manifests in a lack of alternatives to pipeline imports, and a reliance on natural gas in the country's energy transition, requires immediate measures to bolster supply security through flexible LNG import diversification. Although some have called for an early voluntary embargo to trigger necessary adjustment processes [10], the German government, facing potential economic losses and reduced flows through the Nord Stream I pipeline [51], is seeking to accelerate the development of LNG import capacity with FSRUs (see Section 3.2). Germany, however, is not alone in its struggle to diversify away from imports from Russia, and competes with other countries for LNG a tight global market. The UK, for instance, after the closing of the Rough offshore storage facility, possesses less than 2 bcm of active storage capacity [44], and, notwithstanding imports from Norway, is highly reliant on LNG imports.

US LNG, apart from a short-term diversion of cargoes destined for Asia, falls short of offering a sufficient import alternative because of limited liquefication capacity. Although an increase in LNG export capacity by one-third is projected for 2026 [75], the strengthening link between the North American and European markets also raises challenges for domestic gas supply. Although American suppliers in the short term profit greatly from diverting cargoes to Europe in a regime of record prices, market integration with the European continent also leads to domestic price increases and higher inflation in North America [99], which, in the long run, may hurt the governmental support for supplying Europe. However, the availability of US LNG, of which, three-quarters was exported to Europe in the first four months of 2022, was further reduced because of the shutdown of the Freeport LNG export facility following an explosion on 8 June 2022. The effect of this on Europe is especially dire, as the facility, which in May 2022 handled 20% of all US LNG exports, remained non-operational for at least 90 days before a partial restart, putting further upward pressure on European gas prices [100].

The accelerated speed of the construction of necessary LNG infrastructure in Germany, enabled by exceptions for checks of environmental compliance, was made possible by limiting its regulated use for LNG imports until 2040; this can only be prolonged by the import of hydrogen. From a regulatory perspective, the time-limited use of new terminals for LNG imports ensures adherence to decarbonization targets. Although a prioritization of gas imports over climate concerns is reasonable due to the current crisis, the establishment of new regasification terminals may potentially renew Germany's dependence on fossil fuel imports, and thus constitutes a risk factor to long-term decarbonization targets. Germany, aiming to find a balance between the negative economic effects of an embargo and the success of its energy transition, must avoid overinvestment in import infrastructure for an energy source that, under the EU taxonomy, is considered transitory. Furthermore, long-term agreements for LNG import, for instance from Qatar, and for the future import of hydrogen, may create new lock-ins with foreign partners.

Because of the need to provide a balance for the intermittency of increasing shares of renewable energy, independence from fossil fuel imports is an unattainable target in the near future. The German government must therefore exercise options for acquiring gas at European gas hubs, as made possible by additional credit lines after the announcement of the alarm stage of the national emergency plan [56]. Furthermore, EU-initiated demand pooling may also further help improve the purchasing conditions of individual buyers, thereby avoiding new import dependence on other exporters.

Cheap and abundant supplies of natural gas contributed to the development of successful industries, which now must adapt to a new regime of restrictive supply and high prices. Although some may advocate high prices for fossil fuels to accelerate the transition towards a low-carbon economy, an acute shortage threatens industrial business models and supply chains, as there exists no precedent for large-scale fuel switching at a similar scale. For example, because an acute gas shortage in glass production may render ovens unusable, policy makers are encouraged to reconsider a rigid prioritization of household consumers to the disadvantage of the industrial sector. As many output products in the chemical industry are base materials needed for further processing, the survival of key industries should be of national interest. Moreover, during an acute shortage of natural gas during the first year, flexibility should be applied to the implementation of newly introduced storage quotas, to avoid a further tightening of available supply. Although the great heterogeneity in industrial consumption and interdependencies between different subsectors make top-down regulatory measures difficult to implement, regulatory support must also guide possible substitution for natural gas. This support should include financial incentives for fuel switching and compensation to those manufacturers who can temporarily replace gas-intense manufacturing with imports.

When lower temperatures are required, electricity can also replace some industrial gas consumption, as embedded in a national strategy of accelerated deployment of renewable energy. Although the development of new capacity is largely driven by private investment, regulators must lower administrational burdens and reduce bureaucracy. The adoption of renewable energy, which has a 19.5% share in Germany's total energy production [91], should be further accelerated, including the replacement of household gas heaters with heat pumps. However, due to the limited short-term impact of switching to electricity in households and industries, the use of gas-fired power plants should be reduced as much as possible in favor of coal and nuclear sources. Although detrimental to national decarbonization targets, coal power plants offer a short-term alternative for heat, and a possible lifetime extension of nuclear power plants may decrease gas demand when gas is otherwise used for pure power generation.

Although our estimate for the capacities of FSRUs, of 5 bcm/year, is oriented towards the lower stated minimum [1], it is not clear how quickly the necessary 30 km pipeline in Wilhelmshaven and the 60 km connector in Brunsbüttel can be constructed, even under accelerated administrative procedures. In addition, our estimate does not account for new options, such as additional FSRU deployment in neighboring countries having the capacity for exports to Germany. Questions also remain regarding the actual potential for demand reductions. Although previous studies [8] estimate only relatively small potentials for reductions in industrial demand, of 1.8 and 2.3 bcm, respectively, both estimates may be limited because they incorporate only technical feasibility. By comparison, larger contributions offered by other studies [42] take into account overall demand reductions following the negative economic impact of a gas shortage. Consequentially, the estimate presented in Ref. [8] does not consider cost assumptions or the economic feasibility of the suggested measures to reduce consumption. Although a further study [42] indicates the inclusion of cost perspectives, the authors note the significant uncertainties regarding the substitution elasticities of industrial consumers.

Finally, unpreparedness for a natural gas import embargo may lead to severe economic damage and social conflicts. Policy makers, therefore, need to find a balance between the consequences of continuous imports from Russia and the economic consequences of an embargo. Although estimates for the impact of a natural gas embargo vary (Section 4), the joint economic forecast of German research institutes quantifies a possible increase in unemployment of 750,000 [9]. Assuming the authors' forecasted two-year GDP decline of 5.2%, the effects of a gas shortage for the German economy would be detrimental. Given the great uncertainty of cascading negative effects within industry sectors, policy makers are encouraged to allow for flexibility with regards to possible industry restrictions, and should also consider financial support mechanisms for both industrial and household consumers.

8. Conclusions

Supply disruptions from Russia critically impact Germany's short-term natural gas supply security. Because of its historic dependence on Russian natural gas, Germany faces a unique challenge in securing the short-term supply of natural gas. Due to a lack of import alternatives and negative economic consequences of an acute gas shortage, policy makers are urged to identify short-term solutions for supply and demand adjustments. Motivated by this challenge, we undertook a comprehensive review of Germany's natural gas dilemma in the context of the war in Ukraine. Constrained by the limits of import alternatives, we discuss feasible demand adjustments that may help avoid the negative economic consequences of an embargo. Our study offers a relevant link between regulatory responses and practical measures for mitigating the gas crisis, contrasted by lessons for other European countries.

We assumed stated short-term supply diversification commitments, including the deployment of FSRUs, and critically reviewed possibilities for reducing gas demand in consuming sectors. The findings indicate that, even in optimistic demand adjustment scenarios, a short-term import gap of 9 bcm remains. A more conservative assessment of the import gap is 22 bcm, which equates to nearly half of the 46 bcm energy quantity imported from Russia in 2021. Our review indicates that short-term substitutes for Russian natural gas amount to 13 bcm. Accounting for 10.8 bcm, the largest potential for demand reductions lies in heat and power, which can be achieved by substitution of natural gas-fired power plants with coal- and oil-fired generation, increasing shares of renewable energy, and contributions from bioenergy and nuclear power. Through fuel switching, a reduction in industrial consumption of up to 9.2 bcm is possible, although this also entails decreasing industrial demand as a consequence of an import embargo. Accounting for 5.2 bcm, the third-largest reduction in demand is hypothesized for households, largely through reductions in room temperature.

As a result of the triggering of the alarm stage of its emergency plan, Germany has made additional credit lines available for the purchase of gas at European hubs and initiated the establishment of an incentive mechanism to save gas in industry. Based on our findings, we urge policy makers to implement necessary requirements for the temporary increased use of coal-fired power plants. We also call for an open discussion about delaying the phasing out of nuclear power in Germany, and its contribution to indirectly saving gas for heating. A public information campaign is needed to realize possible gas savings in household and commercial heating. To reduce the dependence on natural gas in the future, an accelerated deployment of renewable energy capacity is required. Although the filling of underground storage needs to be prioritized, policy makers in Germany are encouraged to allow for flexibility in applying mandatory storage quotas during an acute shortage, to avoid a further tightening of the available supply. Furthermore, we urge caution with regards to possible restrictions for those industrial consumers who face the destruction of their capital stock as a consequence of cessations in gas supply.

A curtailment in all natural gas imports from Russia, for which preparations have not been made, may potentially result in an economic recession. Therefore, the goal of securing the supply of gas through flexible FSRU options and demand reductions should, in the short term, be of national interest to ensure the economic strength needed for the energy transition.

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