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Research paper

Europe's independence from Russian natural gas — Effects of import restrictions on energy system development

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ABSTRACT

With the Russian invasion on Ukraine in 2022 and the following disruption of Russian natural gas imports, Europe's energy reliance on Russia has become more apparent than ever. To tackle the resulting challenges of a limited supply of fossil fuels from Russia and especially its effects on energy system development, short and long-term effects need to be investigated thoroughly. This paper aims to quantitatively analyze the impact of reduced natural gas availability from Russia on the European energy system, both in the coming years, as well as in the future. Using the Global Energy System Model (GENeSYS-MOD), three scenarios with varying amounts of Russian natural gas and further impacts of reduced fossil fuel imports from Russia are calculated. Results show that strong effects are mostly observed in the short to medium-term, but an overall earlier phase-out of fossil fuels can be achieved in the long-term. The reduction of natural gas imports is tackled by an increase in LNG imports and domestic natural gas production to overcome the supply gap. Strong reactions are seen in the levelized costs of electricity generation between 2022 and 2025, with higher costs in scenarios with restrictions on Russian natural gas imports, but with a negligible difference in the long-term. Most importantly, lower emissions in scenarios with reduced natural gas supply from Russia highlight the positive effect of an early reduction in fossil fuels and investment in renewable technologies, resulting in a near 100% emission-free energy system by 2045, 5 years before the Base scenario with unrestricted Russian gas imports. The results find that a limitation of Russian fossil imports does not pose a long-term threat to the European energy system or its required transition away from fossil fuels, but can rather accelerate its decarbonization and energy demand reductions.

1. Introduction

In 2021, the European Union (EU) adopted the European Green Deal, committing to climate neutrality by 2050 and staying well below a 2-degree global temperature increase compared to pre-industrial levels. To reach this goal, the build-up of renewable energy sources (RES) needs to be accelerated across all sectors of the European energy system, while fossil fuels need to be phased out (European Commission, 2022b). Even so, the EU declared natural gas to be labeled as "green" in 2022 (European Commission, 2022d). It is frequently seen as a bridge technology for the transition towards renewable energy, even though this narrative is misleading due to potentially arising carbon lock-in effects, too little attributed emissions, and stranded assets (Gürsan and de Gooyert, 2021; Kemfert et al., 2022). In 2021, natural gas made up almost one quarter of the EU's primary energy consumption, showing its reliance on this particular fossil fuel (Eurostat, 2022b).

Russia's ongoing war in Ukraine revealed many challenges for the European energy supply. Over the years, Europe, and especially central and eastern European countries built up a strong dependence on cheap natural gas from Russia. Since Russian gas deliveries were cut as a consequence of the Russian aggression in 2022, the necessity to substitute natural gas has grown more apparent than ever (Bella et al., 2022; Holz et al., 2022). High energy prices and the fear of gas shortages in the coming winters raised the question of how the European energy system would react to the reduced gas imports from Russia (IEA, 2022). While in the short-term, natural gas could be substituted by coal in the electricity sector, demand side management

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as well as higher gas and liquefied natural gas (LNG) imports from other countries compensated for the shortages in the heating and industrial sectors (European Commission, 2022a; IEA, 2022). Neither of the latter options, however, helped with the EU's goal to reduce Carbon dioxide (CO_2) emissions. Furthermore, although Russian gas imports were cut, Europe is still dependent on smaller shares coming from Russia (McWilliams et al., 2021). At the time of writing, long-term effects of the natural gas disruptions and the effects of switching to alternative fuels to compensate for short-term gas deficits are not yet quantified in detail.

This paper aims to fill the gap in quantitative research on the effects on energy system development caused by the disruption of Russian natural gas imports into Europe. Although a broad body of literature exists for developments in the short-term, research on long-term effects, especially across the entire energy system, is scarce. Existing literature is to be expanded by adding insights on the consequences of import limitations of Russian natural gas with the use of the Global Energy System Model (GENeSYS-MOD). To evaluate the effects on energy system development, three different scenarios concerning the availability of Russian gas imports to Europe are compared: Unlimited Russian gas imports, limited Russian gas imports, and a complete ban on Russian gas imports. In addition to the complete import stop of Russian natural gas, effects of an import stop of coal and oil from Russia were added to the scenario in the form of price increases. With the addition of the short to medium-term developments (yearly steps from 2018 until 2025), the effects on the energy system for both the coming years as well as towards 2050, are computed and presented. Implications of a reduced Russian gas supply on the overall gas consumption and effects on the decarbonization of the different sectors of the energy system are analyzed and an outlook on resulting electricity generation costs and emissions shall be given.

Summarized, the contributions of this paper are

- to fill the gap in quantitative research on *long-term* effects of the Russian natural gas disruptions,
- analyze short to medium-term implications to add to existing research,
- gain insights on *energy system development* by using three scenarios varying in natural gas availability,
- give an outlook on overall gas consumption, sector-wide decarbonization, electricity generation costs, and emissions.

In the following Section 2, an overview of the relevance of natural gas in the European energy system is given before reviewing relevant literature. Section 3 describes the methodological approach taken for the analysis in this paper, while Appendix B outlines scenario assumptions and data used. The results of the analysis are then presented in Section 4 and further discussed in Section 5. Finally, Section 6 concludes the study.

2. Status quo and relevant literature

The Russian war on Ukraine is occupying politicians and researchers alike. Economic and systemic effects are highly complicated and making predictions on future developments thus needs a thorough understanding of the context. To give a first impression of Europe's dependence on Russia, this section presents an outline of the past role of inexpensive Russian natural gas imports in the European energy system.

2.1. Natural gas in the European energy system

Natural gas is one of Europe's main energy carriers, accounting for 23% of the EU's primary energy consumption in 2021. Only oil and petroleum products show a higher share of 34%, while coal accounts for only 11% (Eurostat, 2022b). The primary use for natural gas is power and heat generation (central heating units), use in households (residential heating and cooking), and the generation of process heat in industry with 31%, 24%, and 23% of total gas consumption respectively in 2021 (Eurostat, 2022a). Especially in the heating sector, natural gas is still used as the main fuel. In 2020, the share of natural gas amounted to 37% of total gross heat production in the EU (European Commission, 2022a). However, only 24% of the final natural gas demand in 2021 was produced within Europe. Instead, Europe imported about 35% of its total available natural gas (15.4 EJ) from Russia, making it Europe's largest supplier of gas (McWilliams et al., 2021; Eurostat, 2022a). Since the start of Russia's war on Ukraine, the gas supply from Russia declined steadily. In the last week of 2022, Russian gas made up only 9% of imported gas to Europe compared to last year's 32% (McWilliams et al., 2021).

Partially, the reduced gas imports are due to Russia cutting its gas exports into Europe (Lan et al., 2022). Another reason is the EU's REPowerEU plan, which was presented in May 2022 to grow more independent of Russian fossil fuel imports, stabilize the European energy system, and accelerate the green transition. In order to achieve that, Russian gas imports were to be reduced by two-thirds by the end of 2022 and even further until 2027 (European Commission, 2022e). In total, up to 300 billion € are mobilized to support investments and reforms. As such, the European target for RES for 2030 was increased to 45%. At the same time, the EU-wide target on energy efficiency was increased from 9% to 13% and the planned renewable energy generation capacities were raised to about 1,236 GW by 2030. Moreover, a push for an updated regulatory framework for hydrogen, combined with an accelerated build-up of electrolyzer capacities is planned (European Commission, 2022e). While the role of energy storage for the energy transition is specifically recognized by the REPowerEU plans, no specific strategy or targets are proposed yet (European Association of Storage of Energy, 2022a). As the generation from conventional power plants decreases, and deployment of variable renewable energy (VRE) and the demand for electricity increases however, energy storage systems become more important. Not only can they help with grid stability and daily fluctuation, but also absorb seasonal variation through power-to-gas (P2G) technologies (Jafari et al., 2022).

However, no detailed investment plans to implement these measures in the long-term exist so far. Especially countries in Central and Eastern Europe with direct pipeline connections strongly rely on natural gas imports from Russia and have to find solutions to the decrease in availability of natural gas (Bella et al., 2022; Holz et al., 2022). Actions taken to overcome the short to medium-term reductions in gas supply, however, can have strong effects on the energy system in the future. Forecasting these potential impacts can be challenging, making it crucial to analyze the long-term developments carefully.

2.2. Review of relevant literature

In the last year, the effects of decreased Russian natural gas deliveries have become a widely discussed topic. To find solutions and show possible future chances for an accelerated transition toward a decarbonized energy system, various studies have analyzed the subject. The majority of studies categorize the effects of a disruption of Russian gas into short-term and long-term effects. Short-term effects describe consequences until the end of 2022 and sometimes include 2023, while long-term effects refer to developments after 2030. In the following, other works shall be summarized and current numbers and actions of real developments until the point of writing this paper are presented.

In the short-term, the effects of most works are in line with each other, differing mostly in numbers. While Hauenstein et al. (2022) is analyzing the German energy system and Bella et al. (2022) and Holz et al. (2022) analyze the European energy system, they all agree that importing LNG is most likely the first option to substitute Russian gas in the short-term. Furthermore, demand reduction and replacement of natural gas through alternative sources are identified as other solutions.

Bella et al. (2022) find that 95 billion cubic meters (bcm) of Russian gas can be substituted by alternative sources of energy with 55 bcm coming from LNG. The rest is accounted for by higher non-Russian pipeline imports, nuclear power, renewable energy sources (RES), gas-to-coal switching, and gas-to-oil switching. Beside the substitution in supply, it is suggested that a reduction of 13 bcm in industrial natural gas demand is possible. However, that would only lead to a possible substitution of 108 bcm, compared to the 174 bcm of natural gas that was imported from Russia in 2021. McWilliams et al. (2021) identify that actual pipeline gas imports from Norway increased from around 88 bcm in 2021 to 94 bcm in 2022, while imports from the United Kingdom (UK) increased by 200% to 26 bcm from 2021 to 2022. Furthermore, imports of LNG rose from 74 bcm in 2021 to 123 bcm in 2022. Corresponding to Bella et al. (2022), the EU pledged to increase energy savings in order to fill up gas storage, since at this point no viable alternatives exist to fully substitute natural gas for heating purposes in the short-term (European Commission, 2022e). By November 2022, the storage was filled over 94% EU-wide exceeding the target of at least 80%. Even at the end of 2022, an average storage level of 83% was achieved (European Commission, 2022f).

Another measure proposed by several other studies is to substitute natural gas used in power generation. In the electricity sector in particular, natural gas can be substituted quite easily. IEA (2022) shows that various countries like Germany, France, and the Netherlands switch from natural gas power generation to coal and oil power generation, as also suggested by Bella et al. (2022). In Germany alone, coal-generated electricity increased by around 17% in the first half of 2022 compared to the first half of 2021 according to Destatis (2022). Although this has increased Europe's carbon emissions for 2022, it is believed that the phase-out of coal power can be accelerated by the planned build-up of RES in the medium to long-term (Hauenstein et al., 2022). For the period between May and August, the EU already obtained a record 12% of its electricity from solar power, while also generating 13% from wind. With the additional ambitious plans from REPowerEU, a growth from 37% in 2021 to 69% in 2030 is expected for the share of RES in the electricity mix (European Commission, 2022f). Moreover, the imposed emission cap by the EU Emissions Trading System (EU ETS) is expected to result in reduced emissions (IEA, 2022). Contributions in recent literature have supported such cap-and-trade market schemes and studied the optimal operation of gas-fired power plants to further reduce emissions in the energy system (Dong et al., 2022; Dimitriadis et al., 2023).

The increase in coal and oil power generation resulted in historically high energy prices. The price for natural gas increased more than five-fold by the end of the first quarter of 2022 compared to early 2021 across Europe (Ari et al., 2022). In August, the price reached its peak of 340 €/MWh (Trading Economics, 2022). At the same time, coal and crude oil prices increased as well. Higher shares of coal and oil in electricity generation also lead to high electricity prices. Although electricity prices vary throughout Europe due to different compositions of the power mix, an increase could be observed over all of Europe according to Ari et al. (2022) and IEA (2022).

In comparison to the short-term effects, there are not many studies yet analyzing the long-term effects of the Russian gas disruption. Auer et al. (2020b) model the future European energy system and compare four different scenarios. In the least ambitious scenario, the Gradual Development scenario, which is still in accordance with a 2 °C target, natural gas consumption decreases from 30 EJ in 2020 to around 20 EJ in 2030 and even further to around 15 EJ in 2035. While this is not directly linked to reduced gas supply, it shows that the decreased demand for natural gas outweighs the supply gap caused by the Russian aggression. The same effect is shown by Pedersen et al. (2022), who analyze the long-term implications of reduced gas imports. In their 1.5 °C scenario, natural gas is pushed out of the system before 2030 even without gas limitations. A normalization of the gas price can already be seen after 2030. Looking at the 2 °C scenario however, a limitation of gas results in a normalization of the gas price after 2045. Moreover, coal is phased out a decade later, while wind and solar PV is build faster before 2030.

Summarizing, a diverse body of literature exists analyzing the short-term effects of reduced Russian natural gas imports, while quantitative research on long-term effects is lacking. In order to better understand the implications that come with an event of that scale, it is crucial to also study the long-term system developments and the direct and indirect causes of short and medium-term reactions to the reduced natural gas imports. Therefore, this study aims to add to the scarce quantitative literature on long-term energy system development, while still considering short and medium-term impacts.

3. Methodology

To analyze the short- and long-term effects of a reduction in Russian fossil imports, the Global Energy System Model (GENeSYS-MOD) is used to represent the future European energy system. In the following section, a brief description of the model is given explaining its general functionality. Further, improvements made in the model formulation specifically for this study are outlined.

3.1. Model description

GENeSYS-MOD is a linear, cost-optimizing, techno-economic energy system model, minimizing the net present value of the modeled energy system. Based on the Open Source Energy Modelling System (OSeMOSYS), it was developed by Löffler et al. (2017) to evaluate pathways towards a low-carbon energy system across the energy sectors electricity, buildings, industry, and transportation. A special focus is placed on sector coupling, using an integrated, holistic approach that optimizes all sectors simultaneously. Given an exogenous demand, the model invests in generation, trade, and storage capacities to satisfy the demand in each timestep. With consideration of capacity expansion, dispatch, energy flows, and sector coupling, the system costs are minimized under perfect foresight. A stylized representation of the model can be seen in Fig. 1, while a more detailed description can be found in Appendix A.

GENeSYS-MOD is versatile and was applied in a macro-regional and global scope (Löffler et al., 2017; Hainsch et al., 2021), as well as in various country-level case studies[1] (Burandt, 2021; Hanto et al., 2021; Löffler et al., 2022). The model is under constant development, extending its functionalities and features for new versions. This paper builds upon the European model version 3.1, developed in the Horizon 2020 project Open ENTRANCE (Auer et al., 2020; Hainsch et al., 2022). A cost-optimized European energy system is computed, analyzing the timeframe from 2018 until 2050.[2] Spatially, Europe is disaggregated into 30 regions, consisting of mainland EU-25, Norway, Switzerland, Turkey, the UK, and an aggregated non-EU Balkan Region (see Fig. 2). Of the four pathways created in the Open ENTRANCE project, the Gradual Development scenario was chosen to serve as the basis for this study. It entails a moderate combination of political, societal, and technological development, while still complying with an ambitious 2 °C climate target and reaching the EU's goal of greenhouse gas neutrality by 2050. Comparing three scenarios, insights on the effects of a complete import stop of Russian natural gas on the energy system's development are analyzed. More information on the specific scenarios and sensitivities calculated in this paper are described in Section 3.3.

[1] For further information on GENeSYS-MOD including a documentation, quick-start guide, and a sample data set, the reader is referred to: https://git.tu-berlin.de/genesysmod/genesys-mod-public.

[2] The years 2018–2025 are modeled on an annual basis, followed by 5-year steps until 2050. 2020 was excluded due to it being an outlier, following the heavy impacts of the COVID-19 pandemic on energy consumption and the strong rebound that ensued afterward.

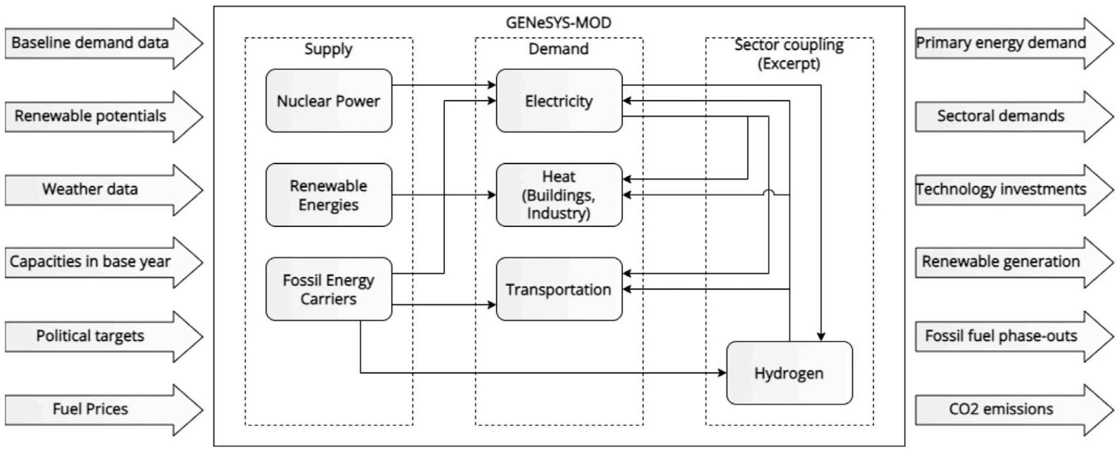

Fig. 1. Stylized representation of GENeSYS-MOD's inputs and outputs.
Source: Own illustration.

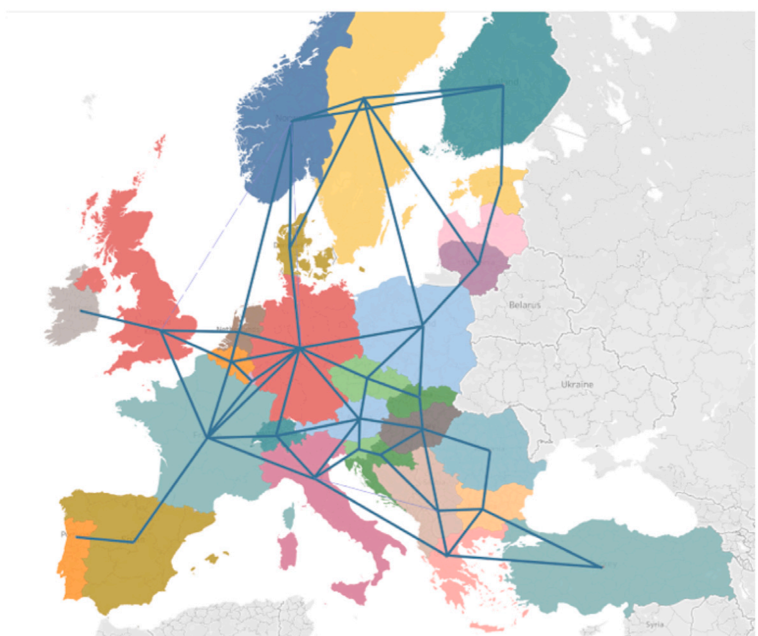

Fig. 2. Regional model set-up used within this paper.
Source: Own illustration.

3.2. Changes in model functionality regarding gas imports

In the previous model version, Russia as well as other non-EU countries were not depicted as individual regions. Imports from outside of the regions mentioned in the above paragraph are aggregated and considered imports from the global market. In order to adjust the incoming natural gas from Russia into Europe, a new parameter *set_limit_russian_gas_supply* was introduced. The parameter can have a value between 0 and 1, specifying the share of original annual natural gas capacities that can be used. However, the parameter can only affect regions that have a pipeline connection to Russia[3] (ENTSO-G, 2019). For these regions, a parameter showcasing the percentage of natural gas pipelines coming from Russia, *TagRussianGasSupply*, was implemented (see Table 1).

Table 1
Parameter values for *TagRussianGasSupply* describing the share of Russian natural gas pipelines for all countries with natural gas transmission capacities outside the modeled region.
Source: ENTSO-G (2019).

	DE	EE	ES	FI	HU	IT	LT	LV	PL	RO	SK	TR
Share	1	1	0	1	1	0	1	1	1	1	1	0.64

For regions that do not import natural gas from other countries outside of Europe or only from sources other than Russia, the parameter is set to 0, meaning that a supply ban on Russian fuels will have no effect on these countries. Turkey is a unique case since external connections to both Russia and Azerbaijan exist as possible import sources (ENTSO-G, 2019). Eq. (1) shows the constraint regarding the Russian gas limitation that was implemented in the model.

[3] I.e., Estonia, Finland, Germany, Hungary, Latvia, Lithuania, Poland, Romania, Slovakia, and Turkey.

$$ProductionByTechnologyAnnual_{(y,Z\_Import\_Gas,Gas\_Natural,r)} \leq TotalTechnologyAnnualActivityUpperLimit_{(r,Z\_Import\_Gas,y)} * (1 - TagRussianGasSupply_r * (1 - \%set\_limit\_russian\_gas\_supply\%)) \quad (1)$$

The variable *ProductionByTechnologyAnnual* hereby describes the imports of natural gas of a specific year and region. It has to be less or equal than the maximum possible import of natural gas for that year and region, defined by the *TotalTechnologyAnnualActivityUpperLimit*, multiplied by the limit that was set for *set_limit_russian_gas_supply*. Since the base year of the computation is set to 2018, the equation is only valid for years after 2021.

Furthermore, a constraint on LNG imports was added to describe the maximum available amount of total LNG terminal capacities for actual feed-in into the gas network. This can also be observed in reality, where the pure import and regasification capacities vastly exceed the maximum feed-in into the gas transmission grid.

For a detailed analysis of the effects in the short to medium-term, intermediate years between 2018 and 2025 were included. The year 2020 however is excluded from the analysis due to the year's COVID-19 related irregular behavior in the energy sector.

3.3. Scenario assumptions

The scenario chosen for this study is taken from the Horizon 2020 project Open ENTRANCE. Out of the four storylines created in the project, the Gradual Development scenario was chosen. The scenario involves equal contributions from societal, industry/technology, and policy factors in achieving a less ambitious climate mitigation target (2 °C) compared to the other pathways (which aim for a much more ambitious target of 1.5 °C). This scenario is a combination of elements from the Techno-Friendly, Societal-Commitment, and Directed Transition pathways, but with a more moderate transformation of the energy system resulting in a decarbonization by 2050.[4] The carbon price is lower, and the cost and efficiency projections for all technologies are less optimistic, with slower improvements and no integration of unproven technologies. This scenario also involves reductions in energy demand, but to a lesser extent than the Societal Commitment scenario and with limited potential for demand shifting (Auer et al., 2020). A visual summary of the four pathways can be seen in Fig. 3.

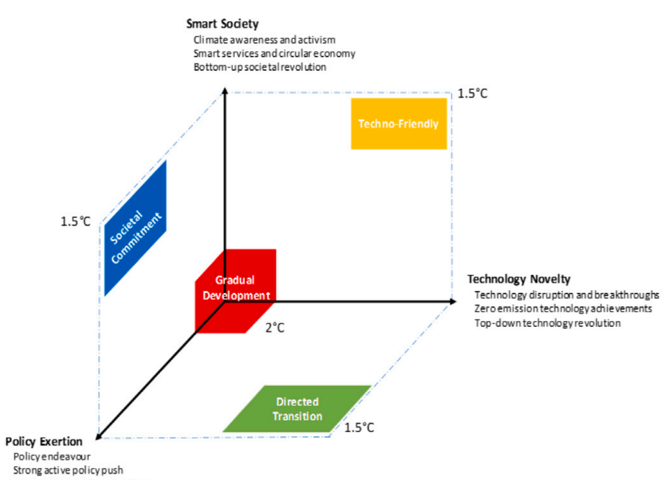

Fig. 3. Scenarios of the H2020 EU project Open ENTRANCE.
Source: Auer et al. (2020b).

[4] For more detailed descriptions of the scenarios, consult Auer et al. (2020).

The reason behind the choice of the Gradual Development scenario is its combination of parts of each of the other scenarios, while still aiming for an ambitious 2 °C goal. Furthermore, the scenario shows the highest amount of natural gas across the Open ENTRANCE pathways, as those aimed at limiting global warming to 1.5 °C will be forced to phase out fossil fuels entirely within the next 17 years, thus making any effects from a Russian import stop negligible (Hainsch et al., 2022; Auer et al., 2020). Thus, effects of the limitations on the Russian gas supply can be analyzed in more detail.

3.4. Sensitivities regarding Russian natural gas imports

In order to accurately investigate the effects of Russian natural gas disruptions, different levels of import limitations are computed. To achieve that, first the newly implemented parameter *limit_russian_gas_supply* and second, fossil fuel prices are varied. Three variations are chosen for the analysis in this paper, which can be seen in Table 2.

Table 2
Overview of scenario assumptions.

	Base Scenario	Lim Scenario	Zero Scenario
Limitation parameter	1	0.25	0
Fuel price assumption	Pre war (2021)	Post war (2023)	Post war (2023 increased)

The first case in which the limitation parameter is set to 1 describes the situation before the Russian aggression. Natural gas imports from Russia are unrestricted as it was in 2021, thus being called the "Base Scenario". For this scenario fossil fuel price projections on the level before the Russian aggression from World Bank Group (2021) are used. The "Lim Scenario" is chosen as a more currently accurate scenario. With natural gas imports from Russia reduced by around 75%–80% in 2022 compared to 2021, the limit set for this scenario is 25% (McWilliams et al., 2021). The updated prices from World Bank Group (2023) are taken for this scenario. As a more extreme scenario and to analyze the effects of a full import stop of Russian fossil fuels, the "Zero Scenario" limits the imports of natural gas to 0%, while using increased prices for coal and oil. In the first years of the "Zero Scenario" the same prices as in the before-mentioned scenario are taken. However, increased prices for coal and oil are assumed from 2022 onward. High import shares of Russian oil and coal into Europe raise security concerns regarding these fuels. Chen et al. (2023) investigate market implications of different scenarios and come to the conclusion of higher fuel prices in case of import restrictions on oil and coal from Russia, which we use to highlight the possibility of a complete import stop of any Russian fossil fuels. Tables with price assumptions can be found in Appendix B.

4. Results

Throughout the results, it is noticeable that the initial restrictions on natural gas imports from Russia have significant effects on the energy system and its development over the years. However, comparing the two scenarios with limited natural gas supply, the differences are only minor. Subsequently, primarily differences between the Base and the Lim scenario will be presented in the main body of this paper. Details on the Zero scenario are provided in Appendix C.

The model results show two major impacts of a restricted natural gas supply from Russia, which can be seen in Fig. 4. First, the total gas consumption in Europe decreases with limited Russian natural gas. The limited availability and thus higher natural gas prices drive a faster reduction in the consumption of natural gas, which cannot be fully substituted by other sources of natural gas. Second, an increase in the use of LNG, imported from abroad (e.g. the United States or from the Middle East), accompanied by an increase in domestic gas extraction within Europe, mostly from the Netherlands and Norway, can be seen.

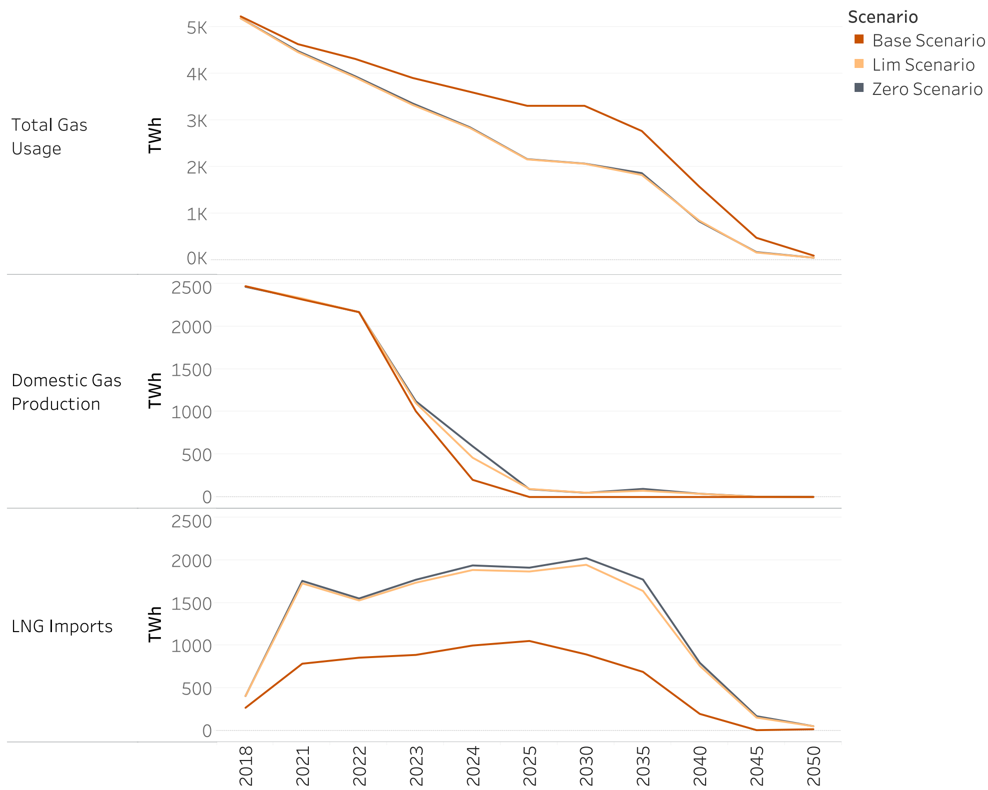

Fig. 4. Results for total European gas use (top), domestic (European) gas production (middle), and LNG imports (bottom) until 2050, considering a 2 °C target. *Source:* Own illustration.

LNG imports steadily increase until 2030 in scenarios with limitations on Russian natural gas, but then quickly decline afterward, as the energy system becomes more and more decarbonized towards 2050 and climate goals have to be met. While LNG imports rise, the domestic gas production falls steadily. In contrast to the Base scenario stopping domestic production by 2025, the scenarios with restricted Russian gas imports rely on small amounts of domestic generation until 2045 to account for the missing gas. Despite increased LNG imports, total natural gas consumption declines steadily over the model period due to decarbonization efforts and rising fossil fuel prices.

Fig. 5 highlights the development of electricity generation in the Base and Lim scenarios. It shows that the amount of fossil gas used for electricity production is steadily decreasing after 2021, with a 100% carbon-free electricity sector in 2045 in the Lim scenario, compared to 2050 in the Base scenario. This can be explained by the ambitious climate target of 2 °C that has been set for this study, requiring a strong coupling of all energy-related sectors, and therefore electrification — either direct (e.g. via heat pumps or battery-electric vehicles) or indirect (via hydrogen). This, however, means that the electricity supply needs to be low-carbon or even carbon-free in order to yield the desired emission reductions when that electricity is later used in other sectors. Combined with low-emission technologies already available and the necessity to substitute the electricity generated by natural gas, this results in an overall earlier phase-out of fossil fuels.

The major share of renewable electricity generation comes from photovoltaics and onshore wind installations, with additional electricity supply from offshore wind, hydropower, and nuclear. On the bottom right of Fig. 5 the difference to the Base scenario can be seen. In the short-term especially, natural gas is substituted by coal. However, climate targets push the generation toward low-carbon technologies as a substitute as early as 2030. Furthermore, an increase in total electricity generation can be noticed, which can be attributed to the necessity of electrifying other sectors to substitute natural gas.

Especially in the buildings sector direct electrification through heat pumps is used as a solution to the natural gas disruptions. Fig. 6 shows that the buildings sector in particular uses natural gas as a major heat source. Although the share of natural gas is decreasing steadily in both scenarios, a stronger effect is visible in the Lim scenario. At its peak, around 600 TWh of natural gas, or 21% of total heat generation, are fully substituted by heat pumps. The effect grows weaker however in later years, when decarbonization efforts push out natural gas. By 2050, more investments are made in hydrogen, ground-sourced heat pumps, and direct electric capacity in the Lim scenario, compared to biogas/biomass and air-sourced heat pumps in the Base scenario.

Similar to the buildings sector, a high share of process heat in industry is generated by natural gas, as can be seen in Fig. 7. Both scenarios display a similar technology mix by 2050, but exhibit different pathways to reach that point. While in the Base scenario process heat generated by hard coal is decreasing steadily, in the Lim scenario an increase until 2025 is visible. Contrary to the high electrification in the buildings sector, natural gas is substituted mostly by hard coal in the short to medium-term. However, because of the necessity to decarbonize the energy system, the share of hard coal is decreasing again after 2025. Due to the higher demand of electricity in other sectors, the share of direct electric process heating until 2035 is lower in the Lim scenario compared to the Base scenario. This further results in increased shares of biomass in the early years of the Lim scenario. Overall the restrictions on natural gas imports from Russia result in a carbon-free industry sector by 2040 in the Lim scenario, compared to 2045 in the Base scenario.

Looking at the levelized costs of electricity generation in Fig. 8, a strong reaction in the intermediate years between 2022 and 2025 can

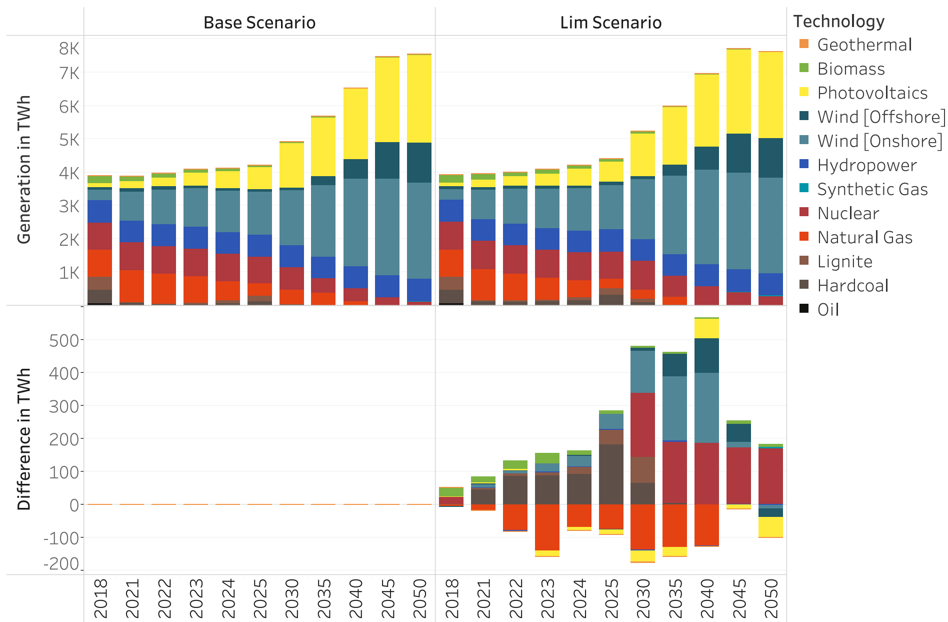

Fig. 5. Development of electricity generation (top) and difference to the Base scenario (bottom) in Europe until 2050.
Source: Own illustration.

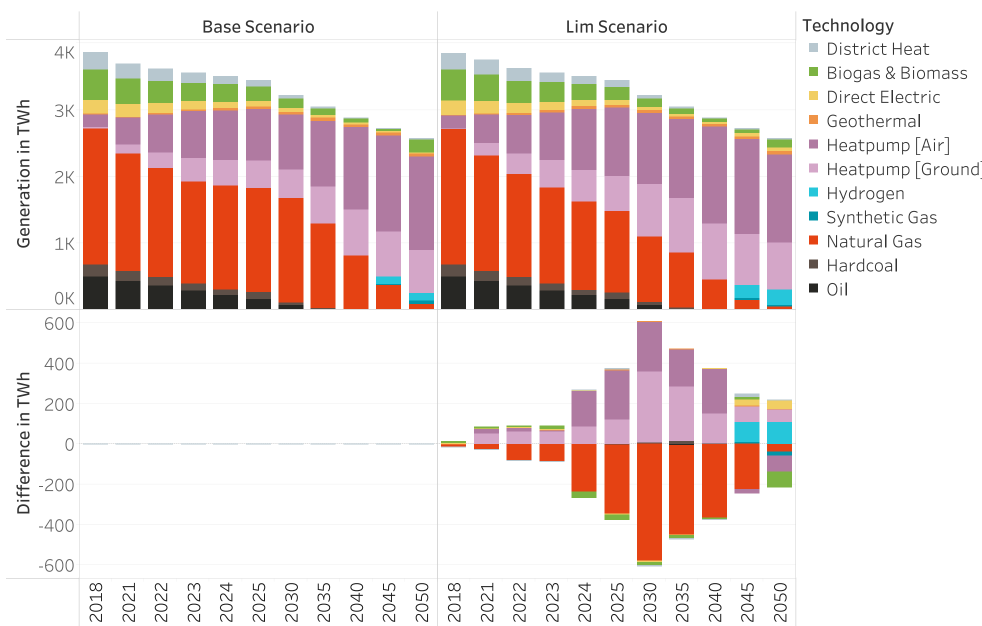

Fig. 6. Development of buildings heat generation (top) and difference to the Base scenario (bottom) in Europe until 2050.
Source: Own illustration.

be observed, especially in scenarios with limited natural gas imports. With the increase of fossil fuel costs (compare Table B.1, Table B.2, and Table B.3) due to the war in Ukraine and sanctions on Russian fossil imports, the costs of electricity rise sharply in 2022. However, contrary to some predictions, fossil fuel costs dropped again as early as 2023, resulting in a rapid decline of electricity generation costs. Another steep decrease can be seen in 2025, after which the costs of electricity generation fall steadily. A noteworthy finding is the limited effect on later periods, where after 2040, only a negligible difference in generation costs can be observed. This can be attributed to the overall reduction of natural gas and increase of renewable technologies to achieve climate goals in the electricity sector.

Especially in scenarios with limited natural gas imports, a faster build-up of RES can be noticed. As Fig. 9 shows, this results in overall lower cumulative CO_2 emissions in 2050. The Lim and Zero scenario exhibit 6.7% and 7.3% lower emissions respectively compared to the Base scenario. Although in the short to medium-term emissions are higher in scenarios with natural gas restrictions, due to the increased use of coal, emissions fall faster after 2025. Consequently, the energy system reaches close to zero CO_2 emissions 5 years earlier compared to the Base scenario. This shows that the impacts of reduced Russian gas imports do not pose a threat to the decarbonization of the energy system and instead can be a chance for a faster reduction in emissions.

Fig. 7. Development of process heat generation in industry (top) and difference to the Base scenario (bottom) in Europe until 2050.
Source: Own illustration.

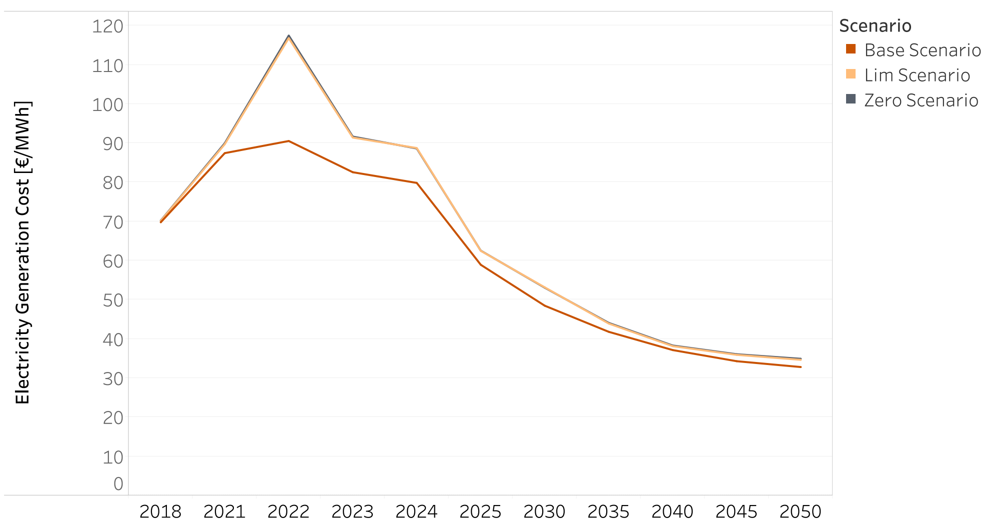

Fig. 8. Results for electricity generation costs in € per MWh until 2050 for the different gas supply scenarios.
Source: Own illustration.

5. Discussion

As shown in the results, restrictions on Russian natural gas imports exhibit strong effects on energy system development, mostly in the near to medium future. However, the decreased dependency of the entire energy sector on fossil fuels due to the determined climate targets means that in the long run, limitations of Russian fossil fuels have less and less effects on the long-term development of the energy system. However, the model results show that the higher energy costs that come along with increased fossil fuel prices lead to positive feedback in terms of emission reductions, as it drives earlier investments into renewable alternatives and energy efficiency measures.

Throughout all energy sectors, stronger reductions in the use of fossil fuels and /or earlier achievement of carbon-neutrality is visible. Even in sectors in which not enough RES capacity can be built early on, this effect can be seen. In the electricity sector, the reactivation of coal-generated electricity plants is an alternative that can also be found in reality. Furthermore, as not enough electrolysis capacity exists yet, coal is used instead of hydrogen as a substitute for natural gas in the industry sector. Although this increases emissions in the short-term, it accelerates the later build-up of renewable technologies. Nevertheless, this should be planned carefully and not serve as a reason to switch back to heavy carbon emitting technologies and generate new lock-in effects.

Both the buildings and industry sector show only small amounts of district heating in our results. Especially the buildings sector relies heavily on heat pumps, resulting in a share of 80%. Likewise, the industry sector is mainly relying on direct electrification for its process heat. Improvements in the model on district heating technologies as well as the use of hydrogen in the industry sector could change these results, possibly resulting in further reductions of fossil fuel use.

Another important topic is that of LNG, which is currently under discussion to form a bridge solution and replacement for Russian gas. Many European countries are currently evaluating plans for new

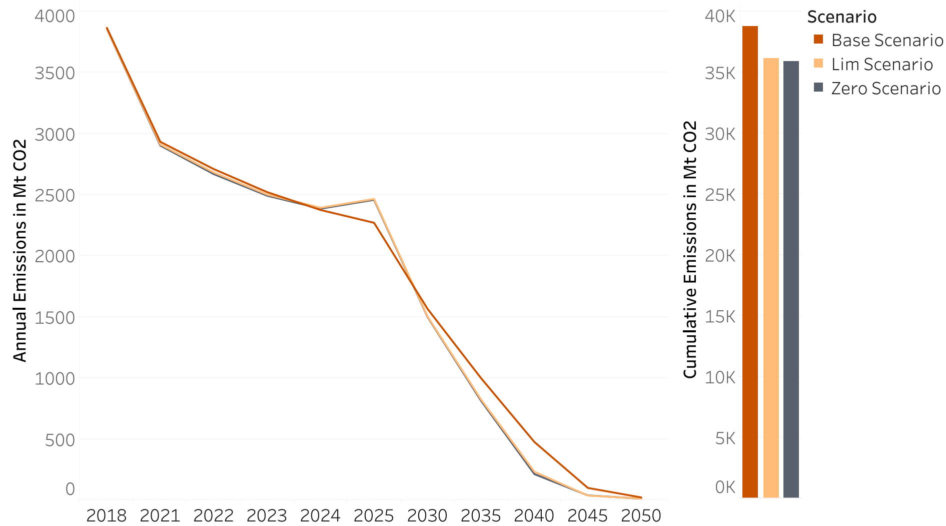

Fig. 9. Results for annual (left) and cumulative emissions (right) in 2050 for the different gas supply scenarios.
Source: Own illustration.

LNG terminals (Holbrook, 2022; American Journal of Transportation, 2022), with Germany as one of the most heavily affected countries of the Russian gas supply shock, both constructing temporary, floating offshore terminals for LNG imports, as well as permanent onshore terminals (Höhne et al., 2022). These onshore installations are especially problematic since they can create negative path dependencies and potentially stranded assets, as those terminals will need to remain in operation for multiple decades to recoup their investments (Höhne et al., 2022; Wettengel, 2022; Holz et al., 2023). With carbon neutrality as a set target for the year 2050, however, these terminals would have a short lifespan, which can also be clearly seen in our modeling results. Furthermore, as demand for LNG rises, prices will likely increase as well. This could result in high wholesale electricity prices as witnessed in the summer of 2022, when LNG and electricity prices peaked at a record high (Global LNG Hub, 2022; Eurostat, 2023). Another unintended drawback of European LNG imports could be an increase in global emissions through countries like Bangladesh, Pakistan, India, and Indonesia. These heavily LNG-dependent countries could potentially switch to coal, when LNG prices increase due to higher demand (Ari et al., 2022). The actual necessity of additional onshore LNG terminal installations, therefore, needs to be critically evaluated.

Since the model performs a system-wide optimization in the form of cost minimization, the results are inherently dependent on the input assumptions, especially regarding costs. Therefore, a clear limitation of this and any study trying to gain insights into future developments is that of forecasting. The sudden invasion of Ukraine by Russia has shown that any prediction in terms of demands, costs, or prices can change drastically within an instant. As such, the results presented in this paper are heavily contingent on the used assumptions on fossil fuel price developments, as well as other scenario assumptions that stem from the use of the Open ENTRANCE scenarios. As the model itself does not contain any markets for fossil fuels or any stochastic elements regarding the future developments of prices, the chosen fossil fuel prices listed in Appendix B are merely an openly available cost prediction, and should not be taken as certain. To combat these shortcomings, sensitivity analyses have been conducted for multiple price levels of fossil fuels, as well as multiple parameter settings for limits on Russian gas imports. Future research should also incorporate possible feedback effects of fuel switches in the energy system, leading to e.g. increased LNG prices, and a detailed analysis of the actual long-term availability of LNG imports on the global market.

6. Conclusion

The Russian invasion of Ukraine caused many challenges for the Europe, including its energy system, raising security of supply issues and steep price hikes for energy costs, posing problems for both consumers and companies. These challenges highlighted a substantial energy reliance on Russian fossil fuels that Europe established over the past decades. With most of its natural gas supply coming from Russia, disruptions in gas delivery are especially challenging to deal with. In order to effectively address these issues, it is crucial to thoroughly analyze the impacts of reduced natural gas availability from Russia and the effects, both in the short-term, as well as in the more distant future.

The Global Energy System Model (GENeSYS-MOD) was used for the quantitative analysis of this study. With improvements to the depiction of natural gas infrastructure, the European energy system is computed until 2050, including the sectors electricity, buildings, industry, and transport. On the basis of a 2 °C compatible pathway, three gas supply scenarios are calculated, each varying the amount of available Russian natural gas (and other fossil fuel imports from Russia) to the system. The results of the computations show that strong effects are mostly observed in the short to medium-term, but an overall earlier phase-out of fossil fuels can be noticed in the long-term, yielding both challenges for the next few years, but opportunities for the future.

Limitations on natural gas imports from Russia result in an earlier and stronger decrease of gas consumption in Europe compared to the Base scenario. As expected, an increase in LNG imports as well as an increase in domestic natural gas production is the response to the absence of Russian natural gas in scenarios with import restrictions. The construction of new LNG terminals, however, is a double-edged sword, since it can cause negative path dependencies and stranded assets.

An overall stronger decrease and earlier phase-out of fossil fuels can be observed throughout all sectors in the Lim and Zero scenario compared to the Base scenario.

Furthermore, all scenarios show strong effects on the levelized costs of electricity generation between 2022 and 2025. In the long term, however, only a negligible difference between the scenarios can be observed.

Most importantly, reduced emissions in scenarios with limited natural gas imports highlight that an early reduction in fossil fuels and investment in energy efficient and low-carbon alternatives has a positive effect on the energy system, namely 6.7% and 7.3% reductions in cumulative emissions in the Lim and Zero scenario respectively. This results in an almost emission free energy system by 2045 in both cases, 5 years earlier than in the Base scenario.

In conclusion, the presented analysis shows that a limitation of natural gas imports from Russia does not pose a long-term threat to the European energy system, but can rather help accelerate its decarbonization. Early reactions in the electricity generation costs normalize in the long term and additional emissions caused by substituting fuels are balanced out by earlier investments into renewable energies. However, support measures for citizens and companies to feather the impact of energy price hikes, as well as forward-looking, long-term planning are needed in order to successfully handle the impacts of such a crisis and lead the development of the energy system in the right direction. Future research should include further analysis on feedback effects of other possible fuel switches, as well as implications on the LNG market and its effect on wholesale prices.

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CRediT authorship contribution statement

Nikita Moskalenko: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Konstantin Löffler:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Karlo Hainsch:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Software, Supervision, Validation, Writing – original draft. **Jonathan Hanto:** Conceptualization, Formal analysis, Investigation, Validation, Writing – original draft. **Philipp Herpich:** Conceptualization, Formal analysis, Investigation, Validation, Writing – original draft.

Declaration of competing interest

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

Data availability

The model and data used in this research can be found at the open Zenodo repository for GENeSYS-MOD data sets (https://zenodo.org/communities/genesys-mod/). Further information on the model can be found on the public GitLab page of GENeSYS-MOD (https://git.tu-berlin.de/genesysmod/genesys-mod-public). Also, the Open ENTRANCE scenario explorer (https://data.ene.iiasa.ac.at/openentrance/) can be used to visualize and download key results from the Gradual Development scenario that was used in this paper.

Appendix A. Model description

GENeSYS-MOD is a cost-optimizing linear program, focusing on long-term pathways for the different sectors of the energy system, specifically targeting emission targets, integration of renewables, and sector-coupling. The model minimizes the objective function, which comprises total system costs (encompassing all costs occurring over the modeled time period) (Löffler et al., 2017; Howells et al., 2011).

The GENeSYS-MOD framework consists of multiple blocks of functionality, that ultimately originate from the OSeMOSYS framework. Fig. A.1 shows the underlying block structure of GENeSYS-MOD v3.0, with the additions made in the last model version (namely the option to compute variable years instead of the fixed 5-year periods, as well as an employment analysis module, in addition to the regional data set and the inclusion of axis-tracking PV).

(Final) Energy demands and weather time series are given exogenously for each modeled time slice, with the model computing the optimal flows of energy, and resulting needs for capacity additions and storages.[5] Additional demands through sector-coupling are derived endogenously. Constraints, such as energy balances (ensuring all demand is met), maximum capacity additions (e.g. to limit the usable potential of renewables), RES feed-in (e.g. to ensure grid stability), emission budgets (given either yearly or as a total budget over the modeled horizon) are given to ensure proper functionality of the model and yield realistic results.

The GENeSYS-MOD v3.0 model version used in this paper uses the time clustering algorithm described in Gerbaulet and Lorenz (2017) and Burandt et al. (2019), with every 73rd hour chosen, resulting in 120 time steps per year, representing 6 days with full hourly resolution and yearly characteristics. The years 2018–2050 are modeled in the following sequence: 2018, 2025, 2030, 2035, 2040, 2045, 2050. All input data is consistent with this time resolution, with all demand and feed-in data being given as full hourly time series. Since GENeSYS-MOD does not feature any stochastic features, all modeled time steps are known to the model at all times. There is no uncertainty about e.g. RES feed-in.

The model allows for investment into all technologies and acts purely economical when computing the resulting pathways (while staying true to the given constraints). It usually assumes the role of a social planner with perfect foresight, optimizing the total welfare through cost minimization.

For more information on the mathematical side of the model, as well as all changes between model versions, please consult (Howells et al., 2011; Löffler et al., 2017; Burandt et al., 2018, 2019).

Appendix B. Data

Building on a previous version of GENeSYS-MOD, relevant data for this study's investigation needed to be updated. Limiting the supply of Russian gas imports means that other gas infrastructure becomes more important. In order to still meet the gas demands, the natural gas has to be imported or traded from alternative regions. This does not only include the natural gas pipeline infrastructure, but also the LNG infrastructure. Therefore, the natural gas and LNG infrastructure was updated using a more recent version of the European Network of Transmission System Operators for Gas (ENTSOG) transmission capacity map (ENTSO-G, 2019).

For the newly implemented maximum available share of total LNG terminal capacity for actual feed-in into the gas network, own assumptions based on European Commission (2022c) were made.

The most important change in the data however was made within the fuel prices. After Russia's invasion of Ukraine, energy and fuel prices increased multiple fold. To account for that, the international fuel prices of oil, hard coal, natural gas and LNG were updated according to World Bank Group (2023). Since in the newer versions of the Commodity Outlook projections are only made until 2024, the development after 2025 was assumed to be the same as in previous versions. A comparison of the fuel price assumptions post and pre war can be found in Tables B.1, B.2, and B.3.

Appendix C. Additional results

Additional results in regard to differences between the Lim and Zero scenario for each sector are visualized in Figs. C.2–C.4.

[5] GENeSYS-MOD offers various storage options: Lithium-ion and redox-flow batteries, pumped hydro storages, compressed air electricity storages, gas (hydrogen and methane) storages, and heat storages.

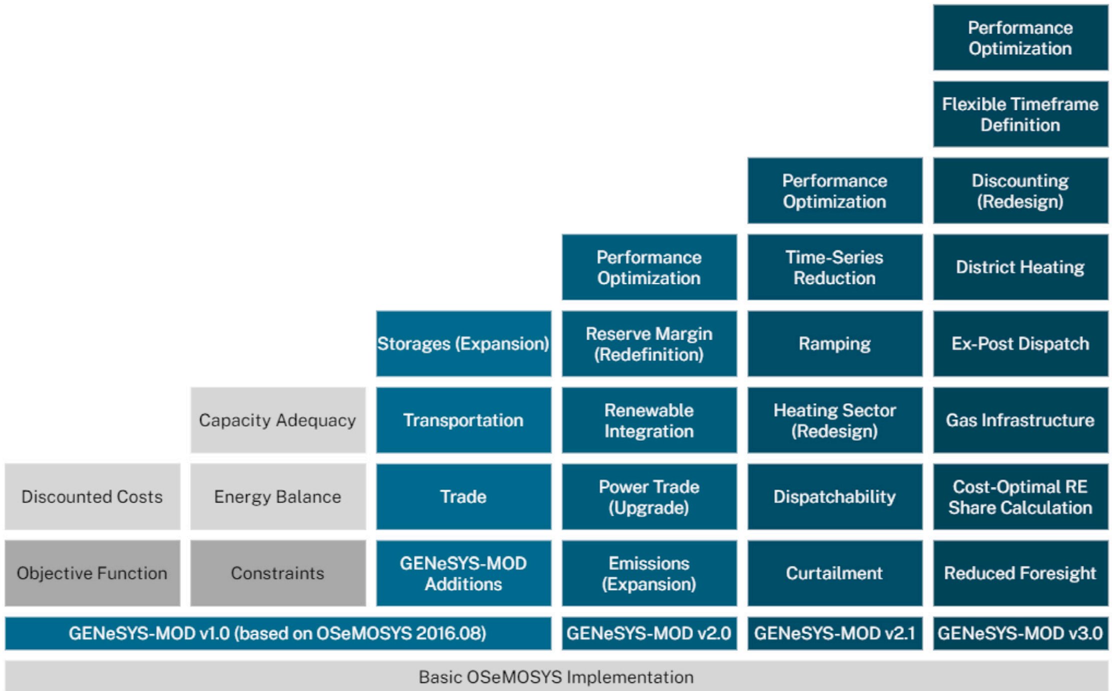

Fig. A.1. Model structure of the GENeSYS-MOD implementation used in this study.

Table B.1
Fuel price projections in M€/PJ dated October 2021, before the Russian aggression.
Source: World Bank Group (2021).

Fuel	2018	2019	2021	2022	2023	2024	2025	2030	2035	2040	2045	2050
Oil	9.07	9.07	10.24	10.65	9.19	6.15	8.97	8.41	8.68	7.81	6.64	5.64
Hardcoal	2.4	2.4	4.27	3.61	2.66	2.51	2.36	1.75	1.41	1.14	0.92	0.74
Natural gas	4.67	4.09	12.37	10.49	7.51	7.17	6.91	5.37	4.69	4.08	3.55	3.09
LNG	9.04	8.55	9.04	8.01	7.71	7.16	6.48	5.46	4.55	3.64	2.76	1.98

Table B.2
Current fuel price projections in M€/PJ after the Russian aggression.
Source: World Bank Group (2023).

Fuel	2018	2019	2021	2022	2023	2024	2025	2030	2035	2040	2045	2050
Oil	9.07	9.07	10.35	14.68	12.35	12.65	18.46	17.31	17.85	16.07	13.66	11.61
Hardcoal	2.40	2.40	4.24	10.59	6.14	4.76	4.49	3.32	2.68	2.17	1.75	1.41
Natural gas	4.67	4.09	13.73	34.38	16.21	14.50	13.98	10.88	9.50	8.26	7.19	6.25
LNG	9.04	9.04	9.21	15.70	15.35	13.65	13.06	10.53	9.35	8.13	7.07	6.15

Table B.3
Increased fuel price projections for hard coal and oil after assumptions from Chen et al. (2023).
Source: Own calculation after World Bank Group (2023) and Chen et al. (2023).

Fuel	2018	2019	2021	2022	2023	2024	2025	2030	2035	2040	2045	2050
Oil	9.07	9.07	10.35	16.44	13.84	14.16	20.67	19.38	19.99	17.99	15.29	13.00
Hardcoal	2.40	2.40	4.24	11.07	6.42	4.97	4.69	3.47	2.80	2.26	1.83	1.47

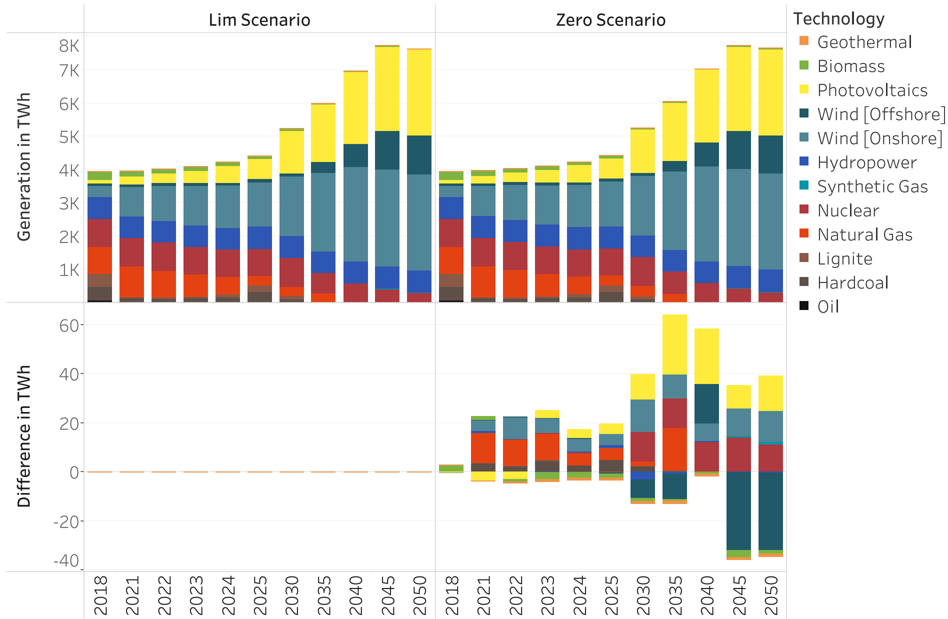

Fig. C.2. Development of electricity generation (top) and difference to the Lim scenario (bottom) in Europe until 2050. *Source:* Own illustration.

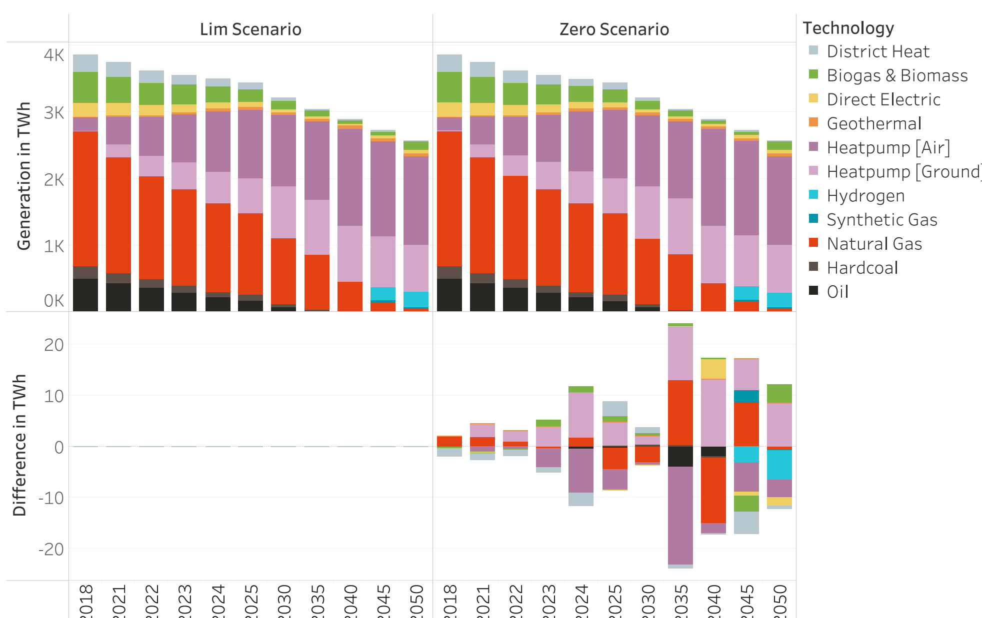

Fig. C.3. Development of buildings heat generation (top) and difference to the Lim scenario (bottom) in Europe until 2050. *Source:* Own illustration.

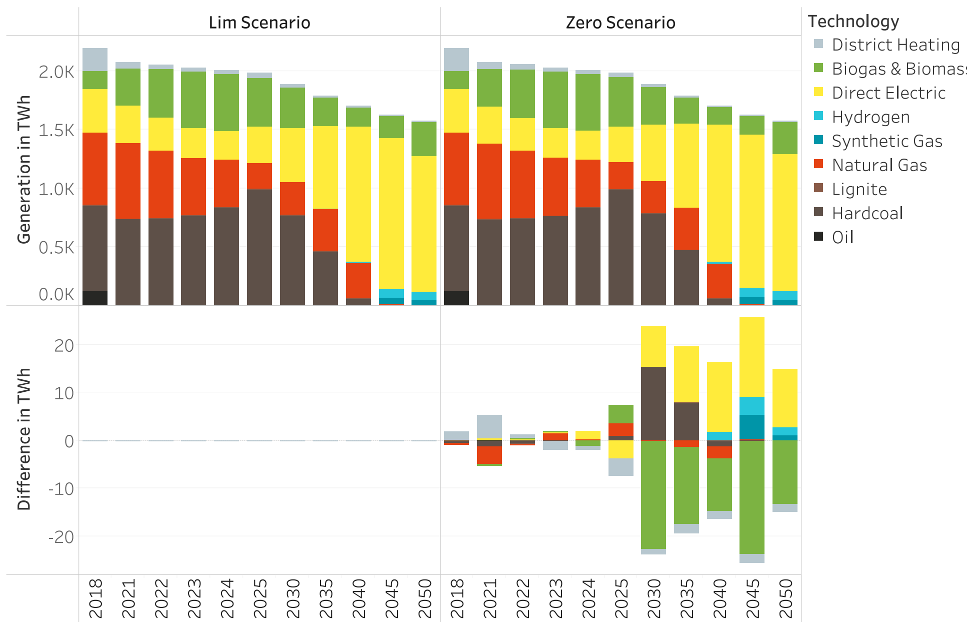

Fig. C.4. Development of process heat generation in industry (top) and difference to the Lim scenario (bottom) in Europe until 2050.
Source: Own illustration.

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