Europe's independence from Russian gas – What effects does a complete import stop have on energy system development?

Nikita Moskalenko[a,*], Konstantin Löffler[a,b,c], Karlo Hainsch[a,c], Jonathan Hanto[a,c], Philipp Herpich[a,c]

[a] *Workgroup for Infrastructure Policy, Technische Universität Berlin, Strasse des 17. Juni 135, 10623 Berlin, Germany*
[b] *Department of Industrial Economics and Technology Management (IØT), NTNU, 7491 Trondheim, Norway*
[c] *Department of Energy and Environmental Management, Europa-Universität Flensburg, Munketoft 3b, 24943 Flensburg, Germany*

Abstract

With the disruption of Russian natural gas imports, Europe's energy reliance on Russia is more apparent than ever. To tackle the resulting challenges of limited gas supply from Russia, short and long-term effects need to be investigated. This paper aims to analyze the impact of reduced natural gas availability from Russia on the European energy system, both in the immediate, as well as in the further future. Using the Global Energy System Model (GENeSYS-MOD), three gas supply scenarios were calculated with varying amounts of available natural gas from Russia. 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 noticed in the long-term. The reduction of natural gas imports is tackled by an increase in LNG imports and domestic natural gas production to bridge the gap in supply. Strong reactions are seen on the levelized costs of electricity generation between 2022 and 2025, with higher costs in scenarios with limited or no Russian gas, but with a negligible difference in the long-term. Importantly, reduced emissions in the scenarios with limited or no Russian gas highlight the positive effect of an early reduction in fossil fuels and investment in renewable technologies, resulting in a 100% emission-free energy system by 2045, 5 years earlier than in the base case with Russian gas imports. The results find that a limitation or full import stop of Russian gas does not pose a long-term threat to the European energy system, but can rather accelerate its decarbonization and energy demand reductions. However, forward-looking, long-term planning and possible support measures for citizens and companies to feather the impact of energy price hikes are needed in order to overcome the currently challenging situation.

Keywords: Energy Security, Energy Policy, Energy System Modeling, Energy Transition, GENeSYS-MOD, Renewables, Decarbonization, Russia, Natural Gas

Alle Autoren sind Jungautoren.

*Corresponding author, Tel: +49-(0)30-314-25139, Fax: +49-(0)30-314-26934

Email addresses: nim@wip.tu-berlin.de (Nikita Moskalenko), kl@wip.tu-berlin.de (Konstantin Löffler), kh@wip.tu-berlin.de (Karlo Hainsch), joh@wip.tu-berlin.de (Jonathan Hanto), phe@wip.tu-berlin.de (Philipp Herpich)

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 labelled as green in 2022 (European Commission, 2022d). It is seen as a bridge technology for the transition towards renewable energy, even though this narrative is misleading due to 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 fourth of the EU's primary energy consumption, showing the EU's reliance on this particular fossil fuel (Eurostat, 2022b).

The current war in Ukraine poses 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 Russian natural gas. Now that gas deliveries from Russia are cut due to the Russian aggression, the necessity to substitute Russian gas grows more apparent than ever (Bella et al., 2022; Holz et al., 2022). High energy prices and the fear of gas shortages in winter raise the question if the European energy system can function without gas imports from Russia (IEA, 2022).

While in the short-term, natural gas can be substituted by coal in the electricity sector, the heating sector compensates the shortage with higher gas and liquefied natural gas (LNG) imports from other countries. Neither of these options, however, helps reducing Carbon dioxide (CO_2) emissions. Furthermore, even in 2023, Europe still imports Russian gas (McWilliams et al., 2021; European Commission, 2022a; IEA, 2022). A full import stop could further increase the EU's independence from Russia and additionally help reach its climate goals. However, finding sustainable short to mid-term solutions in particular proves to be a difficult challenge to tackle and is often not quantified in detail (Bella et al., 2022; Pedersen et al., 2022).

This paper aims to gain insights on the effects of a complete import stop of Russian natural gas on energy system development by applying the Global Energy System Model (GENeSYS-MOD) on the European energy system. To evaluate the effects on the energy system, three different scenarios concerning the availability of Russian gas imports are compared: unlimited Russian gas imports, limited Russian gas imports, and a complete ban of Russian gas imports. With the addition of the short to mid-term effects (yearly steps from 2018 until 2025), the effects on the energy system for both the coming years, but also towards 2050, are computed and presented. The effects of a limited Russian gas supply on the overall gas consumption and effects on the overall decarbonization of the energy system are analyzed and an outlook on the resulting electricity generation costs is given.

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 Section 4.2 outlines scenario assumptions and data used. The results of the analysis are then presented in Section 5 and further discussed in Section 6. Finally, Section 7 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. This section presents an outline of the role of natural gas in the European energy system in order to give a first impression of Europe's dependence on Russia and subsequently reviews current literature.

2.1. Natural gas in the European energy system

Natural gas is one of Europe's main energy carriers, accounting for 24% of the EU's primary energy consumption in 2021 (Eurostat, 2022b). It is primarily used for power and heating generation (central heating units), in households (residential heating and cooking), and 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 amounts to 37% of total gross heat production in the EU (European Commission, 2022a). However, only 24% of the final natural gas demand in 2021 were produced within Europe (McWilliams et al., 2021; Eurostat, 2022a). In 2021, Europe imported about 35% of its total available natural gas (15.4 EJ) from Russia, making it Europe's largest supplier of gas (Eurostat, 2022a; McWilliams et al., 2021). 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 fuel, stabilise the European energy system, and accelerate the green transition. In order to achieve that, Russian gas imports were to be reduced by two-thirds until the end of 2022 and even further until 2027 (European Commission, 2022e; Pedersen et al., 2022). In total, up to 300 billion € are mobilized to support investments and reforms. As such, the European renewables target for 2030 was increased from 40% 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 electrolyser capacities is planned (European Commission, 2022e).

However, most of these measures will only take effect in the long-term, leaving the question of how to react to the gas shortage in the short to mid-term. Especially countries in central and eastern Europe with direct pipeline connections are strongly dependent on natural gas imports from Russia and have to find solutions to the decrease in gas availability (Bella et al., 2022; Holz et al., 2022).

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 towards a decarbonized energy system, various studies have analyzed the subject. The majority of studies categorize the effects of a disruption of Russian gas in 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 actual 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 LNG is the most promising 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 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. Besides 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 mid-October the storage was filled over 91% with several member states exceeding the target of at least 80% by November (European Commission, 2022f).

Another measure that a lot of studies propose is to substitute natural gas used in power generation. In the electricity sector in particular, natural gas can be substituted quite well. 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 in the first half of 2022 increased by around 17% compared to the first half of 2021 according to Destatis (2022). Although this might increase Europe's carbon emissions for 2022, it is believed that the imposed emission cap by the EU Emissions Trading System (EU ETS) and the planned build-up of RES will accelerate the phase-out of coal power in the mid to long-term (Hauenstein et al., 2022; IEA, 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).

The increase of 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. Moreover, Ari et al. (2022) find that these increases have a significant permanent component, possibly lasting through 2026. With higher shares of coal and oil in electricity generation, that 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 a Russian gas disruption. However, this is not surprising. In order to be congruent with at least a 2°C pathway, an accelerated decarbonization of the energy system is crucial. Auer et al. (2020a) 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 to 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. Hence, the reduction of Russian gas supply is lower than the decrease in demand. The same effect is shown by Pedersen et al. (2022), who analyzes 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.

3. Methodology

To analyze the effects of a loss of Russian gas imports, the 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, building, industry, and transportation. Fully implemented into the general algebraic modeling system (GAMS), it is under constant development, extending its functions and improving performance. Given an exogenous demand, the model invests into generation capacities to satisfy the demand in each timestep. With consideration to the 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 figure 1, while a more detailed description can be found in Appendix A.

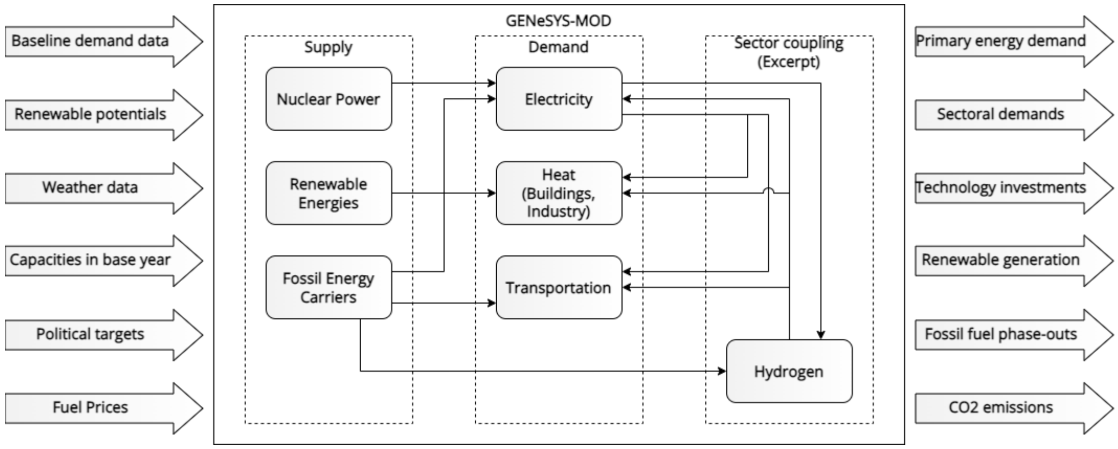

Figure 1: Stylized representation of GENeSYS-MOD's inputs and outputs

Source: Own illustration.

GENeSYS-MOD is quite 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 openENTRANCE (Auer et al., 2020b; 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, UK and an aggregated non-EU Balkan Region (see Figure 2). Of the four pathways created in the openENTRANCE 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 a 2°C climate target and reaching the EU's target of reaching 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 4.

[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 modelled 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 afterwards.

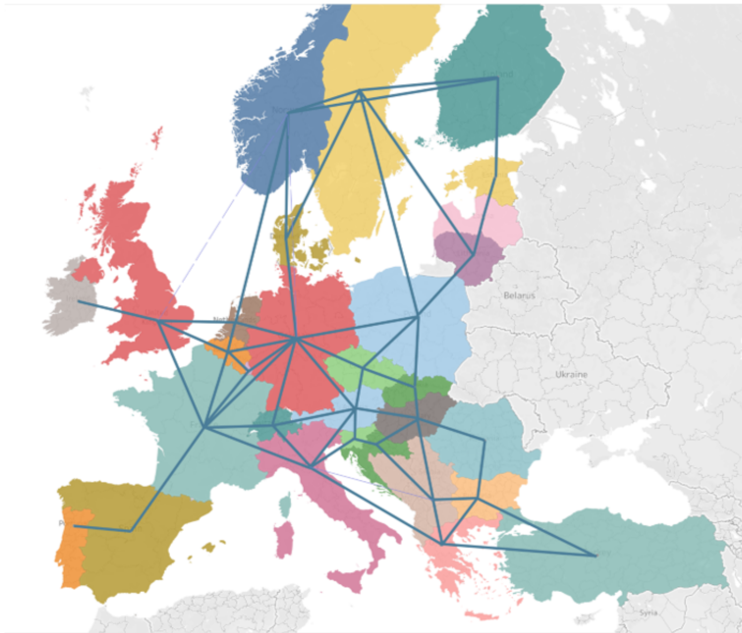

Figure 2: Regional model set-up used within this paper.

Source: Own illustration.

3.2. Changes in model functionality regarding gas imports

In the European model version 3.1, Russia as well as other non-EU countries are not depicted as individual regions. Imports from outside of the regions mentioned in the above paragraph are aggregated and considered as import 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.

	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

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)

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

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

will have no effect on these countries. Turkey is a special case, because it has external connections to both Russia and Azerbaijan as possible import sources (ENTSO-G, 2019). Equation 1 shows the constraint regarding Russian gas limitation that was implemented in the model.

$$
\begin{aligned}
&ProductionByTechnologyAnnual_{(y,Z\_Import\_Gas,Gas\_Natural,r)} \\
&\qquad \leq TotalTechnologyAnnualActivityUpperLimit_{(r,Z\_Import\_Gas,y)} \\
&\qquad * (1 - TagRussianGasSupply_r * (1 - \%set\_limit\_russian\_gas\_supply\%))
\end{aligned} \tag{1}
$$

The variable *ProductionByTechnologyAnnual* describes in this case 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.

By limiting the natural gas imports from Russia so suddenly in 2022, the model tries to switch to LNG imports immediately, resulting in an unrealistic jump in 2022. To avoid that, an upper and lower limit of 0.75 and 1.25 respectively compared to the prior model period was set for the LNG imports. Furthermore, a second constraint on LNG imports was added to describe the maximum available share of total LNG terminal capacity 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 behaviour in the energy sector.

4. Scenario assumptions and data

To better understand the scenario definition for this thesis, it is necessary to explain the origin of the used scenarios. Since the basis of this work's computation lies in the Horizon 2020 project openENTRANCE, the scenario assumptions were also taken from the project (Auer et al., 2020b; Hainsch et al., 2022). The openENTRANCE project consists of four quantitative scenarios, namely: Directed Transition, Societal Commitment, Techno-Friendly, and Gradual Development. In the following, each of the scenarios are shortly summarised, in order to describe the assumptions made for this analysis[4].

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

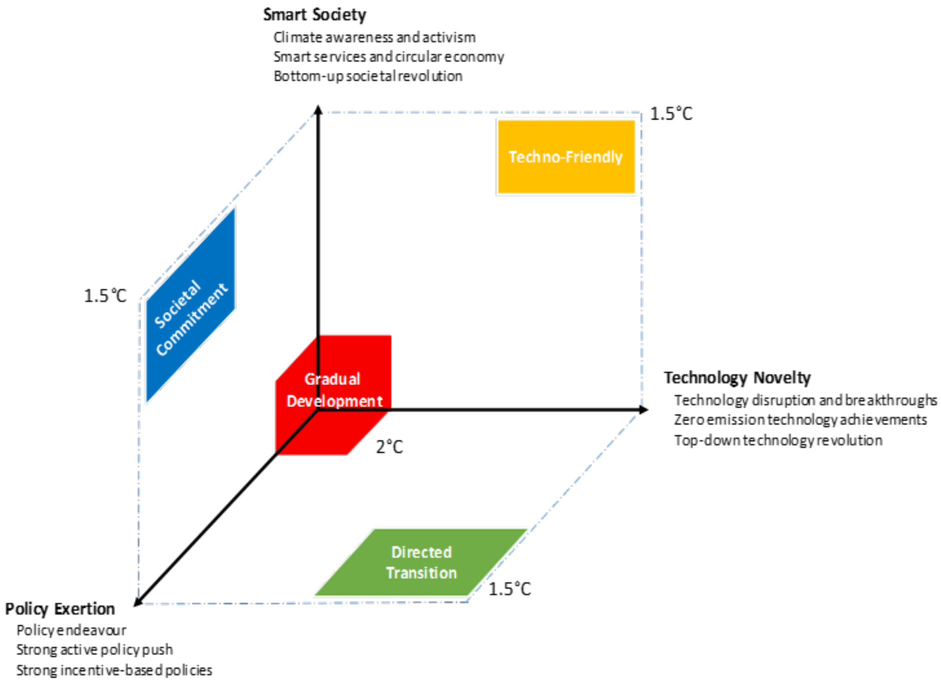

Figure 3: Scenarios of the H2020 EU project openENTRANCE

Source: Auer et al. (2020a)

The Directed Transition scenario describes the efforts to decarbonize the energy system in Europe by 2040. The lack of public participation and technological breakthrough has led to the need for a strong, continuous incentive-based policy push, with support from both European and national levels. The demand for all sectors is slightly lowered due to policy incentives. Currently not available technologies, except for CCS, are not being considered in the model. Net imports of hydrogen are not being considered due to global market factors and energy security. CCS is an option after the initial model periods due to political incentives to reduce emissions, especially in the industrial sector (Auer et al., 2020b).

Following a scenario with a more sustainable society, the Societal Commitment scenario describes reduced energy consumption and a focus on renewable energy sources. There is a shift towards local self-consumption of renewable energy and supportive policymaking, leading to higher market penetration of renewable technologies and investment in the sustainable transformation of the energy system. No negative emission technologies or new nuclear power plants are considered, while fossil fuel prices drop but with a high carbon price leading to an almost decarbonized energy system by 2040 (Auer et al., 2020b).

The Techno-Friendly scenario describes a scenario where novel technologies like floating offshore wind, hydrogen, and carbon capture and storage are being implemented on a large scale to meet energy and transport needs. Energy demand reduction and consumer participation are still needed but are less important. The model incorporates new technologies and improved existing ones, with optimistic values for cost and efficiency development. There is a higher rate of technological learning and infrastructure investment, a medium to high carbon price, and a cross-sectoral and cross-regional emission trading system. Fossil fuel prices drop but the reduction is offset by the combination of the carbon price and improvements in carbon-free technologies (Auer et al., 2020b).

The Gradual Development 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 (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. 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., 2020b).

For this study the Gradual Development scenario was chosen, since it combines parts of each of the other scenarios, while still aiming for an ambitious 2°C goal. Choosing a scenario with a pathway that is too ambitious would limit the model in its ability to find an optimal solution. By choosing the Gradual Development scenario, the model is given enough room to compute not only the newly implemented functions, but also to analyze sensitivities. Furthermore, the scenario shows the highest amount of natural gas. Thus, effects of the limitations to the Russian gas supply can be analyzed better.

4.1. Sensitivities regarding Russian gas imports

In order to accurately investigate the effects of Russian gas disruptions, different levels of gas limitations were computed. To achieve that, the newly implemented parameter *limit_russian_gas_supply* was varied. Three variations were chosen for the analysis in this paper. The first case where the limitation parameter is set to 1 describes the situation before the Russian aggression. Natural gas imports from Russia are fully allowed. Going further, this scenario will be called "With Russian Gas". The "Limited Russian Gas" scenario was chosen as a more currently accurate scenario. With natural gas imports from Russia being down around 75-80% compared to last year, the limit set for this scenario is 25% (McWilliams et al., 2021). As a more extreme scenario and to analyze the effects of a full import stop of Russian natural gas, the "Zero Russian Gas" scenario limits the imports to 0%. For all three scenarios, the international fuel prices are assumed to be on the level of fuel price projections after the Russian aggression.

	(Pre War)	With Russian Gas	Limited Russian Gas	Zero Russian Gas
Limitation parameter	(1)	1	0.25	0
Fuel price assumption	(Pre war)	Post war	Post war	Post war

Table 2: Overview of scenario assumptions

Source: Own assumptions.

4.2. 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 (2022). 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 3 and 4.

Fuel	2018	2019	2021	2022	2023	2024	2025	2030	2035	2040	2045	2050
Oil	9.07	9.07	10.35	14.71	13.53	11.76	17.17	16.10	16.61	14.95	12.70	10.80
Hardcoal	2.40	2.40	4.24	9.83	7.37	6.52	6.14	4.55	3.68	2.97	2.39	1.93
Natural gas	4.67	4.09	13.73	34.12	27.30	23.88	23.03	17.91	15.64	13.61	11.84	10.30
LNG	9.04	9.04	9.21	15.70	14.50	13.56	12.97	10.47	9.29	8.08	7.03	6.12

Table 3: Current fuel price projections in M€/PJ after the Russian aggression

Source: World Bank Group (2022)

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 4: Fuel price projections in M€/PJ dated October 2021, before the Russian aggression

Source: World Bank Group (2021)

5. Results

Our model results show two major impacts of a limited Russian gas supply on total natural gas use and production across Europe. First, an increase of the use of LNG, imported from abroad (e.g. the United States or from the Middle East), accompanied with an increase in domestic gas extraction within Europe, mostly from the Netherlands and Norway. However, as can be seen in Figure 4, total gas use also experiences a dip in the years between 2022 - 2025, as well as after 2035, due to the increase in natural gas prices, which drive a faster reduction in natural gas consumption across Europe.

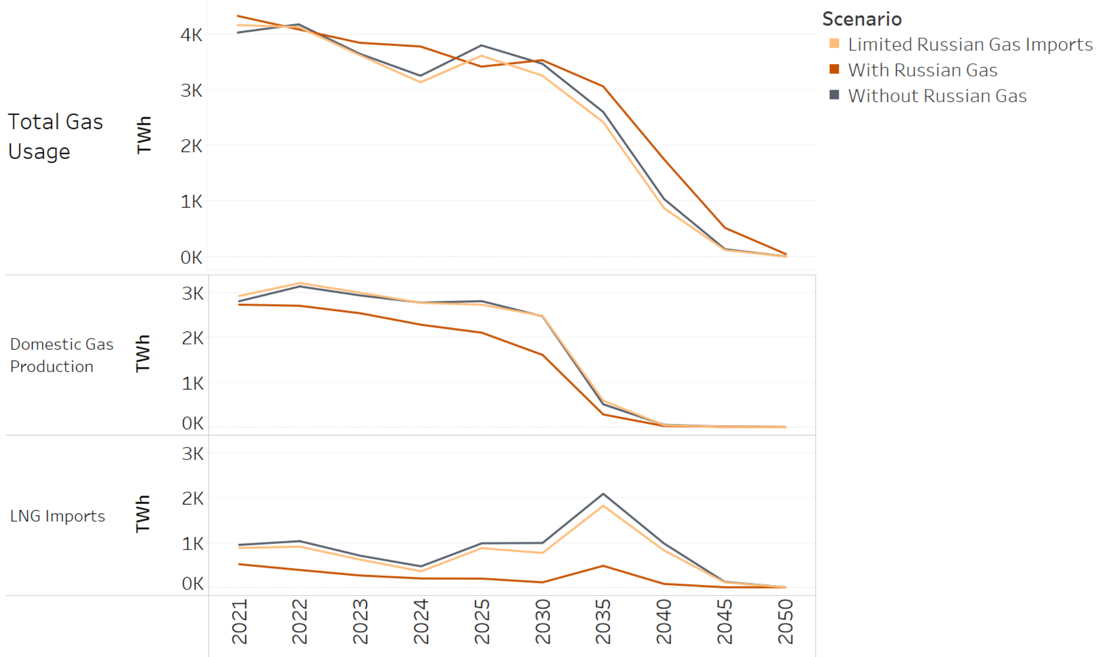

Figure 4: Results for total European gas use (top), domestic (European) gas production (middle), and LNG imports (bottom) until 2050, considering a 2°C target.

Source: Own illustration.

LNG sees a spike around 2035, when natural gas extraction in the Netherlands stops due to their politically determined end, but then quickly declines afterwards, as the energy system becomes more and more decarbonized towards 2050. Despite the spike in LNG imports in 2035, total natural gas consumption is steadily falling after 2030, and no additional LNG import capacities are required. Looking at the levelized costs of electricity generation (see Figure 5), a strong reaction in the intermediate years between 2022 and 2025 can be observed, especially when compared to the pre-war situation. With the increase of fossil fuel costs (compare Tables 4 and 3) due to the war in Ukraine and sanctions on Russian fossil imports, the costs of electricity rise sharply, with an improvement of the situation not in sight until 2025. Another noteworthy finding, however, is the limited effect on later periods, where after 2030, only a negligible difference in generation costs can be observed. This is due to the overall reduction of natural gas, especially in the electricity sector.

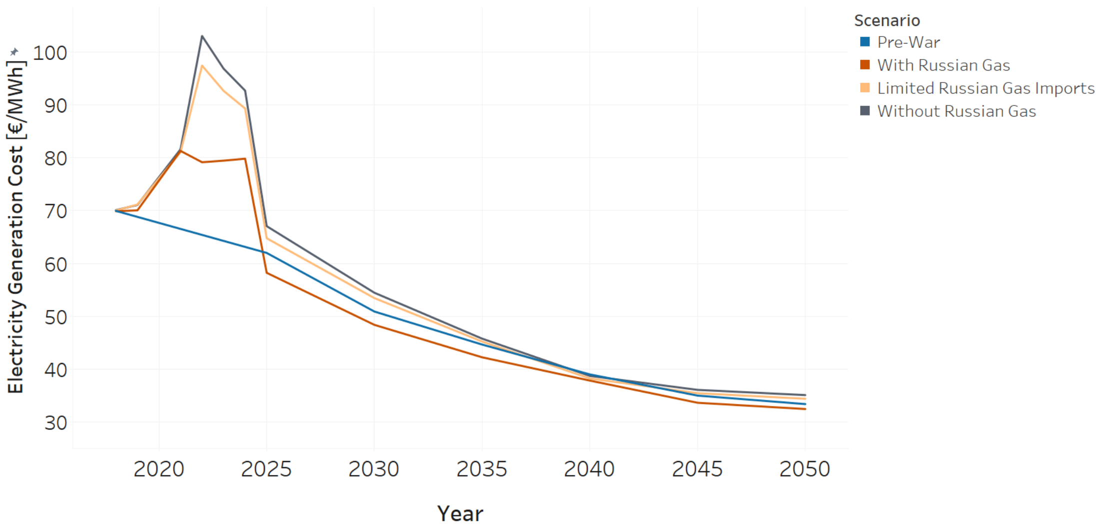

Figure 5: Results for electricity generation generation costs in € per MWh until 2050 for the different gas supply scenarios.

Source: Own illustration.

This change in electricity generation is highlighted in Figure 6, showing that the amount of fossil gas that is being used for electricity production is steadily decreasing, with a 100% emission free electricity sector being achieved around the year 2040. This is due to the ambitious climate target of 2°C that has been set for this study, which required 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 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. This, combined with the low-emission technologies being already available, leads to the electricity sector spearheading the decarbonization efforts. The major share of renewable generation comes from photovoltaics and onshore wind installations, with additional electricity supply coming from offshore wind, hydropower, and nuclear.

On the consumption side, especially industry and transport significantly increase their use of electricity towards 2050. Starting in 2030, electrolysis starts to become another main driver of electricity demand, steadily increasing towards the end of the modeled time period. Hydrogen then serves as a flexibility and decarbonization option for other sectors of the energy system.

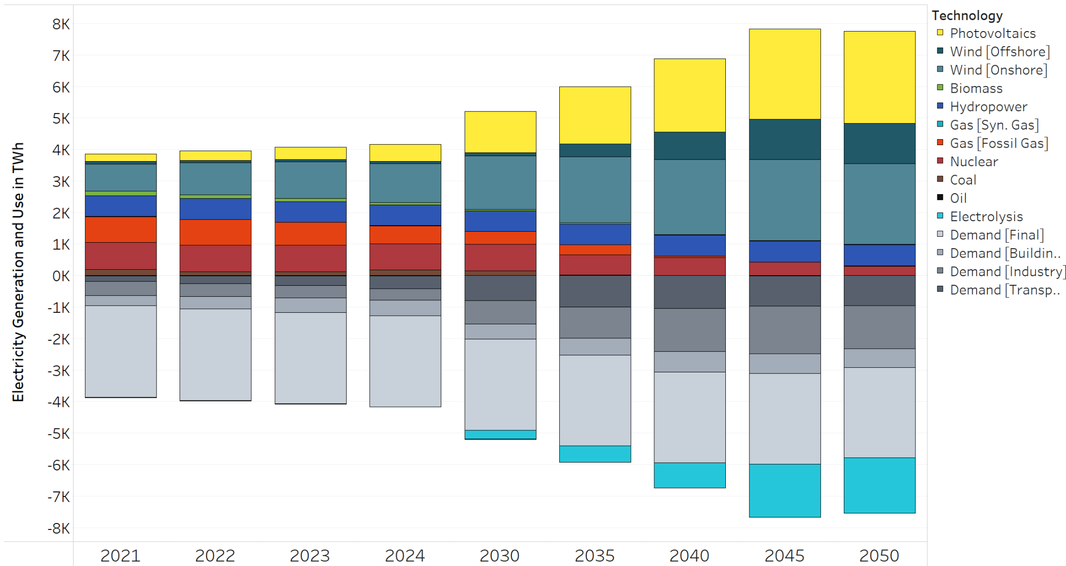

Figure 6: Development of electricity generation (positive values) and consumption (negative values) in the scenario without Russian gas imports after 2022.

Source: Own illustration.

Figure 7 shows the annual and cumulative emissions over the modeled time period. Overall, the sensitivities with either a limit on Russian gas imports, or even a full stop, have reduced emissions

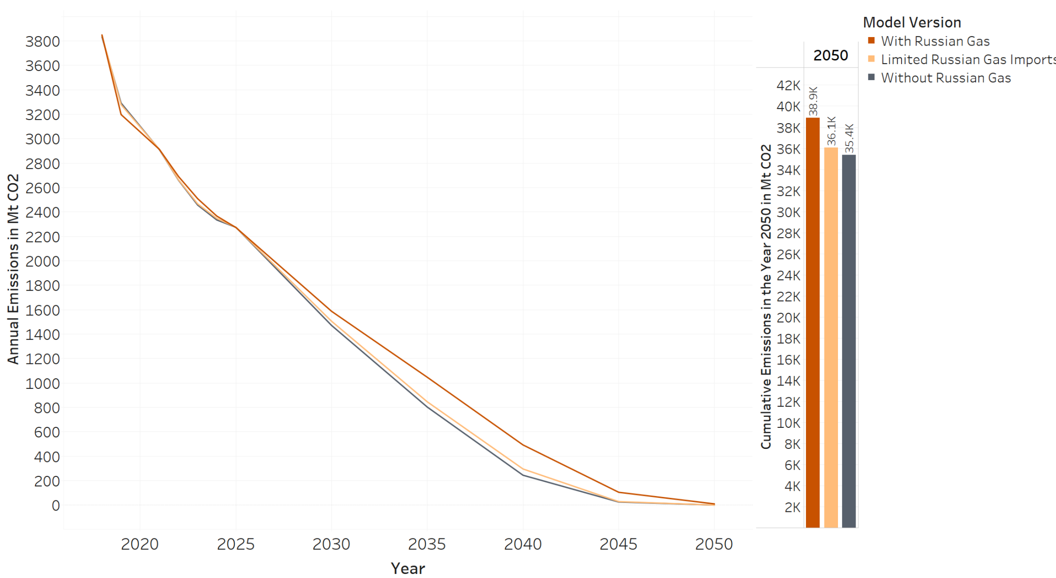

Figure 7: Results for annual (left) and cumulative emissions in 2050 (right) for the different gas supply scenarios.

Source: Own illustration.

compared to the case, where (rather cheap) Russian gas can still be imported and used. In total, a reduction of 7.2% to 9% of total emissions until 2050 can be observed in the case of limited or fully restricted Russian gas imports, respectively. This shows that a stop in Russian gas imports does not pose a threat to the low-carbon transition by increasing emissions elsewhere (or from other fuels) and instead, the increase in fossil fuel (and generally energy) prices observed can actually be a chance for a faster reduction in emissions.

6. Discussion

As shown in the results, a stop of Russian gas imports mostly has a strong effect in the near to medium future, where the electricity generation costs react quite heavily to the increased fuel costs, as not enough renewable generation is available yet to overcome the gaps in supply. However, this changes over time, as more renewable generation capacities are required for the fulfillment of Europe's ambitious climate targets. This decrease in dependency of the entire energy sector on fossil fuels means that in the long run, a supply ban of Russian fossil gas has less and less effect on the long-term development of the energy system. However, our 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.

An 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 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). With carbon neutrality being a set target for the year 2045, however, these terminals would have a short lifespan, which can also be clearly seen in our modeling results. 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 a 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 openENTRANCE 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 Table 3 are merely an openly available cost prediction, and should not be taken as given. 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.

7. Conclusion

The current crisis created by the Russian invasion on Ukraine poses many challenges for the European energy system, including security of supply issues and steep price hikes for energy costs, posing problems for both consumers and companies. With this current crisis, it is clearly highlighted that Europe established a substantial energy reliance on Russia in the past. 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 short and long-term impacts of reduced natural gas availability from Russia and find answers into possible solutions towards the future.

The Global Energy System Model (GENeSYS-MOD) was used for the quantitative analysis of this study. With improvements to the natural gas infrastructure, the European energy system including the sectors electricity, heat, and transport is depicted until 2050. On the basis of a 2°C compatible pathway, three gas supply scenarios are calculated, each varying the amount of available Russian natural gas 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, yieling both challenges for the next few years, but opportunities for the future.

A limitation or complete stop of natural gas imports from Russia results in an earlier and stronger decrease of gas consumption in Europe compared to the scenario with unlimited Russian gas imports. Overall, gas consumption is steadily falling after 2030 across all scenarios. As expected, an increase in LNG imports as well as an increase in domestic natural gas production is the response on the absence of Russian natural gas in scenarios where imports are limited or prohibited. The construction of new LNG terminals however is a double-edged sword, since it can cause negative path dependencies and stranded assets (Höhne et al., 2022; Wettengel, 2022). All scenarios show strong reactions on the levelized costs of electricity generation between 2022 and 2025. The stricter the reduction of Russian gas imports, the higher are the costs of electricity generation. This is due to RES capacities not being sufficient yet to fully replace gas-based electricity generation across the entire year, leading to extreme price peaks in hours where other generation is not able to meet the demands. In the long term, however, only a negligible difference between the scenarios can be observed.
Most importantly, reduced emissions in the sensitivities with limited or no Russian gas highlight that an early reduction in fossil fuels and investment in energy efficient alternatives has a positive effect on the energy system. Compared to the scenario with unlimited Russian gas imports, total cumulative emissions until 2050 are reduced by 7.2% and 9% in the scenario with limited Russian gas and zero Russian gas respectively. This results in an 100% emission free energy system by 2045 in both cases, 5 years earlier than in the case with Russian gas imports.

In conclusion, this studies analysis on the effects of a complete import stop of Russian gas shows that a limitation or full import stop does not pose a long-term threat to the European energy system, but rather helps 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 overcome the currently challenging situation.

Data availability. The model and data used in this research can be found at the public GitLab page of GENeSYS-MOD (https://git.tu-berlin.de/genesysmod/genesys-mod-public) and the open Zenodo repository for GENeSYS-MOD datasets (https://zenodo.org/communities/genesys-mod/). Also, the openENTRANCE 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.

CRediT author statement. Conceptualization: K.L., K.H., J.H., P.H., and N.M.; Data curation: N.M., K.L., and K.H.; Formal analysis: N.M., K.L., K.H., J.H., and P.H.; Funding acquisition: K.L. and K.H.; Investigation: K.L., K.H., J.H., P.H., and N.M.; Methodology: N.M., K.L., and K.H.; Project administration: K.L. and K.H.; Software: N.M., K.L., and K.H.; Supervision: K.L. and K.H.; Validation: K.L., K.H., J.H., P.H., and N.M.; Visualization: N.M. and K.L.; Writing – original draft: K.L., K.H., J.H., P.H., and N.M.

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Appendices

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. Figure A.1 shows the underlying block structure of GENeSYS-MOD v2.9, with the additions made in the current 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).

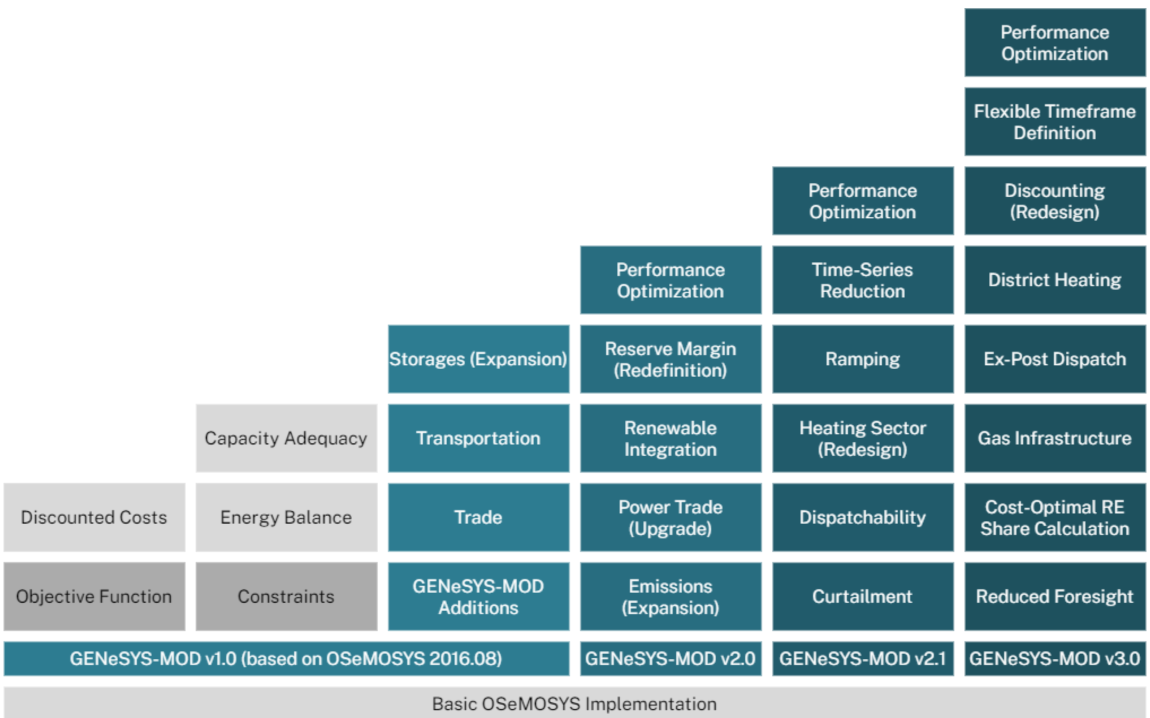

Figure A.1: Model structure of the GENeSYS-MOD implementation used in this study.

(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 v2.9 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 2017-2050 are modeled in the following sequence: 2017, 2022, 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. In this paper, an add-on allowing for myopic foresight using multiple computational stages, is introduced. All fiscal units are handled in 2015 terms (with amounts in other years being discounted towards the base year).

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).

[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.