



Operation of Conventional Power Plants During the German Energy Transition: A Mini Review

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Several unforeseen events have affected the energy market in recent years, both on the consumer side and on the primary energy supply side. Once again, the question is being asked, which impact conventional power plants can have on Germany's energy transition. In this work various energy system studies from the last 4 years are evaluated, covering a time span of 30 years. Summarized, most studies expect an increasing use of natural gas, peaking in the years between 2030 and 2035. While the overall gross electricity generation from conventional power plants decreases, the share of synthetic energy carriers will increase from around zero until 2040 to 100% in 2050. Hereby the technological openness of the used energy system model strongly influences the final installed capacities. While more open simulations lead to a median of about 50 GW in 2050, more restrictive ones expect roughly 30 GW. However, the full load hours will decrease significantly in both cases. Since the synthesis of synthetic energy carriers requires large amounts of renewable electricity, this development is linked to a national electricity demand of over 200 TWh for power-to-x applications and an additional import of 350 TWh of power-to-x products.

Keywords: energy system studies, meta analysis, conventional power plants, energy transition (Energiewende), synthetic energy carriers

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1 INTRODUCTION

With the EU Taxonomy Complementary Climate Delegated Act, the European Commission approved the addition of certain nuclear and gas technologies in the coming years to be labeled as investments directing to climate neutral energy systems. This can ultimately lead to an increased investment in natural gas-based technologies, including pure power generation, co-generation of heat and power as well as district heating/cooling (European Commission, 2022; Meager, 2022). In short term, a higher share of gas-powered plants can push coal-based plants from the energy market and hereby decrease the overall greenhouse gas emissions, as the act proposes an appropriate emission limit for fossil gas utilization. In the long term, however, this could make it more difficult to achieve a complete defossilization of the energy supply that is purely market-driven. Even before the discussion of EU taxonomy, energy system studies from the last years already considered natural gas as one of the most important transition technologies (Buttler and Spliethoff, 2016), neglecting influences such as pandemic situations and political crises. Using natural gas to start sustainability developments of energy systems in the ASEAN region has already been evaluated (Mohammad et al., 2021). Regarding the German energy system, current meta studies only focus on other aspects of the energy transition. Research exists on the use of biomass for decarbonization (Hahn et al., 2020), sector coupling (AEE e.V., 2017),

(de-)centrality (acatech et al., 2020) or hydrogen usage (Wietschel et al., 2021), while literature lacks an evaluation of the use of conventional power plants as key technology of the energy system. In this work the impact of conventional power plants on the German energy transition, fueled by natural gas or a sustainable alternative, is analyzed by comparing recent system studies in a meta analysis.

2 METHODS

Energy system studies are normally based on energy system optimization, as they are used for scientific or economic debates. Compared to energy system simulations, optimization models are best suited for forecasting possible future energy system portfolios under specific boundary conditions and assumptions (Lund et al., 2017). However, as stated by Grunwald, the use of just one study or even only one scenario can be misleading and the “meta-knowledge” of various studies should be used for decision making (Grunwald, 2011). Moreover, he states, the results are always influenced by the actual author and/or client sponsoring the study. Therefore, this work uses various studies to balance the impact of uncertainties or the client’s and author’s bias. In order to limit the selection of studies that can be used for the targeted evaluations, the following selection criteria are defined:

- **Timeline:** The considered horizon should extend at least to the year 2030, in the best case to 2050.
- **Relevance:** The publication date should be at least 2017.
- **Reference area:** Only studies that look at the development of the German energy system are considered; studies that only depict a part of Germany are excluded.
- **Topic:** The studies should at least cover the electricity sector. General system parameters such as greenhouse gas emissions, energy demand and other sectors or sector coupling topics are desired.
- **Type of study:** Only studies with quantitative results will be considered for the analyses; purely qualitative descriptions of system developments will not be included in the comparison.
- **Client:** Clients from different fields of operation should be represented.

The majority of the studies found consists of between two and four scenarios, while the maximum is ten. The clients range from purely scientific (e.g., Fraunhofer) or political (e.g., BMWi) institutions to interest groups (e.g., WWF) and large companies (e.g., Shell, RWE). The list of authors, on the other hand, consists mainly of scientific institutions or consulting firms. Methodologically, with more than 75%, most of the studies use optimization of the overall system costs to calculate the scenarios, which is equivalent to the most reasonable solution from an economic point of view. At the same time this also means that social and corporate interests can only be considered to a limited extent. Since these limitations are based on the boundary conditions and assumptions used, the evaluation of a large number of scenarios allows the identification of overall trends without neglecting upper and lower extremes. Nevertheless, the

basis of the scenario definitions must be considered. Using the above list of criteria, the following set of 38 energy system studies with over 100 scenarios in total is found:

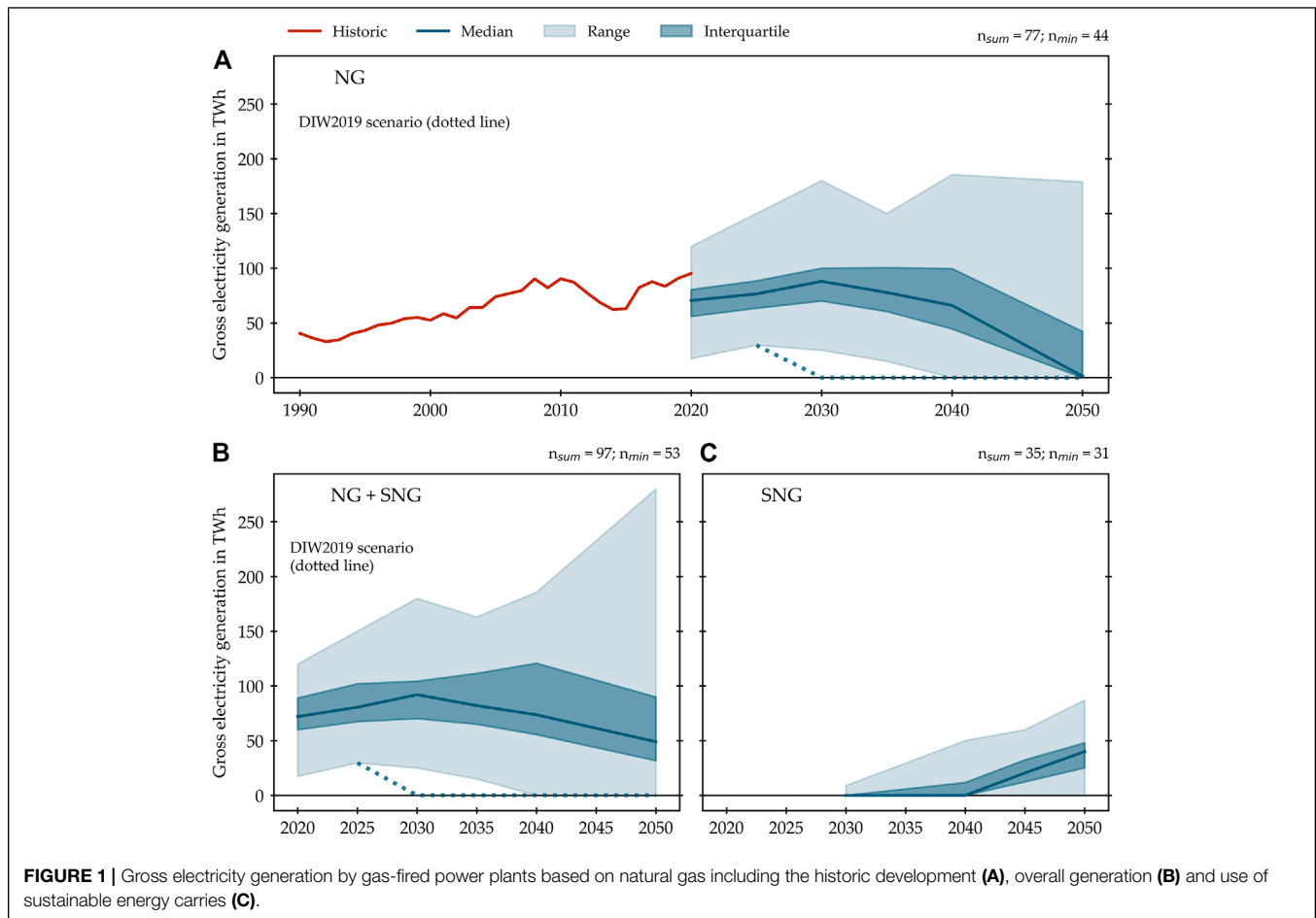
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|---|--|
| • Enervis Energy advisors GmbH (2021) | • BEE e.V. (2019) |
| • Prognos et al. (2021a) | • Nitsch (2019) |
| • Burstedde and Nicolosi (2021) | • Cao et al. (2019) |
| • Prognos et al. (2021b) | • Bartholdsen et al. (2019) |
| • Übertragungsnetzbetreiber (2021) | • Günther et al. (2019) |
| • BEE e.V. (2021) | • Übertragungsnetzbetreiber (2019) |
| • Deutsche Energie-Agentur GmbH (2021) | • Oei et al. (2019) |
| • Prognos et al. (2020) | • Fraunhofer ISI et al. (2017) |
| • Enervis Energy advisors GmbH (2020) | • Deutsche Energie-Agentur GmbH (2018) |
| • Sterchele et al. (2020) | • Gerbert et al. (2018) |
| • Öko-Institut e.V. and Fraunhofer ISI (2020) | • Brandstätt et al. (2018) |
| • KIT et al. (2020) | • Repenning et al. (2018) |
| • Robinius et al. (2020) | • Bareiß et al. (2018) |
| • Schimek et al. (2020) | • Hecking et al. (2017) |
| • Max et al. (2019) | • acatech et al. (2017) |
| • BMU, (2019) | • Hermann et al. (2017) |
| • Matthes et al. (2019) | • Matthes et al. (2017) |
| • Öko-Institut e.V. et al. (2019) | • Klein et al. (2017) |

In general, the scenarios can be divided into clusters such as trend or reference scenarios, as well as ambitious and less ambitious scenarios. Here, the first ones form the basis on which changing boundary conditions can be discussed, also referred to as “business as usual” in case of trend scenarios. Therefore, studies usually consist of one trend/reference scenario and at least one or more ambitious or less ambitious scenarios. While the classification is single-choice, typical characteristics such as the technology openness of a system can be used to analyze explicit boundary conditions independent of scenarios. In this study, however, no differentiation between scenario types is used. Instead, a high number of scenarios including all kinds, trend, reference, ambitious and low ambitious environments are combined, to be able to discuss a broad variety of assumptions.

To evaluate the collected data, a graphical representation over the entire range of data points, the interquartile range (inner 50%) and the median are used. Most of the studies use the years 2020, 2030, 2040 and 2050 as support year, some have additional data points for the intermediate years of 2025, 2035 or 2045. As the graphical presentation equals a linear interpolation, in all cases of one missing data point (e.g., 2030 and 2040 is given, but not 2035) these interpolated values are used to improve the presentation. Nevertheless, there are various missing values, as they are not calculated or not explicitly given in the publications. Therefore, the number of scenarios for the support year with the fewest data points is given (n_{min}), as well as the total number of scenarios used (n_{sum}). Additionally, the historic development from 1990 until 2020, based on the Eurostat energy database, is shown.

3 CURRENT SITUATION

Conventional power plants can be divided into coal, natural gas (NG) and nuclear power plants, which all can be used both as



power plants or as combined heat and power plants. Regarding the German energy system, coal based and nuclear power plants are planned to be shut down latest by 2038¹ or end of 2022², respectively. While the atomic energy act is based on safety concerns, the coal-phase out is purely motivated by greenhouse gas emissions. However, in 2021 the net power generation was covered by more than 40% by fossil and more than 10% by nuclear fired power stations Fraunhofer ISE (2022). Neglecting current discussions regarding a longer utilization of coal and nuclear power stations to reduce the high NG dependence of the German energy system, this study focuses more detailed on the use of gas-fired power plants in current energy system studies.

As main indicator, the gross electricity generation is used, to describe the trends in use of gas-fired conventional power plants, combining power and co-generation plants. The illustration in **Figure 1** hereby is separated into:

- (A) **NG**: Historic NG-based electricity generation and their corresponding future development, based on the energy system studies
- (B) **NG + SNG**: Assumed electricity generation, based on all (conventional and sustainable) gas-fired power plants
- (C) **SNG**: Electricity generation based on sustainable gaseous fuels

First of all, the historic line in **Figure 1A** shows the growth in use of gas turbines in the early 2000s. The strong increase of renewable power generation, high NG prices and low CO₂ emission allowance costs led to a decrease in the mid-2010s. Rising CO₂ certificate prices, phase-out of nuclear power stations in Germany and an overall reduction of the hard coal utilization increased the demand on NG for power generation in Germany. Comparing the actual gross electricity generation of around 95 TWh in 2020 with the shown Median of 70 TWh, most of the studies underestimated the gas-based share. This higher share of NG in the German energy mix reflects the missed match with the targeted climate goals prior to 2020. The ultimate achievement of the emission targets in 2020 cannot be attributed to energy policy decisions, but rather to the combination of a mild winter and the subsequent pandemic situation. This is also confirmed

¹Law on the Reduction and End Coal-Fired Power Generation and further Amendments (Coal Phase-Out Act).

²Law on the Peaceful Use of Nuclear Energy and Protection against its Dangers (Atomic Energy Act).

TABLE 1 | Installed capacities and respective full load hours of gas fired power plants in future energy systems, depending of the restrictiveness of the energy system model.

		2020	2030	2040	2050
Installed capacities	Technologically open	29GW	41GW	53GW	52GW
	Technologically restricted	26GW	31GW	39GW	33GW
Full load hours	-	2,770 h a ⁻¹	3,030 h a ⁻¹	2,180 h a ⁻¹	1,230 h a ⁻¹

by AGORA's calculations, which show a significant increase and thus exceeding of the targets in 2021 and assume no relaxation for 2022 (Agora Energiewende, 2022).

4 COMPARISON OF SYSTEM STUDIES

Focusing on the system studies, a peak of NG usage between 2030 and 2040 can be identified (**Figure 1A**). At least 75% of the considered scenarios assume a maximum of 100 TWh of electricity generation via NG fired power plants. In contrast, in (Oei et al., 2019) one scenario already operates without NG in 2030, while all other scenarios require NG at least until 2040. However, most of the scenarios hold the zero-emission targets of Germany in 2050. At this point, it again must be referred to the widespread scenario structure. Looking at a reduced dataset by neglecting trend and “business as usual” scenarios, even the updated net-zero emissions target under the German climate protection act³ is largely achieved by 2045. In contrary, when using only trend and “business as usual” scenarios, the use of NG until beyond 2050 is not uncommon.

As in NG usage, the overall usage of NG and SNG peaks between 2030 and 2040 with a light shift towards 2040 (**Figure 1B**), what matches the expected global peak of NG demand (McKinsey and Company, 2021). More or less all studies consider gas-fired power plants to be necessary until at least 2050. While the overall NG utilization is assumed to end in 2050 (or 2045, respectively)⁴, an increase in the SNG demand can be observed (**Figure 1C**). As more gas power plants are installed in the mid-2020s, their availability until or beyond 2050 gives the energy system a flexibility option by simply synthesizing synthetic energy carriers as SNG to further use the power plants. As SNG production can be assumed as climate neutral by neglecting process-based emissions, this enables both achieving climate neutrality and security of supply.

The demand for synthetic energy carriers will increase not only due to the demand in power plants, but also due to other applications such as mobility and industry. As future energy systems will most likely be fully based on renewable power generation via photovoltaics and wind turbines, power-to-x technologies are assumed to cover a large share of this demand. If the median of the studies is used, an increase in the power-to-gas demand in Germany from 2.5 GW in 2030 to over 40 GW in 2050 is assumed. The corresponding electricity demand for all

power-to-x applications adds up to over 200 TWh in 2050. This, however, is also expected to not cover the overall demand on power-to-x products, which will lead to an additional net import of synthetic energy carriers of roughly 20 TWh in 2030 and more than 350 TWh in 2050. Nevertheless, most studies in principle would allow the import or use of natural gas. Therefore, more than 50% of the studies assume a natural gas price of between 25 and 35 €/MWh by 2050. Since the studies consider different approaches ranging from SNG synthesis, pure hydrogen-based gas turbines to blending hydrogen into the existing natural gas grid, it is not possible to analyze the respective production and import costs.

Looking deeper into the actual utilization of the installed capacities, key-performance-indicators like full load hours can be used to determine the mode of gas-fired power plant operation. Based on the actual 2020 data (Fraunhofer ISE, 2022), an average of 3,000 h a⁻¹ can be calculated. Based on the medians of the installed capacities of the developments from the studies, as well as the respective energy quantities provided, average full-load hours of 3,030 h a⁻¹, 2,180 h a⁻¹ and 1,230 h a⁻¹ emerge for the years 2030, 2040 and 2050 (**Table 1**). As the operating hours are distributed over several power plants, some of the units will be operated as base or mid-load power plants with up to 4,500 h a⁻¹. The majority, however, will have fewer operating hours, covering only peak load or even being used only as back up, e.g., for black start events.

Using a differentiation by the actual scenario definitions, two clusters can be identified. First scenarios with a more technologically open environment, and second, scenarios with more restrictive boundary conditions regarding the final technology portfolio. While both groups follow the mentioned trend during the energy transition peaking in 2030/2040, the actual medians of the installed capacities differ. In technologically open scenarios the median's peak is at 53 GW, while the restrictive one is 39 GW. In summary, this implies that under the respective selected boundary conditions, cost-optimal energy systems would tend to use larger gas-fired power plant capacities, while at the same time meeting the emission targets. One reason is the possibility to reduce the required installed renewable energy technology and battery capacities by using SNG or equivalent energy carriers as a long-term storage.

Regarding the use of coal-fired power plants, almost all studies include the phase-out by 2038. Only individual studies still use coal-fired power plants to compare more ambitious and trend scenarios with strictly conservative ones. Nuclear power stations, on the other hand, basically are no longer a component of German energy system studies.

³German climate protection act: Section 3 I KSG.

5 CONCLUSION

The evaluation of several current energy system studies on the subject of the energy transition in Germany and the associated need for conventional power plant capacities shows that gas-fired power plants in particular will play an important role. The demand will peak between 2030 and 2040, with natural gas still being used initially. In order to achieve the climate targets, however, most studies assume that power plants will continue to be operated, but using synthetic natural gas. Especially in view of the current discussions about designating investments in natural gas and nuclear power plants as green, these changing boundary conditions must be considered in future studies.

Since current system studies, respectively, the underlying model, partly still have limited possibilities of flexibility, new developments and technologies must always be implemented and added to the benchmark. For example, enabling bi-directional charging of electric cars could already lead to a reduction in the average flexibility requirement by conventional power plants. Alternative technologies such as reversible fuel cells, for example in direct coupling with wind farms, can also cover the flexibility requirement to a certain extent. Finally, a differentiated analysis of the synthetic energy carriers as well as the hydrogen integration into today's natural gas system is necessary.

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AUTHOR CONTRIBUTIONS

AH: Writing original draft, data analysis and concept development, SF: Concept development and supervision, HS: Concept development and supervision. All authors reviewed the manuscript.

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