TEK5410

Geopolitical Threats: Impact on the German Energy Transition

Energy System Modelling in GAMS

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Abstract

In response to the shifting geopolitical landscape, energy systems worldwide are navigating complexities, balancing regional conflicts, resource dependencies, and evolving policies, intertwined with efforts to combat the climate crisis. This is stimulating a substantial transition to renewable energy sources. Germany has been a front-runner in this transition with the "Energiewende" transition plan. This study investigates how geopolitical instability and conflict might shape this transition through a scenario-based modeling approach. Three scenarios are implemented, reflecting varying degrees of international cooperation, climate targets, and geopolitical tensions. The findings strongly advocate for a substantial boost in wind and PV capacities, potentially up to six times the current levels in Germany, to meet forthcoming energy needs effectively. Critical parameter estimates significantly influenced the optimal solution, reinforced through a sensitivity analysis. Despite being subject to several simplifications, this study offers valuable insights into potential impacts of uncertain trends and geopolitical disorder.

1 Introduction

The past decade has witnessed a surge in geopolitical instability, marked by the emergence of larger regional conflicts that have disrupted the geopolitical landscape. A consequence of this is uncertainty regarding future energy system configurations. While research into renewable energy deployment has extensively explored economic, institutional, technological, and socioeconomic challenges, one aspect remains unexplored: the influence of regional conflicts and geopolitical uncertainty.

The literature presents divergent perspectives on the effect of geopolitical instability. Some argue that conflicts and instability discourage the deployment of renewables, while others call it encouraging for their adoption (Itay Fischhendler and David, 2022). A 2023 study underscored economic development as a key-factor in a country's vulnerability to larger geopolitical conflicts (Cheikh and Zaied, 2023). According to the study, high-income countries might be incentivized to shift away from fossil fuels in times of geopolitical uncertainty. Several studies have indicated a threshold value for the income-to-renewables ratio (Bellakhal et al., 2019; Cadoret and Padovano, 2016; Caetano et al., 2022). Beyond this threshold, the share of renewables appears to diminish due to their inability to meet escalating demand. This phenomenon is attributed to the proportionality between income and energy consumption within a country. The deployment of renewables in the realm of geopolitical turmoil often involves a trade-off between such discouraging and encouraging factors.

1.1 Research Question

In order to investigate how geopolitical instability affects the optimal configuration of an energy system, and the coherent investment costs, a case study is conducted on the German energy system. Germany is not only the largest primary energy consumer in Europe, but also a frontrunner when it comes to the implementation of renewable energy sources, through the national transition plan "Energiwende" (F.M.E.T, 2010). The feasibility of such ambitious transitions is dependent upon several factors like societal developments, cost of energy, resource availability, and cross-country collaborations (Hansen et al., 2019). To investigate some of these implications with an emphasis on the geopolitics, a scenario-based model is developed. In addition to a "business-as-usual" base scenario, reflecting the current trends in the German energy system, two other scenarios are introduced. Different constraints are implemented to account for the varying degree of geopolitical tensions and (in)stability. The research question can be explicitly formulated as:

How can Geopolitical Threats affect the German Energy Transition?

The paper is organized according to the IMRaD-model. Section (2) presents the theoretical foundation for the work conducted in the project, with an emphasis on modelling framework and mathematical formulations. Further, section (3) presents the results from the model, visualized with plots and figures. Section (4) presents a critical discussion of the results, and tries to identify how the different scenarios impacted the overall optimal solution to the problem. Finally, some concluding remarks are given in section (5).

2 Theory

This section presents a brief overview of the German energy transition (2.1), as well as an introduction to energy system modelling and mathematical optimization (2.2). Furthermore, section (2.3) discusses the key-points from literature on geopolitical instability, ultimately leading to the formulation of the scenarios in section (2.4), and the model(s) in section (2.5).

2.1 The German Energy Transition

The German "Energiewende," translated as "energy transition," embodies one of the most ambitious and influential energy policies globally. This comprehensive initiative involves phasing out nuclear power and reducing reliance on fossil fuels, striving for an energy mix dominated by renewables. Energy savings and increased energy efficiency are emphasized as vital to stay within a sustainable resource consumption level (Hansen et al., 2019). Despite challenges like intermittency in renewable sources, grid modernization, and energy supply disruptions (Eddy, 2022), the Energiewende remains a paradigm for global energy transitions (Hoffart et al., 2022).

2.2 Energy Models and Mathematical Optimization

Energy system modeling involves constructing mathematical or computational representations of energy systems to simulate, analyze, and optimize their behavior. It integrates various system components to understand their interactions, make predictions, and devise strategies for the future. Energy system models are used to provide critical insights and decision support to policy makers (Scheller, 2019). A common denominator for energy models is that they usually incorporate some form of mathematical optimization.

Mathematical optimization involves the formulation and solution of mathematical models to find the best possible solution among a set of feasible alternatives. Linear programming, which involves a linear relationship among variables and constraints, is the method implemented in this study. Equation. (1) shows an example of the objective function for a minimization problem. In this simplified example, an optimal value for the decision variable x has to be found. This variable is then subject to the constraint, where α can represent a minimum threshold for x. Several decision variables and constraints are usually implemented in optimization problems, but there is always a trade-off between model complexity and necessity (Kotzur et al., 2021). The optimization model in this study is written in the General Algebraic Modeling System (GAMS), and three scenarios are developed as input to the model.

Objective Function:

$$Z = \min f(x) \tag{1}$$

Decision Variable(s):

$$x : \text{Independent variable}$$

Constraint(s):

$$x \geq \alpha$$

2.3 The Implications of Geopolitical Instability on Energy Systems

This section summarizes key points from the literature on how regional conflicts and geopolitical risks (GPR) may impact the German energy system. An emphasis have been put on the SSP3 scenario from (O'Neill, 2017), which serves as an inspiration for the scenarios presented in section (2.4).

The Shared Socioeconomic Pathways (SSPs) were established in 2017 to explore how changes in several socioeconomic dimensions like demographics, technology, and environmental concern could impact the ability to meet/prevent the climate crisis (O'Neill, 2017). Regional Rivalry is the name and context of the third scenario (SSP3) in the Shared Socioeconomic Pathways, and have been used as an inspiration for the scenario development in this project. In SSP3, energy use is dominated by fossil fuels due to constrained technological advancements and limited efforts to curb greenhouse gas emissions, resulting in substantial environmental pressures and climate change impacts. The current geopolitical trends makes the SSP3 projections seem more plausible. Therefore, investigating how such negative trends may impact a country, and especially its energy dimension, becomes important.

The literature is not united on how a country will be affected by geopolitical uncertainty (Itay Fischhendler and David, 2022). Geopolitical conflicts often cause a rise in oil and gas prices, making alternative energy sources more attractive (Olanipekun et al., 2023). According to (Sweidan, 2021), higher geopolitical instability may therefore facilitate the deployment of renewables in some areas. A country's deployment rate is expected to drop after a certain income level, due to the fact that these alternative energy sources can prove unsatisfactory in meeting the increasing demand (Cheikh and Zaied, 2023). Technology and knowledge transfer are essential for a more renewable-based energy mix, which implies that countries with trade openness, more transparent policies (and less corruption) will more likely adopt renewable energy sources (Damania et al., 2003). In order to implement and investigate these factors even further, three scenarios are made.

2.4 Scenario Formulation

"Harmony Horizon" and "Turbulent Times" are the names of the two scenarios developed in this study, in addition to a base scenario, to reflect large future deviations from the current German energy trends. According to literature, internal consistency and plausibility are the most important aspects regarding scenario validation (Amer et al., 2013). Additionally, relevant and memorable names for the scenarios are proven crucial for the impact of the scenario planning problem (Amer et al., 2013).

2.4.1 "Harmony Horizon"

The first scenario, Harmony Horizon (HH), depicts a future sustainable energy system given global cooperation, and a continued rapid deployment of renewables. In this scenario, the government have put forward ambitious targets on emission reductions, and deployment of renewables. Cross-border trade and international cooperation is prosperous, so commodity-prices and technology-costs are lower than usual. To drive the transition further, tighter constraints are set on emissions. This scenario is supposed to reflect a future where geopolitical tensions are low.

2.4.2 "Turbulent Times"

The second scenario, Turbulent Times (TT), is supposed to reflect the challenges and limitations that comes with regional instability and lack of global cooperation. This scenario reflects a society where the energy consumption is on the rise, with a low effort on mitigating climate change. There is no reluctance to use fossil-fuels, and the policy-makers and institutions are not encouraging a rapid deployment of renewables. The international and cross-border cooperation is lacking, meaning that access to neighbouring technologies and power is limited. This scenario is supposed to reflect a future where geopolitical tensions are high.

2.4.3 Base Scenario

For comparison, a base scenario is created, depicting the current energy system in Germany. In this scenario, the current trends in the German energy system are extrapolated. The deployment of renewables is satisfactory, but the country is still reliant on some fossil-fuel based generation to meet peak demand. Furthermore, the improved energy savings- and efficiency measures are compensated by an increase in population. This leads to no significant changes in the demand for electricity. This scenario is supposed to reflect a future where geopolitical tensions are moderate.

For simplicity and to provide a better description of the possible futures, some key aspects for the three scenarios are given in Table (1). These descriptions also serves as a basis for the model parameter adjustments in section (2.5).

Table 1: Description of societal developments in the three scenarios based on the degree of geopolitical instability, as interpreted from literature. These descriptions serve as a theoretical basis for the model parameter adjustments in Tab. (3).

Scenario Element	**"Harmony Horizon"**	**"Turbulent Times"**	**Base Scenario**
Energy Consumption	Low	High	Unevenly distributed
Emission Intensity	Low	High in regions with fossil fuels	Medium
Fossil Constraints	Preferences shift away from fossil fuels	No limitations; utilization of unconventional resources for local use	No specific trend
International Trade and Cooperation	Strong	Weak	Moderate
Environmental Policy	Enhanced management of local and global affairs with stricter control of pollutants	Minimal emphasis on environmental concerns	Focus on local pollutants, effectiveness varies
Institutions	Effective at national and international levels	Weak global institutions; dominance of national governments in societal decisions	Uneven distribution
Alternative Energy Sources	Shift away from fossil fuels, focus on efficiency and renewables	Gradual technological change aimed at domestic energy sources	Partial investment in renewables, continued dependence on fossil fuels

2.5 Model Formulation

Based on the proposed scenarios, the actual model(s) are developed. The scenario formulation (2.4) elaborated on the consequences of geopolitical instability and how it affected some areas of society more than others. Based on these findings, specific model parameters are introduced and adjusted to account for this effect. In this model, the following parameters have been subject to adjustments: emission target, renewable target, discount rate, capacity factor for gas, maximum threshold for installed capacities, annuitised costs, and energy demand. Table (2) shows the variable cost, emission intensity, and lifetime for the respective technologies, and have been kept at a fixed value in the model.

Additionally, some assumptions on the German energy system have been made, in order to make the problem more feasible. First, the German energy system is looked upon as one large unit, rather than several divided zones. This simplification changes the resolution of the model, and the only requirement in this context is that the total demand is met at all times. Additionally, to account for necessary load shedding, additional imports, energy storage, or other technologies, a bin called "other" is included in the model. This bin is supposed to capture the excess/deficit of energy generation, when the other technologies are subject to limiting constraints. This bin is not subject to any limitations or constraints, but has a symbolic (very high) annutised and variable cost to serve as a "last resort" for the system solution. As this "other" bin may represent net-zero technologies such as hydro storage, it is included among the renewable sources. This may have implications on the system configuration when determining the renewable target for the total system, which should be kept in mind when interpreting the results.

Tech.	Variable Costs [EUR/MWh]	Emission Intensity [tCO2/MWh]	Lifetime [Years]
Wind	0.5	0.013	20
PV	0.035	0.035	30
Hydro	0.3	0.011	25
Gas	3.5	0.593	30
Coal	13	1.152	40
Biomass	5.0	0.230	30
Other	10000	0	-

Table 2: Variable Costs [EUR/MWh], Emission Intensity, and Lifetime of the technologies (Kost, 2021)

2.5.1 Model Parameters

The emission target γ is supposed to reflect the scenario-dependent decrease in emissions, using Germany's 1250 MtCO2eq. from 1990 as reference emissions (Horowitz, 2016). For the base scenario, a reduction target of 40% is set, in line with the current German energy trends (Affairs and Energy, 2016). In the TT scenario, a lower emphasis on reducing greenhouse gas emissions as well as lack of energy security leads to a target value of only 10%. In HH, an ambitious target value of 80% is set, reflecting the most optimistic pathways in "Energiewende" (F.M.E.T, 2010).

The percentage of renewables in the system is set by the renewable target μ. For the "business-as-usual" base scenario, where an intermediate solution is most likely, this value is set to 40%. In TT, where fossil-fuels (and energy security) is more prioritized, this value is set to only 15%. In HH, the value is 70%, in line with (Affairs and Energy, 2016).

The discount rate (DR) reflects the time value of money and accounts for the opportunity cost of capital (García-Gusano et al., 2016a). It usually ranges from 5% to above 15% in various research applications. Several factors influence the choice of discount rate, but in general one could say that long-term stability and a growing economy (low risk) favors a lower rate, while geopolitical tensions and market instability (high risk) favors a higher rate (García-Gusano et al., 2016b). In the base scenario, where the long-term stability is rather good, the rate is set to 6%. In TT, to reflect a larger risk and increased geopolitical tensions, the value is set to 15%. An intermediate value of 10% is chosen for HH. The DR is used to calculated the annuitised costs used in the model, and will therefore lead to different cost-estimates for the three scenarios, as indicated in Table. (4).

Another consequence of a rise in geopolitical- and regional tension, is reduced global cooperation and cross-border trade. This effect is implemented in the model through the import/export capability. For the German system, heavily reliant on the import of gas, this capacity factor is adjusted to reflect restrictions on import/export. Note that this is a naive simplification, as the actual effect would be more complex to model. In the base scenario, the capacity factor for Gas is set to 0.8. A value of 0.4 is chosen in TT to account for decreased import capability. In HH, a value of 1.0 is reflecting perfect cross-border trade and regional cooperation.

A maximum threshold κ for installed capacities is introduced for the different technologies, reflecting the scenario-specific environment. In the base scenario, the upper threshold for gas, biomass, and 'other' is set to infinity. For wind and PV the upper threshold is set to 400 GW, which is a 6-fold expansion of the 2022 installed capacity (66 and 69 GW respectively), in line with current trends (Affairs and Energy (2016). As Hydropower has limited potential for expansion due to area conflicts, turbine upgrades and efficiency measures are expected to increase this capacity to 9 GW. For HH, no upper threshold is set for wind, PV, and biomass. Hydro is increased to an upper threshold of 12 GW, reflecting significant improvements of current installed capacities. Upper thresholds for fossil-based generation is set, reflecting the hard constraints on emissions. Finally, TT has no upper thresholds for fossil-based generation such as gas and coal, to reflect a lower emphasis on renewables and a higher emphasis on energy security. The upper threshold for wind and PV is set to 200 GW, a 3-fold expansion of current trends. This is assumed to be a reasonable system development in the coming decades, despite geopolitical challenges.

Finally, the energy demand data is scaled according to changes in the scenarios, using a scaling factor η. A 10% decrease in demand is used in the base scenario, corresponding to a scaling factor of 0.9, in line with the current "middle of the road" trends. The following increase in energy demand is expected to be compensated for through some smaller energy savings and efficiency measures. In TT, the effect of energy savings and increased energy efficiency is low, and an additional population growth leads to an increase in energy consumption. Overall, a scaling factor of 1.1 is used to account for a 10% increase in demand from 2022. In HH, the global population growth is limited which leads to a lower energy consumption. Additionally, energy efficiency and energy savings reduce the demand even further. A reduction of 40% is expected, equivalent to a scaling factor of 0.6, and in line with (Affairs and Energy, 2016). The model parameters for the different scenarios is summarized in Table (3).

Table 3: Model Parameters for the Scenarios Harmony Horizon, Turbulent Times, and the base scenario. The reference energy system is a simplification of the German energy system in 2022.

Parameter	**Harmony Horizon**	**Turbulent Times**	**Base Scenario**
Emission Target γ	-80%	-10%	-40%
Renewable Target μ	70%	15%	40%
Discount Rate DR	10%	15%	6%
Capacity Factor Gas	1.0	0.4	0.8
Demand Scaling η	-40%	+10%	+0%
Maximum Capacity κ	Wind: INF PV: INF Hydro: 12 GW Gas: 32 GW Coal: 38 GW Biomass: INF Other: INF	Wind: 200 GW PV: 200 GW Hydro: 4.9 GW Gas: INF Coal: INF Biomass: INF Other: INF	Wind: 400 GW PV: 400 GW Hydro: 9 GW Gas: INF Coal: 38 GW Biomass: INF Other: INF

Furthermore, for the annutised costs for the different technologies, assumptions on DR, technology lifetime, and investment costs have been made. The lifetime estimates are given in Tab. (2), and investment costs from (Administration, 2022). The scenario-specific annuitised costs are visualized in Table. (4).

Tech.	Harmony Horizon (10% DR)	Turbulent Times (15% DR)	Base Scenario (6% DR)
Wind	315 700 [EUR/MW]	416 600 [EUR/MW]	240 770 [EUR/MW]
PV	95 970 [EUR/MW]	132 270 [EUR/MW]	67 750 [EUR/MW]
Gas	115 160 [EUR/MW]	158 730 [EUR/MW]	81 300 [EUR/MW]
Coal	371 400 [EUR/MW]	523 500 [EUR/MW]	249 300 [EUR/MW]
Biomass	383 870 [EUR/MW]	529 100 [EUR/MW]	271 000 [EUR/MW]
Hydro	297 900 [EUR/MW]	402 140 [EUR/MW]	217 700 [EUR/MW]
Other	10 000 000 [EUR/MW]	10 000 000 [EUR/MW]	10 000 000 [EUR/MW]

Table 4: Calculated annuitised costs for the three scenarios. Note the different Discount Rates (DR) implemented in the three scenarios.

2.5.2 Mathematical Formulation

The objective function is given in eq. (2), where Z represent the total system costs. The total costs consist of the summed annuitised costs C_{ann} and variable costs C_{var} for the given technologies t. For clarity, functions only dependent upon the technology is denoted with a parentheses (t), while functions dependent upon both technology and time (hours) is denoted (t, h).

The primary decision variables are how much to generate from each technology in each hour h, and the total installed capacity for each technology.

The first constraint (3) ensures that the variable generation $V_G(t, h)$ for a given hour is greater or equal to the scenario-specific scaled demand $\eta D(h)$ for that hour. Constraint (4) ensures that the variable generation is less than or equal to the maximum possible generation for that technology. This is given by the capacity factor $Cf(t, h)$ and the installed capacity $I_C(t)$. In addition, a constraint κ on the maximum amount of installed capacity is introduced in the three scenarios, reflected in constraint (5). Furthermore, constraint (6) oversees that the total emissions $V_E(t, h)$ are in line with the reduction target γ. The total emissions are given by the emission intensity $Ei(t)$ multiplied by the total variable generation $V_G(t, h)$ for that technology. Finally, constraint (7) ensures that the total variable generation from renewables satisfy the minimum share μ of the total generation.

Objective Function:

$$Z = \min \sum_t C_{ann}(t) + \sum_t \sum_h C_{var}(t, h) \tag{2}$$

Decision Variables:

$V_G(t, h)$: Variable generation from a given technology for a given hour

$I_C(t)$: Total installed capacity for a given technology

Parameters:

μ : Target value for renewables

γ : Target value for reducing emissions

η : Demand scaling factor

κ : Maximum Installed Capacity

$\eta D(h)$: Scenario-specific demand

$Cf(t, h)$: Capacity factor

$V_E(t, h)$: Total emissions

$Ei(t)$: Emission intensity

$V_G^{REN}(t, h)$: Variable generation renewables

Constraints:

$$V_G(t, h) \geq \eta D(h) \tag{3}$$

$$V_G(t, h) \leq I_C(t) Cf(t, h) \tag{4}$$

$$I_C(t) \leq \kappa \tag{5}$$

$$V_E(t, h) \leq V_G(t, h) Ei(t)(1 - \gamma) \tag{6}$$

$$V_G^{REN}(t, h) \geq \mu V_G(t, h) \tag{7}$$

2.6 Data Acquisition and Processing

This section provides an overview of the datasets used in the model presented in (2.5), and also how the data is processed. All the datasets described in this section is from 2022, unless explicitly stated otherwise.

2.6.1 Demand Dataset

The German electricity demand is extracted from (ENTSO-E, 2022), and can be seen on an hourly timescale for the year 2022 in Fig. (1). The data is used as input to the model in GAMS, and is scaled according to the specific scenarios.

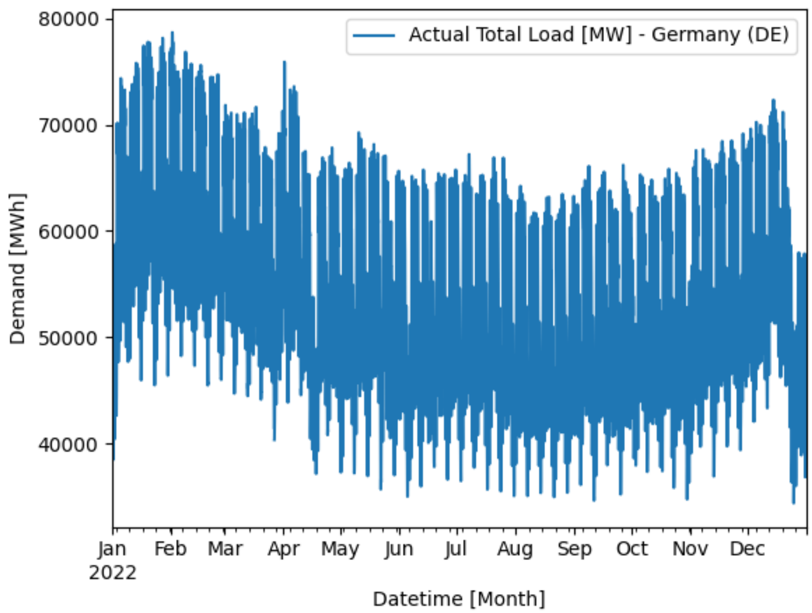


Figure 1: German electricity demand fro 2022 plotted as a time series. This dataset serves as the basis for the demand to be met in the three scenarios.

2.6.2 Emission Intensity Data

Data on emission intensity is extracted from (Portal, 2022), and the values are kept fixed for all scenarios. The values represent the intensity of CO2-equivalents the technology emits. Given some constraints on emissions, the accuracy of this data is important for the optimal solution.

2.6.3 Capacity Factor

Capacity Factor (CF) for a technology is the ratio of actual power output to maximum potential output. The CFs for wind and PV is taken from (RenewablesNinja, 2022), while the rest of the capacity factors are aggregated based on estimates from literature (EIA, 2022).

```
h1.wind 0.4487
h2.wind 0.4918
h3.wind 0.5389
h4.wind 0.5713
h5.wind 0.6156
h6.wind 0.6572
h7.wind 0.6884
h8.wind 0.7076
```

Figure 2: Example of the CF formatting. Here is the first eight hours of wind CFs.

2.6.4 Variable Costs

Variable costs are the price per unit of produced output, given in EUR/MWh. The numbers for the variable costs are implemented based on estimates from several references (Kost, 2021; Henning, 2015), and should therefore not be interpreted as perfectly accurate. In converting the costs from USD to EUR, an exchange rate of 1 USD = 0.91 EUR is used (Nov. 2023). The emphasis in this study is more on the effect of changes in model parameters, rather than the exact system costs.

2.6.5 Annuitised Costs

The annutised cost is a financial term used to spread the initial investment cost of constructing a power plant or energy infrastructure over its expected lifetime. The annuitised costs for the technologies used in this study are calculated using the investment cost I_0 from (Administration, 2022), a discount rate DR (García-Gusano et al., 2016b), and the estimated lifetime t of the respective technology. The lifetime of a power generating technology refers to the amount of time, given in years, that the power plant/energy infrastructure is expected to operate. The formula for the annuitised cost is given in eq.(8), and the costs are shown in (4):

$$\mathrm{a} = \frac{I_0}{\sum_t \frac{1}{(1+r)^t}} \tag{8}$$

3 Results

Based on the mathematical model and the implemented data in GAMS, an optimal solution for the three scenarios is found. This section summarizes these results. Figure (3) visualizes the cost-optimal system configuration for the three scenarios. In the first panel, demonstrating the optimal solution for the base scenario, there is a mix of generation from wind, PV, hydro, and gas. In all scenarios, there are some generation allocated to the "other" bin. This bin is representing the amount of generation that is not covered by the included technologies, but rather import, energy storage, or other (smaller) technologies as elaborated in section (2.5). In the second panel, for the Harmony Horizon scenario, the amount of installed wind- and PV capacity is exceeding the other scenarios, as expected. In right panel, for the Turbulent Times scenario, the cost-optimal solution includes more (cheaper) fossil-based generation. The solutions are also plotted as pie-charts in Figure (4) for an alternative visualization.

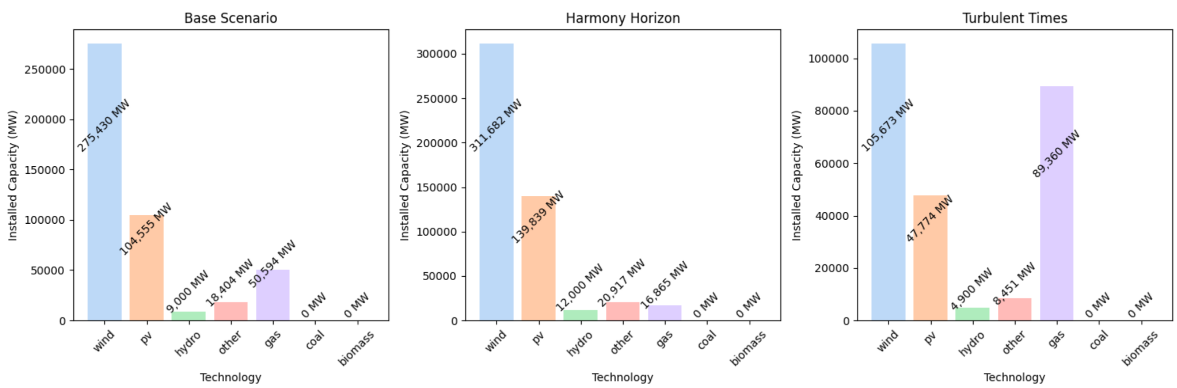


Figure 3: The installed capacity of different technologies, for the three scenarios in the model. The results clearly demonstrate how the scenario-specific constraints affect the system design.

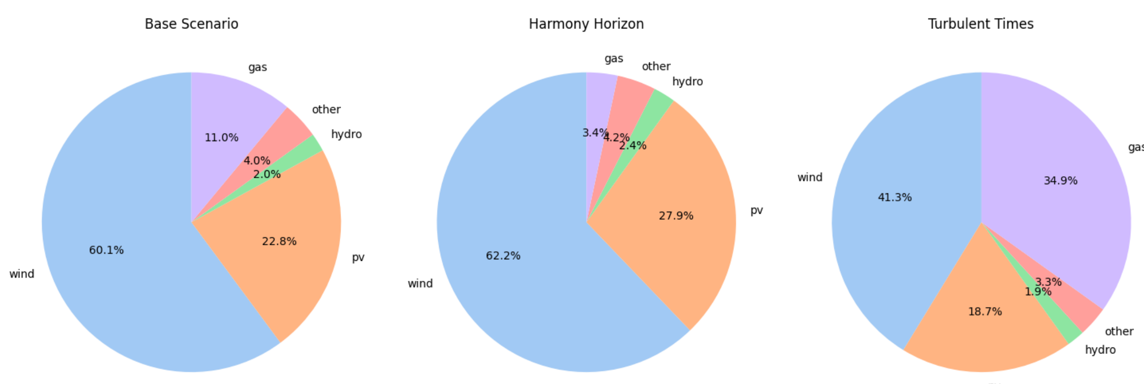


Figure 4: The installed capacity of different technologies, plotted as a pie chart.

Figure (5), Figure (6), and Figure (7) shows the optimal variable generation throughout a year, for the base scenario, Harmony Horizon, and Turbulent Times, respectively. The figures are split into subplots to clearly show each technology's contribution to the system. Note the changing y-axis scale in the plots. Finally, Figure (8) shows the total system costs for the three scenarios.

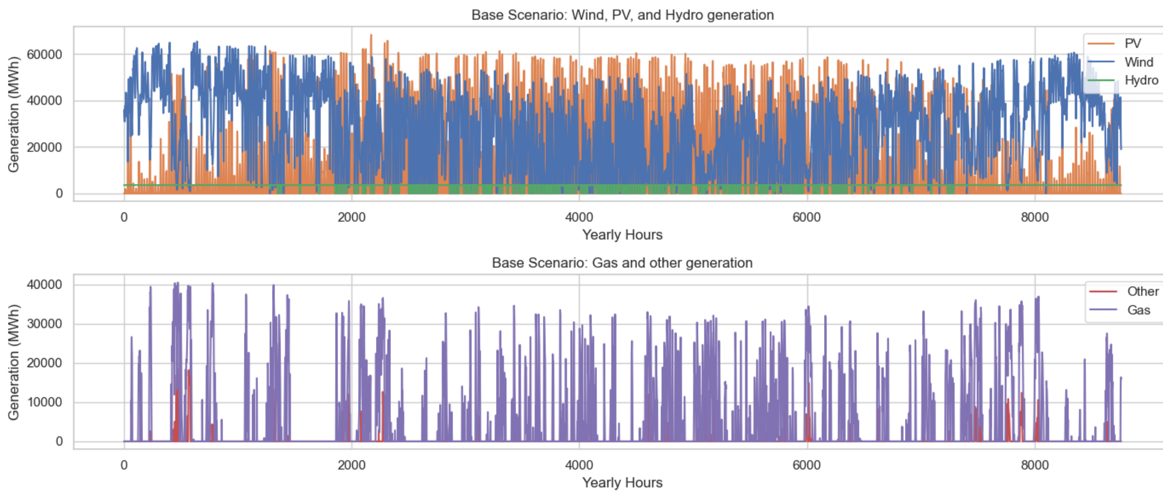


Figure 5: Base Scenario: Variable generation for one year. Demonstrating which technologies that are dominating in the scenario-optimal energy system.

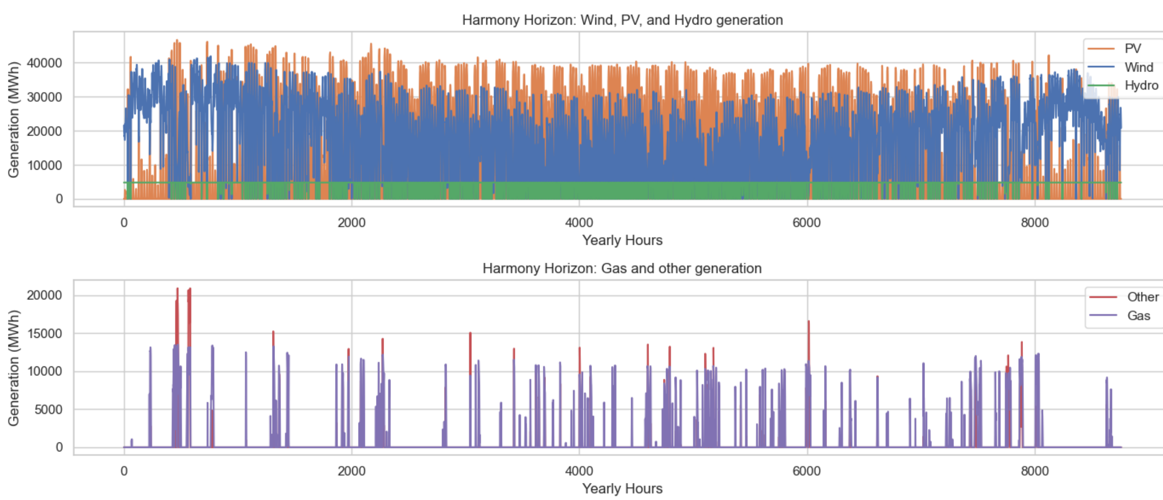


Figure 6: Harmony Horizon: Variable generation for one year. Demonstrating which technologies that are dominating in the scenario-optimal energy system.

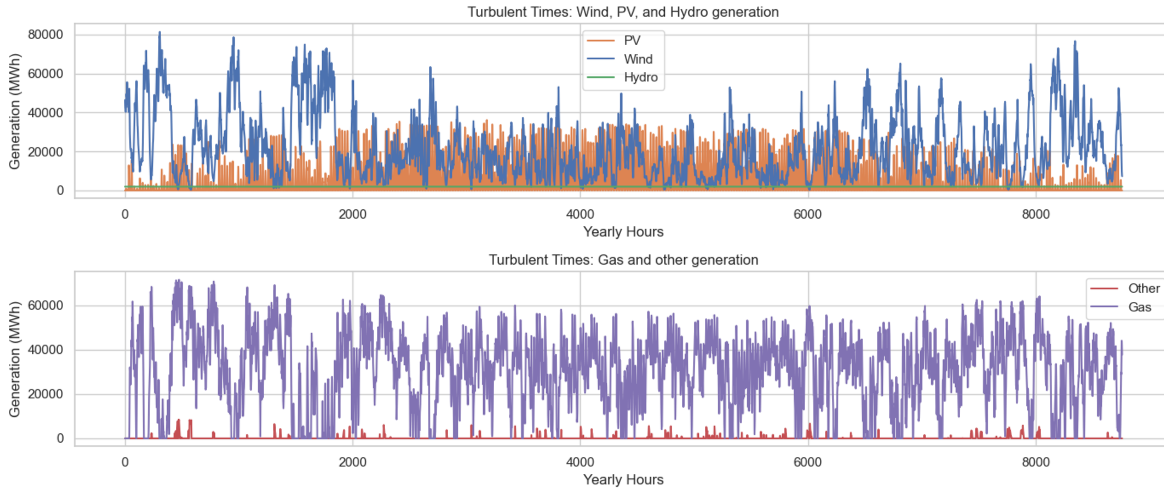


Figure 7: Turbulent Times: Variable generation for one year. Demonstrating which technologies that are dominating in the scenario-optimal energy system.

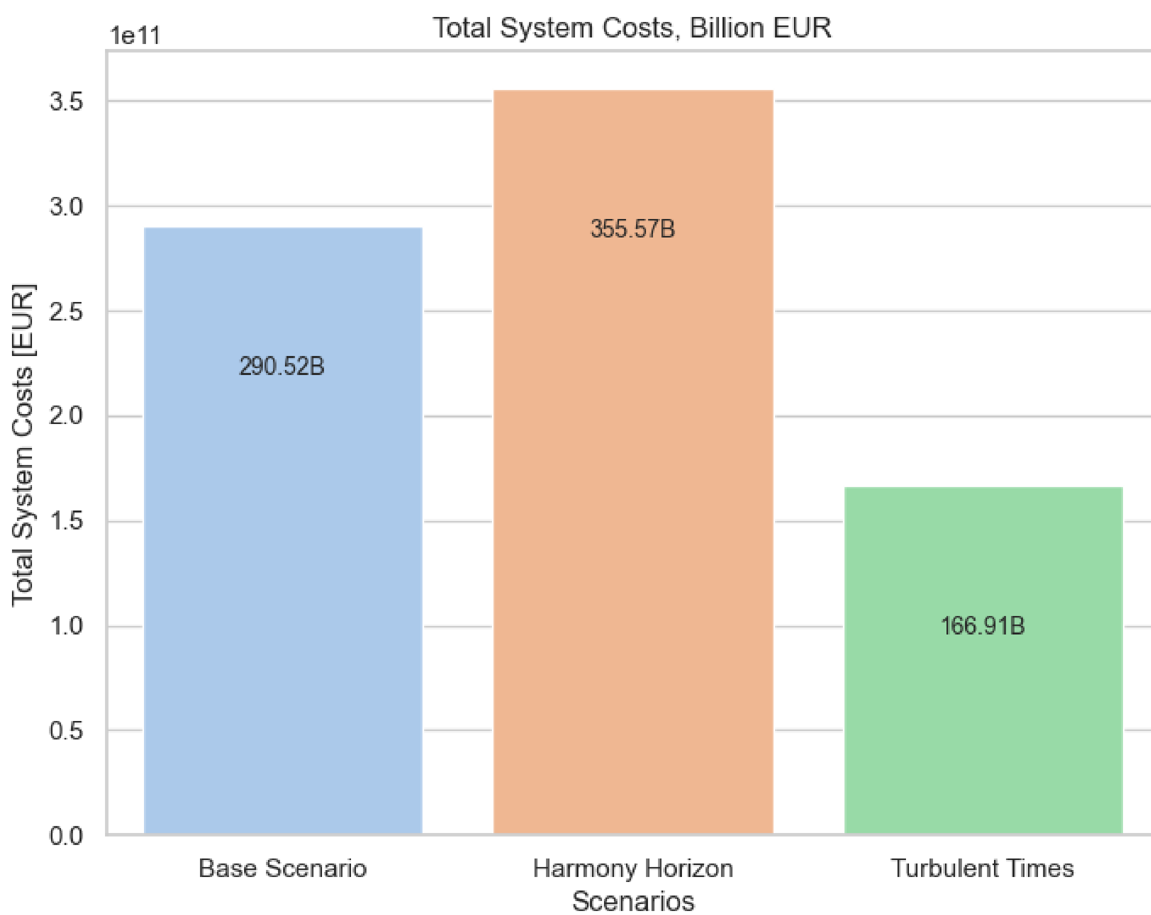


Figure 8: Total system costs for the three scenarios. Demonstrates that the Harmony Horizon scenario with relatively hard constraints yields a higher system costs. Furthermore, in the Turbulent Times scenario, the costs are lower because constraints on emissions and renewables penetration are softer.

3.1 Sensitivity Analysis

To be able to better interpret the results, this section includes a simple sensitivity analysis on some of the model parameters. The sensitivity analysis in modelling problems refers to how a change in the input variables or constraints, leads to a change in the optimal value. Energy system modelling often involves making several assumptions. Therefore, conducting a sensitivity analysis before interpreting the results is beneficial for a deeper insight. In this simple analysis, emphasis have been put on two parameters, namely the renewable target μ, and the capacity factor for gas. Their impact on the total system costs are visualized using lineplots in Figure (9) and Figure (11). For the analysis, both the renewable targets and CF for gas were evaluated, ranging from 0.1 to 1.0.

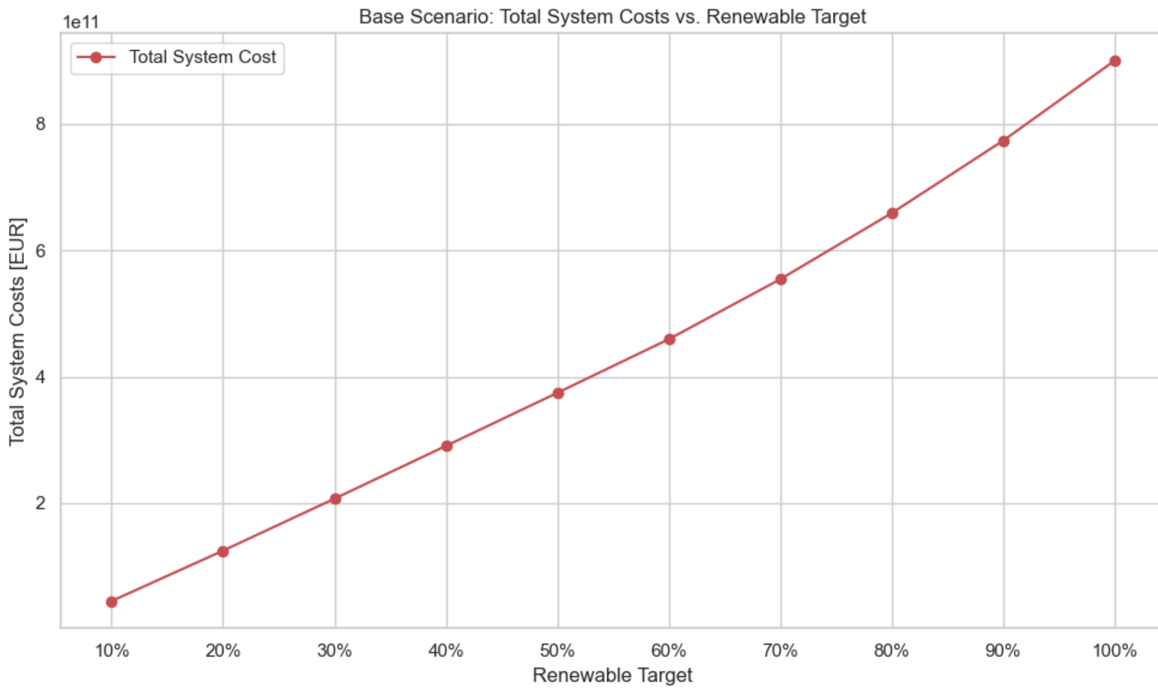
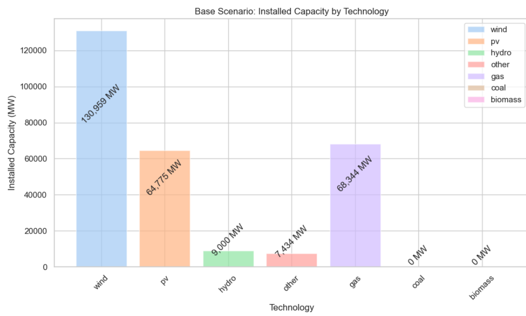
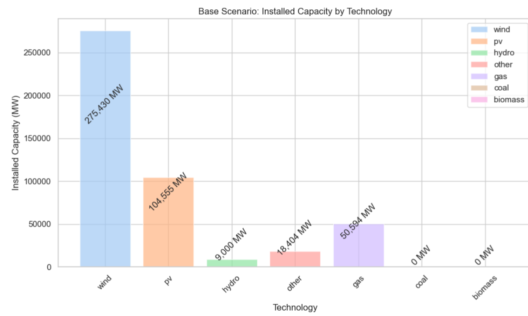


Figure 9: The total system costs versus changes in renewable target. As the target for renewables in the system increases, so does the total system costs. This is expected, but compared to the impact on costs, this parameter is much more sensitive to changes than the capacity factor for gas, which are emphaiszed by the change on the y-axis values.

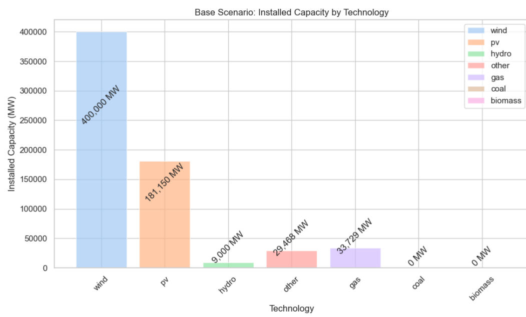
The renewable target sensitivity analysis is investigating how the total costs changes as the total percentage of renewables changes. Keep in mind that the "other" generation bin in the model is also included under "renewables". Fig. (9) clearly demonstrate a positive linear relationship between renewable target and system costs. As the y-axis demonstrates, the changes in costs are quite significant, which means that this parameter is sensitive to input changes. In the study, the renewable targets for the scenarios are put to 15%, 40% and 70%, respectively. Based on this analysis, it is expected that the optimal solution and overall costs will change (significantly) if one alter these target values. This correlation can be seen in Fig. (10), visualizing how the optimal installed capacities varies for different renewable targets.



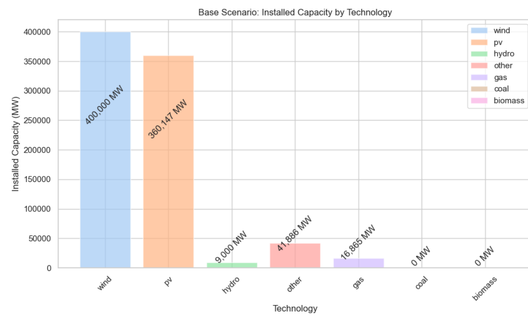
((a)) Optimal Solution with 20% renewables



((b)) Optimal Solution with 40% renewables



((c)) Optimal Solution with 60% renewables



((d)) Optimal Solution with 80% renewables

Figure 10: Base Scenario: Installed capacity for different renewable percentage targets

Further, Fig. (11) demonstrates the (almost) inversely proportional relationship between system costs and an increase in CF for gas. Note that the change in values on the y-axis is less than for the renewable target, indicating a smaller sensitivity to changes in input. Also, the overall costs seems to stabilize as the CF for gas reaches 1.0. This result makes sense, as the other model constraints, such as emission and renewable targets, would make the model prioritize other technologies than gas, despite an increasing CF.

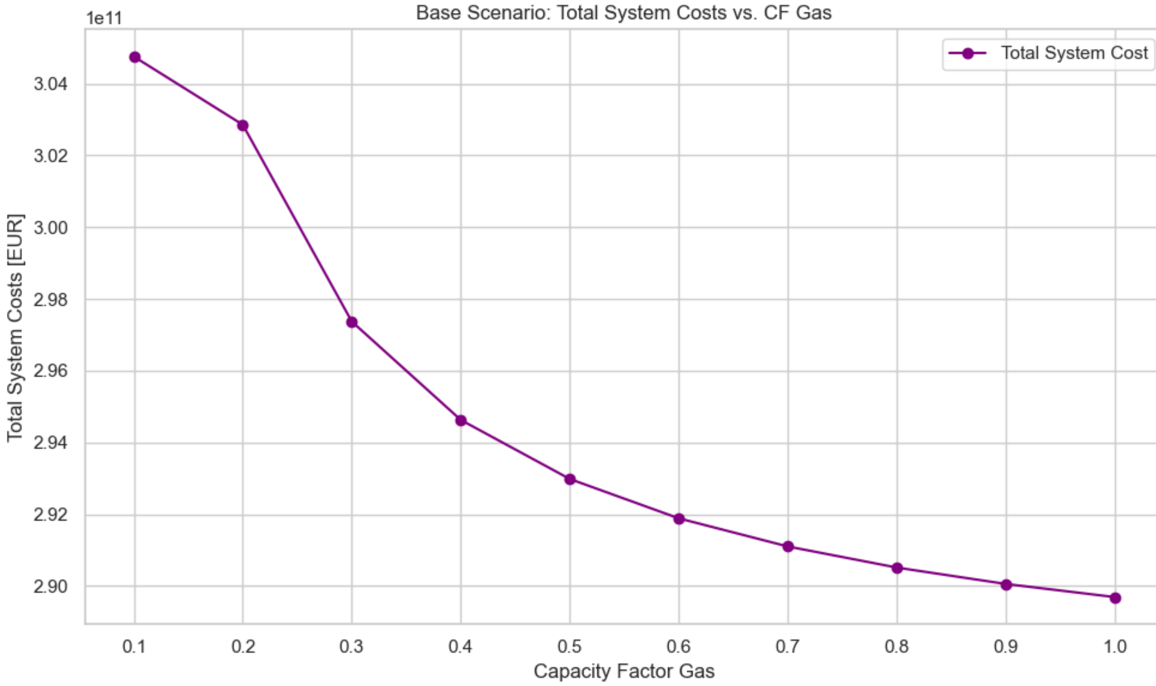


Figure 11: The total system costs versus changes in capacity factor for Gas. Germany is reliant on import of gas in its energy system, so this plot demonstrates consequences of restrictions in import capacities. Note the scale on the y-axis, and how the change in system cost flatten out as the CF increases.

Overall, this simple analysis visualizes that the the system costs are more sensitive to changes in the renewable target value, than changes in the capacity factor for gas. In this study, the CF for gas were included (and changed) to account for import/export restrictions. Based on the sensitivity analysis, one might argue that the effect on the system (from the CF) is too small to account for such an important factor as import/export. Expanding the sensitivity analysis to encompass additional parameters would provide deeper insights into the energy system design, and the effect of geopolitical instability.

4 Discussion

In summary, the examination of the cost-optimal system configurations across the three scenarios illustrates substantial variations driven by constraints and geopolitical considerations. Notably, the large share of wind and PV in the optimal solutions underscores their importance in the future energy system. Conversely, the Turbulent Times scenario, characterized by relaxed constraints on renewables and emissions, portrays a strong reliance on fossil fuels, particularly gas. These results may indicate a priority shift towards energy security and stability in the face of geopolitical tensions.

The findings strongly advocate for a substantial expansion of wind and PV capacities, potentially up to six times the current levels in Germany, to meet future energy demands effectively. The Turbulent Times scenario revealed the German dependence on gas, despite poor capacity factor (less imports). In late 2022, Germany re-opened 10 GW of decommissioned coal-power to replace the "lost" Russian gas imports, clearly demonstrating a vulnerability in the largest primary energy consuming country in Europe (Eddy, 2022).

It's important to note the significance of cost estimates in interpreting these results. The variations in energy costs, annuitised costs, and variable costs, shaped by societal shifts and priorities, significantly influence the optimal solution. The scenarios incorporated in this study depends on several cost estimates, and changes in these directly impact the derived optimal solutions. An important aspect not included in this report is the expected rise in variable costs for oil- and gas, as a consequence of geopolitical conflicts (Bazilian et al., 2020). It would have been interesting to implement this in the model, and to see how it would impact the cost-optimal solution.

The sensitivity analysis revealed the role of the renewable target value, and the capacity factor for gas, in shaping the cost-optimal solution. Notably, even a modest 10% shift in the renewable target could sway total costs by 40-50%, showcasing the considerable influence of such adjustments. The CF for gas proved less impactful for the total costs, and might therefore not be a good representation of the cross-border trade (import/export). Expanding the sensitivity analysis to include other model parameters would provide invaluable insights, and further knowledge on the influential factors in energy system design.

Overall, due to the many assumptions and simplifications in the modeling framework, the study should be regarded more as a guideline indicating possible consequences of specific societal trends. It still emphasizes the most contributing factors to the overall energy system, and in this case the effect of geopolitical instability in the German energy system.

5 Conclusion

To conclude, this study investigated how geopolitical turmoil and regional conflicts could affect the energy transition in Germany. This was investigated through a scenario-based model, with one base scenario that reflected the ongoing trend in the current German Energy System, extrapolated to 2050. Secondly, Harmony Horizon reflected a future in line with the ambitious targets in the German energy transition plan "Energiwende", including 80% reduction in GHG emissions, and a renewable target of 70%. Finally, to investigate how geopolitical instability and conflicts could impact the energy transition, Turbulent Times introduced less global cooperation, restricted imports, and an overall shift away from the unpredictability of renewables.

The results strongly support the need for a significant increase in wind and PV capacities, possibly scaling up to sixfold the existing levels in Germany, in order to adequately meet the future energy requirements. Choosing appropriate estimates for model parameters were proven crucial, since parameter changes greatly impacted the optimal solution, also emphasized in the sensitivity analysis. Also, because the model was subject to several simplifications, it is better to view it as a general guide indicating how certain social changes might impact the German energy system. It does highlight important factors affecting the optimal solution, and ultimately the possible consequences of geopolitical issues.

Further research should better investigate the restrictions on import/export, as well as the role of energy storage which have been neglected in this study. Energy storage could replace the use of fossil-fuels in periods of lower generation capacity, which could save both costs and the environment. Also, a more accurate representation of the costs, both in terms of annuitised and variable costs, should be implemented. Finally, investigating how a rise in oil-and gas prices could impact the optimal solution would prove beneficial in understanding the impacts of geopolitical conflicts.

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