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How Dependent Are European Power Systems and Economies on Natural Gas?—A Macroeconomic Optimization for Security of Electricity Supply

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Abstract: How dependent are European power systems and economies on natural gas? To answer this pressing question, we coupled a simulation model for assessing security of electricity supply and an economic optimization model. With this, we were able to analyze different reduction scenarios of the amount of gas utilized in the power sector. Our results show that reducing the amount of natural gas in the European power sector by up to 30% has a relatively moderate impact on the security of electricity supply. Restrictions of 40% or more result in substantially higher reductions in electricity demand shortfall and are associated with economic costs of more than EUR 77 billion. Furthermore, we demonstrate that a close coordination of gas distribution on a European level would be instrumental in mitigating negative economic consequences. Finally, it can be deduced that a coordinated delay of planned power plant shutdowns could effectively compensate for reduced gas volumes in the electricity sector.

Keywords: security of electricity supply; natural gas; European power system; economic optimization

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1. Introduction

As a result of the Russian Invasion of Ukraine in February 2022 and the ongoing war since then, the countries of the European Union (EU) have imposed a wide range of sanctions against Russia. In the energy sector, a coal embargo was decided at the beginning of April 2022, but initially it was explicitly not for imports of pipeline-bound natural gas, which would be difficult to replace in the short term because of concerns about massive economic damage. However, the natural gas supply via one of the largest pipelines, Nord Stream 1, which connects Russia with Germany, was completely discontinued in August 2022. Against this background, the question arises to what extent a reduction or even cessation of natural gas imports from Russia would have an impact on the security of the electricity supply. With an import share of 55.1%, more than every second cubic meter of natural gas consumed in Germany in 2020 originated from Russia [1]. For the EU as a whole, the import share of Russian natural gas in the same year was around 32.9% (see Figure 1).

While a large share of the natural gas is used for heating and manufacturing, electricity generation still accounts for a significant share of total natural gas demand, at 25.8% in Germany and 31.7% in the EU (see Figure 1). In our research, we therefore addressed the question as to what extent restrictions in the availability of natural gas would affect the European electricity supply. We have chosen the year 2025 as target year for our investigations. In other words, our research question is "How resilient is the European power system in 2025 against restrictions in the availability of natural gas?"

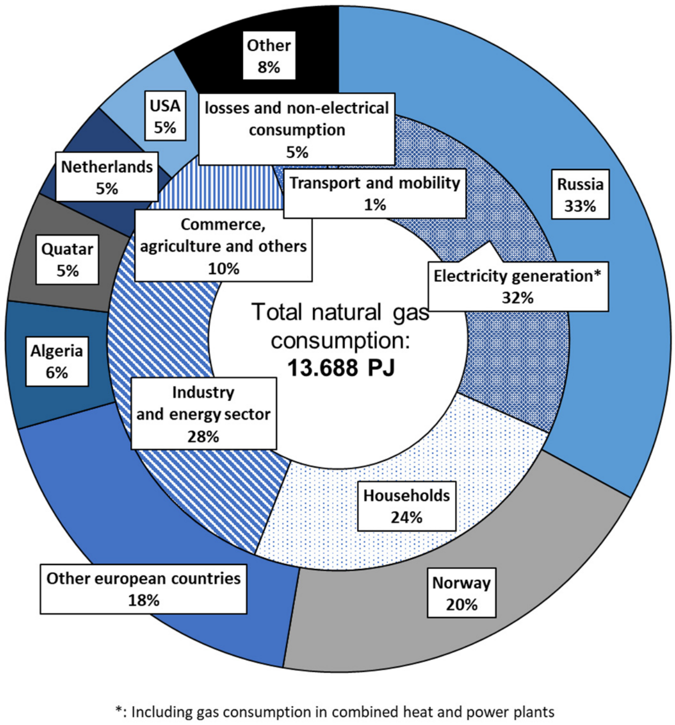

Figure 1. Import origin share of natural gas consumption in Europe (outer ring, sum of pipeline and liquid gas imports) and sectoral breakdown of natural gas consumption (inner ring) in Europe in 2020. Data sources: [1,2].

The economic impact of a reduction in natural gas supplies from Russia has been examined in several recent studies due to the immediate relevance of the topic. In this context, Bachmann et al. [3] analyzed the economic consequences a complete halt to Russian natural gas imports starting in August 2022 would have for Germany. Berger et al. [4] provided an overview of estimates of the effect on the economic outlook not only for Germany, but the whole of Europe based on current studies. To our knowledge, there is no detailed analysis of the impact of natural gas reductions on the power system and the associated direct economic effects.

To assess the security of the electricity supply in the sense of resource adequacy, as well as potential economic impacts of supply reductions, there are several key indicators. The technical indicators Loss of Load Expectation (LoLE) and Expected Energy not Served (EEnS), as well as the socioeconomic indicator Value of Lost Load (VoLL) are considered as appropriate indicators [5–8]. The technical indicators can be calculated especially from probabilistic methods, which can be found exemplarily in the references by Baumanns, Nolting and Praktiknjo, ACER, Consentec and r2b energy consulting, EICom, ENTSO-E and Pentalateral Energy Forum [6,7,9–14]. While probabilistic indicators focus on the technical dimension of resource adequacy, socioeconomic indicators represent costs and benefits associated with resource adequacy. As such, the indicator VoLL represents the monetized value of damages for electricity consumers affected by interruptions of supply [15]. There is a wide range of methods for determining the VoLL for electricity consumers. Based on Bateman et al. [16] and Praktiknjo [15] the approaches and respective methodologies for the assessment can be categorized in (1) theoretical approaches (macro- and micro-economic models), (2) revealed preferences approaches and (3) stated preferences approaches.

To access the technical and economic impacts of reduced electricity generation from natural gas, we combine the technical and socioeconomic indicators. To this end, we use a three-step methodology: (1) translation of possible developments into scenarios, (2) simulation and evaluation of the security of the electricity supply using a probabilistic simulation model and (3) minimization and evaluation of economic implications using a techno-economic simulation model on a macro level (see Figure 2).

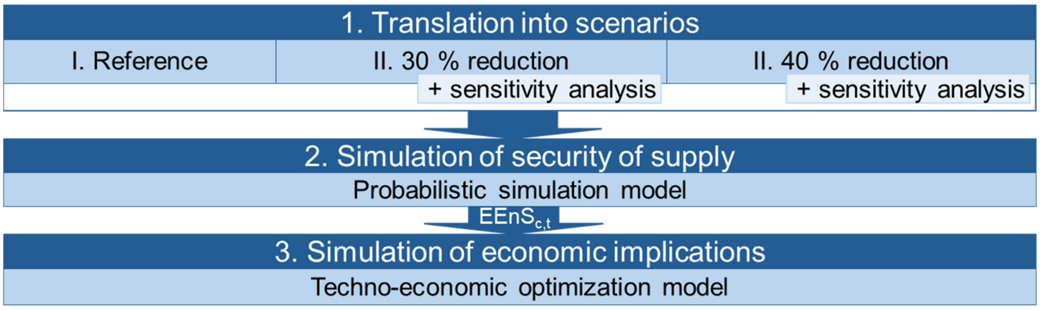

Figure 2. Three-step methodology to assess the technical and economic impacts of reduced average natural gas consumption in the power sector.

The remainder of the contribution is structured as follows. First, we state the models used for our methodology and the corresponding data in Section 2. The results of our analysis are presented in Section 3. In Section 4, these results are discussed, and our research is concluded.

2. Materials and Methods

The following section is structured accordingly to the three-step methodology as shown in Figure 2. We state the translation of possible developments into possible scenarios in Section 2.1. Based on this, the security of supply for those scenarios is simulated with a probabilistic model described in Section 2.2. The outputs are hourly time series of the technical indicator EEnS for each country, which we use in Section 2.3 to assess the economic implications based on a techno-economic optimization model.

2.1. Step 1: Translation into Scenarios

The share of natural gas consumption used in the power system is influenced by various factors and the question of the allocation of natural gas for the European power system in the event of a supply embargo is not trivial. In fact, the availability of natural gas for the power system depends on a very complex interplay of a whole range of factors. Among other things, the following questions arise:

- Can Russian natural gas be substituted by other natural gas supplies or even other energy sources? When will these substitutes be available and what costs would be associated with them?
- How do natural gas and electricity prices develop in relation to other energy prices and CO_2 taxes?
- How do sectors outside the power system (e.g., heat and industry) react to a shortage and increase in the price of natural gas supplies? Which sectors would have regulatory or economic priority in the supply of natural gas?
- How will natural gas storage levels develop? How will natural gas storage facilities be operated in the near future?
- How much renewable energy will be fed into the power grids in the next few years? What additional capacity can we expect? What types of weather years will we have?
- What will the future power plant mix look like? Will previously planned power plant decommissioning be postponed?

Due to the described complexity regarding the allocation of natural gas for power generation in case of a supply embargo, we use exogenous reduction scenarios for our study, which we select specifically for the power system.

In order to determine the impact of the reduction of electricity generation from natural gas on electricity consumption, we first translate possible developments into the following scenarios for the EU-28 (excluding Malta and Cyprus, including Norway) in the year 2025: (I) a reference scenario without reductions in the amount of natural gas available in the electricity sector, (II) a 30% reduction scenario and (III) a 40% reduction scenario. For the reduction scenarios, we assume equally distributed cuts in natural gas availability based on the calculated average natural gas demand in each country for the power sector. Which import pathways cause this reduction in natural gas availability and how these can be mitigated is beyond our scope of investigation. For each of the reduction scenarios, we examine delays in the planned decommissioning of coal-fired power plants in European countries in the course of sensitivity analyses.

2.2. Step 2: Security of Supply

Based on these scenarios, the second step is to simulate and evaluate the security of the electricity supply using a probabilistic simulation model developed at RWTH Aachen University, considering uncertainties due to weather and outages. The complete mathematical formulation of the model is given in Baumanns [9]. The probabilistic model is based on a Monte Carlo approach. The Monte Carlo approach describes a numerical solution approach based on probability theory, in which a deterministic random experiment is repeated frequently. With a high number of random experiments, the results converge towards the expected value, according to the law of large numbers. Figure 3 shows a simplified illustration of the probabilistic model.

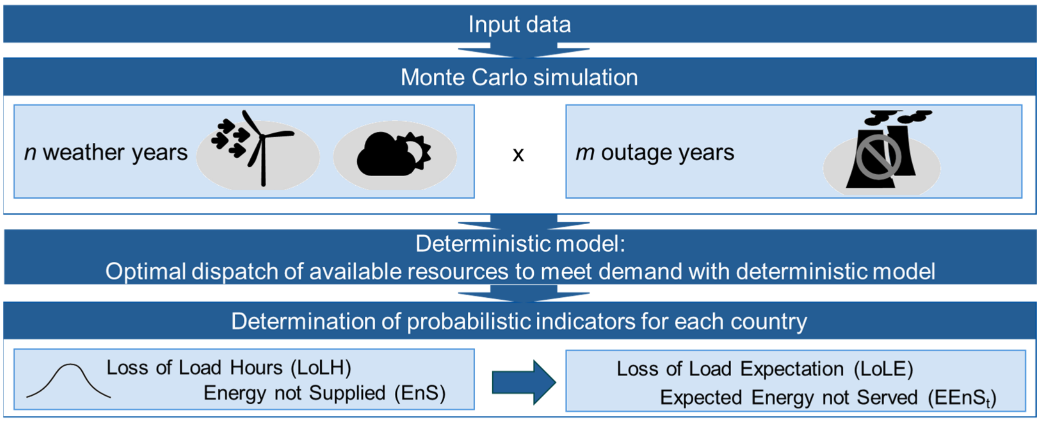

Figure 3. Probabilistic model for the assessment of the European security for electricity supply.

As input data, the model is first provided with the data of the scenarios to be considered. Furthermore, time series are needed to represent the inflexible demand and the supply of renewable energy sources (in particular, solar radiation, wind supply, hydraulic supply) on the basis of 35 historical weather years to represent the uncertain climate influences. Uncertainties due to unplanned outages of power plants are represented by stochastic parameters. From these stochastic parameters, 300 outage years are drawn using Markov chains.

For each combination of the n weather and m outage years, the optimal use of available resources to meet demand is determined using a deterministic optimization model. Subsequently, the indicators $LoLH$ (Loss of Load Hours, [h/a]) and EnS (Energy not Supplied, [MWh/a]) are determined for each combination. From the distribution of $LoLH$ and EnS, the two probabilistic indicators $LoLE$ and $EEnS$ can be derived:

$$LoLE_{area} = \frac{1}{n \cdot m} \sum_{x=1}^{n \cdot m} LoLH_{area,x} \tag{1}$$

$$EEnS_{area} = \frac{1}{n \cdot m} \sum_{x=1}^{n \cdot m} EnS_{area,\,x} \tag{2}$$

The deterministic optimization model is based on a linear optimization problem. The goal of the optimization is to minimize the demand shortfall as part of an overall cost minimization across all market areas while complying with the specified constraints. The optimization problem is solved time coupled and closed over one year. The time granularity is hourly.

The following variables are considered in the linear optimization problem:

- Dispatch of power plants as well as storage units (especially hydraulic storage and pumped storage power plants)
- Curtailment of generation from renewable energy sources
- Electricity exchanges between coupled market areas
- Demand flexibility (load shifting and/or load shedding)
- Energy not served

The following constraints must be met as part of the optimization problem:

- Cover of demand per market area
- Limited availability of power plants and storage units
- Mandatory dispatch for combined heat and power (CHP) power plants
- Continuity of storage levels
- Transmission capacity restrictions for electricity exchanges (NTC or FBMC)
- Restrictions of flexibility potentials on the demand side

In the following, we focus on the key indicator Expected Energy not Served (EEnS), which is minimized in the probabilistic model. The indicator EEnS represents the amount of energy that cannot be supplied in a year, against expected demand. We use the data set from the European Resource Adequacy Assessment (ERAA) 2021 for our simulations. [17]. For the reference scenario, we assume unrestricted natural gas availability in our simulation runs. In our simulations, a maximum natural gas consumption value in the power sector of about 1000 TWh_{therm} and a minimum value of about 750 TWh_{therm} result for the year 2025.

On average, about 833 TWh_{therm} of natural gas are used for electricity generation. For the reduction scenarios, the natural gas demand is thus limited to about 30% and 40% of the average natural gas demand compared to a mean weather and outage year. Due to the uncertainties regarding the development of the meteorological conditions, the specified percentage reduction values are therefore subject to an uncertainty band of about 10 percentage points. Furthermore, we assume for our analysis that all CHP obligations are fulfilled as a matter of priority in order to avoid displacement of demand reductions into the heat sector [18].

2.3. Step 3: Economic Impact

In the third step, the economic implications of possible power supply deviations due to restrictions on natural gas-fired power generation are evaluated by applying a techno-economic simulation model also developed at RWTH Aachen University. For this, we use economic and energy input-output data [2,19,20]. In our simulations, we examine in particular the Value of Lost Load (VoLL) indicator, which indicates the consumption-weighted average welfare loss of consumers in euros per unit of energy not supplied. We differentiate according to 15 consumer groups i, due to the heterogeneous structure of the different electricity consumers.

Based on the assumption of the dependence of gross value added (GVA) on annual energy consumption ($\bar{E}$) as stated by Praktiknjo [20–22], the average loss of gross value added per unit of unsubscribed energy per consumer group can be calculated according to Equation (3). This is also referred to as the Value of Lost Load ($VoLL_{i,\,c}$) for each consumer group i and each country c.

$$VoLL_{i,\,c} = \frac{GVA_{i,\,c}}{\overline{E}_{i,\,c}} \tag{3}$$

Possible demand shortfalls due to natural gas restrictions are allocated by the model by minimizing the cumulative VoLL, i.e., the lost consumer surplus (CS_{lost}), in each individual country I at each hour (t) over the entire study year and all observed consumer groups (i) and thus the lost consumer surplus. The objective function for our optimization model is represented in Equation (4). The optimization is performed individually for each country. The decision variable represents the expected amount of energy not served in each sector at each hour and for each country ($EEnS_{t,i,c}$).

$$min\text{CSlost, c} = min \sum_i (VoLL_{i,\ c} \sum_t (EEnS_{i,t,\ c})) = min \sum_i \sum_t (VoLL_{i,c} * EEnS_{i,t,c}) \quad (4)$$

Thus, on the demand side, we proceed analogously to a merit-order model (see Figure 4). In our model, the amount of energy that cannot be supplied per consumer group is limited by the hourly energy demand in that sector ($E_{i,t.}$) as stated in Equation (5). We assume that the electricity demand of the individual sectors remains constant for our scenario year 2025, as we do not expect any efficiency gains in the production processes. An increase in electricity demand due to, for example, a switch from currently natural gas-based processes to electricity-based processes is not taken into account in our analysis. Other constraints include the coverage of energy not served across all sectors for each country (6) and the non-negativity condition (7). For the individual consumer groups, we use published data sources [23] and synthetic load profiles available at RWTH Aachen University [24].

$$EEnS_{\ i,t,\ c} \leq E_{i,t,\ c} \ \forall \ i,t,\ c \quad (5)$$

$$\sum_i EEnS_{\ i,t,\ c} = EEnS_{t,c} \qquad \forall \ t,\ c \quad (6)$$

$$EEnS_{\ i,t,\ c} \geq 0 \qquad \forall \ i,t,\ c \quad (7)$$

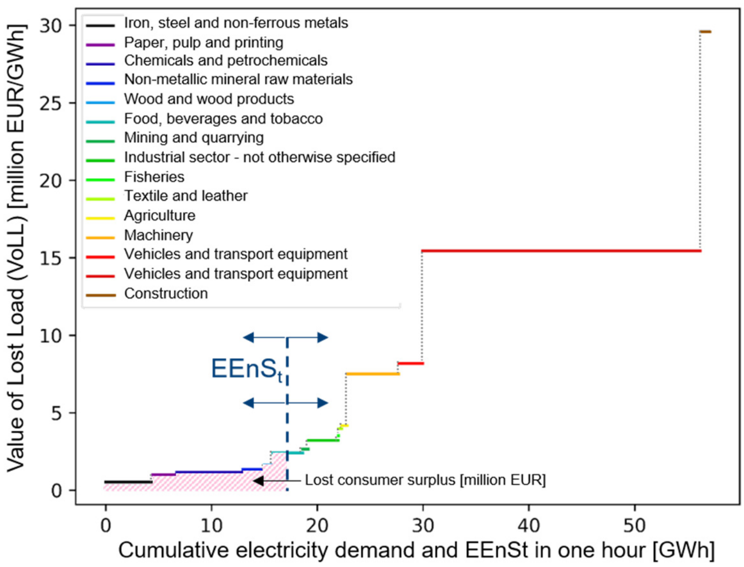

Figure 4. Merit order of electricity interruption costs in different consumer groups—here, the exemplary representation for Germany in one sample hour t.

3. Results

Our results of the reference scenario, as well as the scenarios for 30% or 40% reduction of natural gas in the electricity sector, are presented in Section 3.1. Based on this, the results of the same scenarios but with additional coal power plant capacities are shown and discussed in Section 3.2.

3.1. Reference and Reduction Scenarios

With a 30% reduction in the amount of natural gas available for electricity generation compared to the reference scenario, consumers in Europe would have to forego a moderate amount of planned electricity supply of 1.6 TWh on average. This undelivered amount is mainly distributed among Belgium (BE), Germany (DE), Denmark (DK), France (FR), Greece (GR), Ireland (IE), Italy (IT), Luxembourg (LU), Latvia (LV), the Netherlands (NL) and the United Kingdom (UK). This implies a relatively moderate economic cost of around EUR 1.47 billion for the affected consumers. The results are shown in Table 1.

Table 1. Additional expected energy not served (EEnS) and economic costs in the 30% reduction scenario. The totals given refer in each case to the entire area under consideration.

30% Reduction Scenario	BE	DE	DK	FR	GR	IE	IT	LU	LV	NL	UK	Total
Expected energy not served (EEnS) [GWh]	32.7	2.2	0.9	21.0	5.2	1202.6	61.8	0.8	0.8	11.4	243.1	**1590.9**
EEnS relative to national electricity demand [%]	0.0	0.0	0.0	0.0	0.0	4.2	0.0	0.1	0.0	0.0	0.1	-
Economic costs [million EUR]	14.8	1.2	0.9	7.7	0.9	1015.6	26.8	75.6	0.6	5.3	222.1	**1371.5**
Costs relative to national GDP [%]	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.1	0.0	0.0	0.0	-

For an illustration of the regional distribution of the collected indicators in the 30% reduction scenario compared to the reference case without gas quantity restriction, see Figure 5.

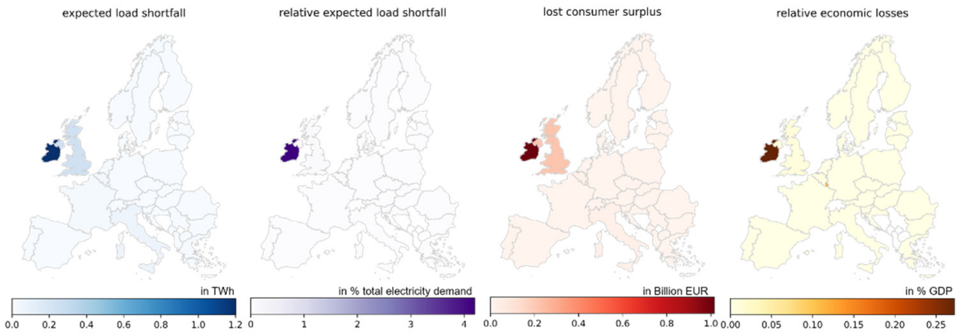

Figure 5. Regional distribution of the determined indicators in the 30% reduction scenario.

The model results show that even a 30% reduction in the amount of natural gas available in the electricity sector would have an impact on the level of security of electricity supply, particularly in Ireland, and would therefore result in economic losses. In Ireland, two factors come together: On the one hand, the country has only limited access to cross-border load balancing as it is an island state in the European interconnected grid and therefore experiences high absolute load shortfall levels. On the other hand, there are comparatively few economic sectors with low flexibility costs in Ireland which are not sufficiently represented to cover the shortfall quantities with electricity determined in the model at low cost. Therefore, in the scenarios in Ireland, there are more and more power cuts in the commercial sector and even in private households. However, these are comparatively very cost-intensive due to a high VoLL (i.e., high welfare losses are associated with load curtailments in these sectors).

This problem is further intensified when considering the results for a 40% reduction of the natural gas quantity in the electricity sector. In this reduction scenario, the allocation of natural gas consumption is essentially shaped by obligations for CHP generation mapped in the model. A summary of the investigation results for this scenario is shown in Table 2. While the amount of expected energy not served increases to about 37.8 TWh, the associated economic costs in Europe increase to about EUR 77.8 billion. With cost shares of just under 57.7% and over 37.8% of the total European costs, it is evident that Ireland and Italy in particular would have to bear the consequences of such a distribution allocation of natural gas reductions in Europe without taking into account the national value-added losses. In these countries, additional supply interruptions in the amount of 7.5 TWh and 26.6 TWh, respectively, and costs of up to 12.0% of Ireland's and 1.8% of Italy's gross domestic product (GDP), would be incurred in this scenario. In these two countries, in addition to their peripheral location and their grids, the high dependence on natural gas due to a large number of installed capacities of natural gas power plants comes into effect.

Table 2. Additional expected load interruption quantities (EEnS) and economic costs in the 40% reduction scenario compared to the reference scenario. The totals given refer in each case to the entire area under consideration.

40% Reduction Scenario	BE	DE	DK	FR	GR	IE	IT	LU	LV	NL	UK	Total
Expected energy not served (EenS) [GWh]	362.7	60.5	4.9	47.1	743.8	7473.7	26,598.7	41.1	1.5	185.4	2265.4	**37,785.5**
EenS relative to national electricity demand [%]	0.5	0.0	0.0	0.0	1.6	26.1	9.7	0.7	0.0	0.2	0.8	**-**
Economic costs [million EUR]	182.2	32.2	4.8	17.2	128.4	44,849.9	29,435.2	532.0	1.0	93.4	2510.3	**77,787.1**
Costs relative to national GDP [%]	0.0	0.0	0.0	0.0	0.1	12.0	1.8	0.8	0.0	0.0	0.1	**-**

For an illustration of the regional distribution of the collected indicators in the 40% reduction scenario compared to the reference case without natural gas quantity restriction see Figure 6.

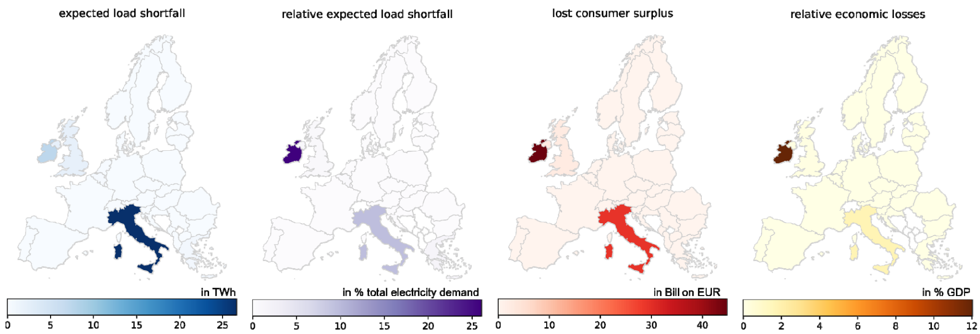

Figure 6. Regional distribution of the determined indicators in the 40% reduction scenario.

3.2. *Sensitivity Analyses on the Impact of Delayed Power Plant Shutdowns*

One measure currently under political discussion to cushion the impact on the energy system and the national economy as a result of possible restrictions on natural gas volumes is the delay of power plant decommissioning that are actually planned ahead. In order to map these developments, we assume generation potentials that can be reactivated in the short term compared to the baseline scenario 2025. Our sensitivity analyses are based on the coal capacities existing in 2020 and coal expansions planned until 2025 [10]. Further, we assume sufficient availability of hard coal on the world markets. The additional capacity assumed is 6.9 GW for lignite and 14.8 GW for hard coal in Germany and a further 12.6 GW and 39.5 GW in the rest of Europe (cf. Figure 7). Additional nuclear power capacity is not assumed in our sensitivity studies as we expect both technical and societal problems associated with such an endeavor.

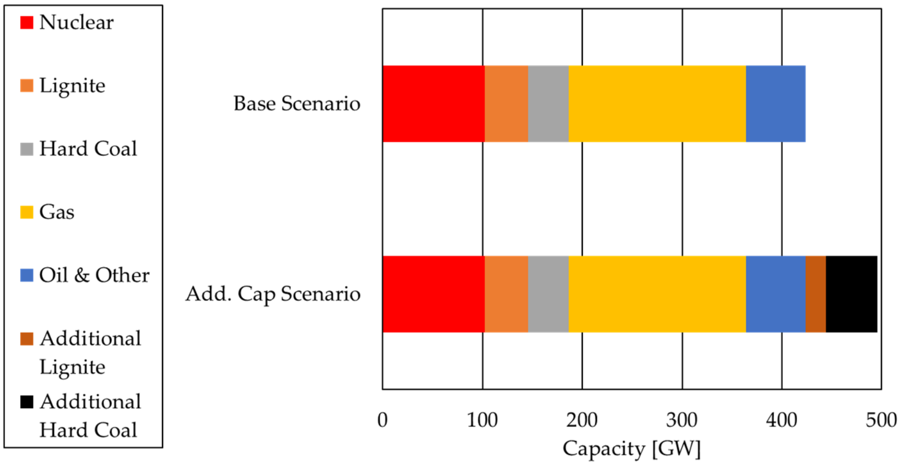

Figure 7. Installed Capacities per Scenario.

Figure 8 shows the respective expected load shortfalls and the associated economic costs in the sensitivity scenarios considered. Our results indicate that the considered delays of power plant decommissioning in the 30% reduction scenario can fully compensate the effects of natural gas quantity restrictions on supply security and economic costs. In the 40% reduction scenario, the expected impacts can be significantly reduced, although they still amount to a considerable amount of 9.4 TWh and EUR 26.4 billion.

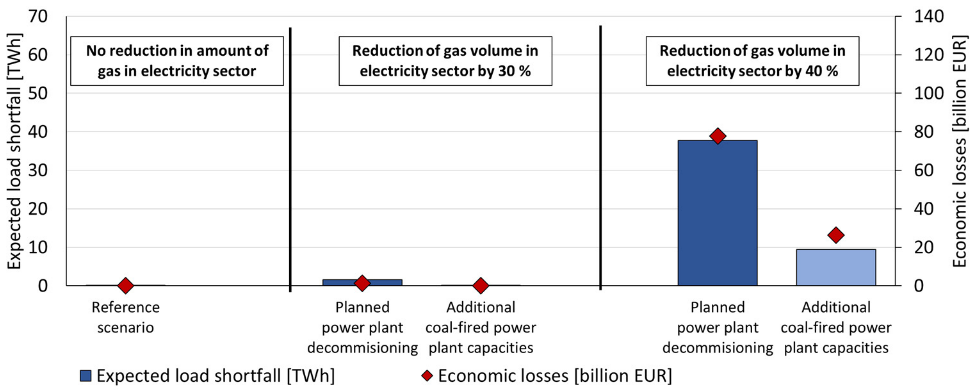

Figure 8. Expected electricity not served and economic costs in all scenarios considered.

4. Discussion and Conclusions

Based on a probabilistic analysis of the expected power supply interruptions and an economic analysis of the associated costs, we have investigated various scenarios for the European natural gas supply.

Compared to a reference scenario without quantity restrictions in natural gas consumption for electricity generation, the 30% reduction scenario shows rather moderate effects on the security of electricity supply and economic costs. However, based on our model results, a tipping point seems to be reached when the amount of natural gas used for electricity generation is reduced by an average of 40% compared to the reference scenario: Here, substantial supply interruptions result in shortfalls in electricity supply and associated extensive damages for the European economy of EUR 77.8 billion. The investigation of the sensitivity scenarios has also shown that a delay of planned power plant decommissioning in Europe substantially reduces expected load shortfalls and limits the associated economic damage in the 40 % reduction scenario to EUR 26.4 billion.

The following implications can be derived from the results:

- **Effects of a solidary coordinated natural gas distribution in Europe:** A solidary-based coordinated distribution of the total natural gas available for power generation in Europe could be an effective means to avoid the current limited cross-border power capacities leading to increased national congestions and very high value-added losses in individual countries. Especially for countries with high dependencies on natural gas, increasing the volume of imports under existing trade agreements or creating new import opportunities to these countries could reduce their economic costs.

- **Necessity of coordinating reductions in the power plant fleet at the European level:** The results of the sensitivity studies show that a joint delay of planned power plant decommissioning is in principle an effective measure to increase the security of the electricity supply in the event of reduced natural gas volumes. However, in view of the recent EU sanctions on Russian coal, the availability of increasing imports of hard coal from other exporting countries would have to be urgently examined. In particular, ecological effects from the continued operation of emission-intensive lignite and hard coal-fired power plants would also have to be taken into account.
- **Coordination of natural gas consumption between the electricity sector and other sectors:** Reducing natural gas consumption, especially in the heat and industrial sectors, could increase the amount of natural gas available for power generation in the event of supply shortages, thus supporting the security of the electricity supply.
- **Relevance of European load balancing:** In particular, the very high shortfall quantities in the island state of Ireland show the relevance of the balancing potential in the European interconnected grid. In order to absorb national bottlenecks as efficiently as possible, an intensified expansion of cross-border interconnection capacities is therefore advisable.

The results presented in our study are based on a short-term analysis of current developments. These should therefore be extended by comprehensive studies. Thus, the results shown here are based on technical scenarios in which the amount of non-delivered electrical energy in Europe is minimized. However, minimizing the amount of non-delivered electrical energy probably does not simultaneously lead to a scenario with minimal welfare losses. The impact of a welfare-oriented natural gas allocation on security of supply and economic costs is currently the subject of further research at RWTH Aachen University.

Finally, it should be noted that due to the currently very high natural gas prices, natural gas consumption for power generation has probably already been reduced to a considerable extent for economic reasons alone. When interpreting our results, it should therefore be borne in mind that a certain reduction in natural gas consumption in the power system due to the high natural gas prices in the merit order is thus already implicitly included in our two reduction scenarios.

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Data Availability Statement: The data for hourly useful energy demands used in this study is openly available in Priesmann et al. through https://doi.org/10.6084/m9.figshare.c.5245457 and visualized in an interactive tool accessible through https://jericho-energy.de/e-usage [24]. The data for hourly final energy consumption used in this study are openly available at https://opendata.ffe.de/dataset/final-energy-consumption-of-the-tertiary-sector-extremos-solideu-scenario-europe-nuts-0/ and https://opendata.ffe.de/dataset/final-energy-consumption-of-the-industry-sector-extremos-solideu-scenario-

europe-nuts-0/ [23]. The data for input-output tables used in this study are openly available at https://ec.europa.eu/eurostat/de/web/esa-supply-use-input-tables/data/database [19]. The data for energy balances used in this study are openly available at https://ec.europa.eu/eurostat/de/web/energy/data/energy-balances [2].

Conflicts of Interest: The authors declare no conflict of interest.

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