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**Working Paper**

## Welfare implications of power rationing: An application to Germany

HWWI Research Paper, No. 148

**Provided in Cooperation with:**

Hamburg Institute of International Economics (HWWI)

*Suggested Citation:* Wenzel, Lars; Wolf, André (2014) : Welfare implications of power rationing: An application to Germany, HWWI Research Paper, No. 148, Hamburgisches WeltWirtschaftsInstitut (HWWI), Hamburg

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# Welfare implications of power rationing: an application to Germany

Lars Wenzel, André Wolf

HWWI Research

Paper 148

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**ISSN 1861-504X**

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**February 2014**

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Lars Wenzel, André Wolf

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# 1 | Introduction

Currently, Germany follows one of the most ambitious energy strategies in the world, as it stands on the forefront of the transition towards renewable energy sources. The rapid transformation the electricity sector has experienced in the last couple of years has been a growing reason for concern, as actors in the market struggle to adapt. The nuclear phase-out puts pressure on alternative forms of electricity generation. In 2012, Germany attained as much as 22 per cent of Gross Electricity Production through renewable resources (BMW, 2013). This has become a source of debate, since electricity generation from Wind and Solar energy is volatile and difficult to predict. Furthermore, storage capacities are not yet sufficiently developed. Grid operators in particular have been challenged and are increasingly forced to intervene to avoid system failures, because the balance between electricity supply and demand becomes difficult to maintain. These interventions start with routine measures like the use of balancing energy. In case of more serious threats, line voltages are adjusted and single major power plants or electricity consumers (e.g. energy-intensive manufacturers) are disconnected on short term. If all these measures prove insufficient, a region-wide intervention can become necessary. In the situation of a shortage in electricity supply, this can take the form of spatial rationing.

In 2012, EnBW as one of the largest grid operators in Germany announced it would institute regional rolling blackouts, if necessary, as a measure of last resort to prevent a potential grid collapse (Preuß, 2012). Rolling blackouts are a standard rationing procedure to avoid complete blackouts in times of excess electricity demand. They represent a form of load shedding, where single regions or districts within cities are successively switched off for specified periods of time. Based on the principle of equal treatment, the common procedure is to ration regions in a random order (Random rationing). The most prominent examples in the developed world are the rolling blackouts implemented in California in 2000.

From a researcher's point of view, the topic is of interest because estimates of outage costs are crucial to a cost-benefit-analysis for investments in supply security. It is thus important to know the level of cost savings successful rationing can achieve compared to an uncontrolled blackout. In this regard, structural differences across regions imply that random rationing is likely to be inferior to other rationing schemes. An economic analysis thus has to discuss the optimal way of rationing as well. While a bulk of literature has assessed the costs of uncontrolled blackouts, de Nooij et al. (2009) in their simulations for the Netherlands have so far made the only attempt to quantify the cost savings from efficient power rationing in a nation-wide analysis. In their scenario, to maintain system stability, an exogenous level of nation-wide electricity use has to be saved by switching off a sufficient amount of communities during a given time frame.

They show that a rationing order strictly based on the criterion of total cost minimization is associated with cost reductions of 60 to 90 percent compared to a random-based procedure. Terming such a criterion efficient, however, requires the researcher to postulate a strictly utilitarian welfare function where the sum of aggregate costs within all regions represents the correct measure of societal damage. If more emphasis is placed on issues of spatial inequality and the economic burden imposed on single regions, welfare analysis would suggest other concepts of optimal rationing with different consequences.

Based on these thoughts, this paper applies the basic methodology of de Nooij et al. (2009) to a scenario of power rationing in Germany. In a first step, costs of short-run blackouts at county level are estimated based on the dominant production function approach. Then, the costs of rationing strategies are assessed given a nation-wide supply shortage in the German grid. In addition to random rationing and the total cost criterion, we propose two additional criteria for determining an optimal rationing order among counties (minimizing the damage per capita in the worst affected region and minimizing the number of people affected). Beside the issue's current relevance, it is the diverse economic landscape that makes Germany an interesting case to analyze the spatial implications of different rationing regimes. Indeed, the spectrum of results reveals the urgent need to initiate a public debate on the goals of these measures of last resort.

Section 2 outlines the methodology for estimating outage costs for firms and households as well as highlighting relevant literature. Section 3 aims to explore the alternative rationing models and examines their impact. In section 4, a sensitivity analysis is performed in order to test the model under different parameters. The results are discussed in section 5. Section 6 concludes this paper.

## 2 | Estimating the costs of regional power cuts

### 2.1 | Cost estimates at firm level

To assess the consequences of power cuts for firms, researchers have applied a variety of methods. They can be categorized into survey-based approaches (Serra & Fiero (1997); Beenstock et al. (1998); Carlsson & Martinsson (2008)), market-based approaches (Brown & Johnson, 1969; Beenstock, 1991; Bental & Ravid, 1982) and production function approaches (Munashinge & Gellerson, 1979; de Nooij et al., 2007; Linares & Rey, 2012). The latter approach focuses on the role of electricity as an input into the generation of output by firms and utility by households. Blackout costs are

determined as the output decline resulting from the absence of this input. Starting with the seminal contribution by Munashinge & Gellerson (1979), this method has gained increasing popularity for various reasons. In contrast to survey-based approaches, results are less specific to certain incidents and counterfactual scenarios can be assessed. In contrast to market-based approaches, results are obtained at a macroeconomic level and not only for specific consumer groups.

To reduce the amount of required information in a generally data-scarce environment, implementations so far have made use of the simplest setup of linear production functions. These assume a proportional relationship between the levels of output and electricity use. At a regional level, de Nooij et al. (2007) have implemented this approach for municipalities in the Netherlands and Nick et al. (2013) for federal states in Germany. The first step is to compute the ratio between annual output and annual electricity consumption, which is defined as the **Value of Lost Load (VoLL)**:

$$\text{VoLL}_c^s = \frac{\text{GVA}_c^s}{\text{EC}_c^s}, \quad [1]$$

where  $\text{GVA}_c^s$  denotes annual Gross Value Added (in Euros) of sector  $s$  in county  $c$  and  $\text{EC}_c^s$  describes annual electricity consumption (in kilowatt hours (kWh)). In general, the VoLL indicates how much output can be traced back to the use of one kWh of electricity. It is hence a measure of productivity. In order to estimate time specific losses, information on the production intensity at a given time ( $t$ ) is required. Given the proportionality assumption, knowledge of total electricity consumption by firms during that time can be used to deduce total outage costs ( $O$ ):

$$O_{c,t}^s = \text{VoLL}_c^s \cdot \text{EC}_{c,t}^s \quad [2]$$

As discussed by de Nooij et al. (2009), such an approach can be argued to both over- and underestimate the real magnitude of outage costs. An overestimation results from neglecting the existence of backup generators and catch-up effects: firms might be in the position to catch up on delayed production through overtime hours and increased stock-keeping. For the purpose of cross-regional comparisons, we consider this only a minor problem. In general, there is no reason to expect differences in the degree of preparation by firms across regions. Perhaps more serious is a potential underestimation resulting from the specific vulnerabilities of certain production processes. Most prominently, processes in the chemical and the paper industry are highly sensitive to outages, implying that several hours can pass until processes are restarted. Moreover, for blackouts of longer duration, additional contagion effects resulting from disruptions of local supply chains have to be taken into account. The uncertainty involved in damage estimation is thus increasing with the time span of power cuts.



This methodology forms the backbone of the ensuing rationing analysis, by providing the necessary estimates for outage costs. Sector-specific VoLLs are estimated to account for sectoral differences in electricity intensity. We distinguish between manufacturing, agriculture, construction and services. For each German county, these estimates are used as sectoral weights in calculating county-specific VoLLs. In this way, county-specific measures of the average monetary loss resulting from the withdrawal of one kWh of electricity from production are obtained. Regional cost levels are thus influenced by both absolute economic activity and regional sector mixes. To minimize biases resulting from the negligence of indirect effects, we restrict our analysis to blackouts of a standardized length of one hour (see e.g. Bliem, 2007; Reichl et al., 2013). A detailed explanation of the estimation approach and the data sources used is given in Appendix A1.

## 2.2 | Cost estimates at the level of households

Applying the production function approach at household level requires observable proxies for the utility received through electricity consumption. A reasonable proxy suggested by the literature is the pleasure the households gain from electricity-dependent leisure activities. To quantify its extent, information on the average number of hours devoted to leisure as well as on the monetary worth of a single hour of leisure is needed. The former can be deduced from the average number of working hours ( $WH$ ) and the total amount of available hours ( $T$ ). A further restriction is that not all leisure activities require the use of electricity. We attempt to determine the share of electricity-dependent leisure from results of a time use study for Germany undertaken by the Federal Statistical Office (2003). The given leisure activities are classified as electricity- or non-electricity-dependent. In turn, the share of electricity-dependent activities in total leisure time is computed. The result is an estimated share of 0.65. To assess the implication of this choice, it will be modified later on as part of a sensitivity analysis.

To determine the value of one hour of leisure, standard microeconomic theory as pioneered by Becker (1965) is applied. Labor supply is interpreted as the result of a utility maximizing decision in the light of a trade-off between consumption and leisure. The optimality condition is that the marginal benefits of one hour of leisure should equal its costs in terms of foregone labor income. Average net wages per hour ( $W$ ) thus serve as a proxy for the value of one hour (electricity-dependent) leisure time for all employed persons.<sup>1</sup> For unemployed persons, this approximation would seem inappropriate. Part of the reason for their unemployment could be a low potential

---

<sup>1</sup> Strictly speaking, this reasoning only applies to the last marginal hour of leisure consumed: However, accounting for a changing marginal utility would require estimating a household's utility function, which is impossible with the available data.

remuneration and thus lower opportunity costs of leisure. Besides, the presence of involuntary unemployment can lead to an overestimation of the value of leisure, as leisure consumption is higher than optimal. To account for this, we follow de Nooij et al. (2007, 2009) in assuming that the value of each hour of leisure for an unemployed person is 50 per cent that of an employed person. The total value of leisure ( $VL$ ) for an employed ( $emp$ ) and an unemployed ( $uemp$ ) person in county  $c$ , respectively, is thus calculated in the following way:

$$VL_c^{emp} = 0.65 \cdot (T - WH_c) \cdot W_c$$

$$VL_c^{uemp} = 0.65 \cdot T \cdot (0.5 \cdot W_c)$$

Given information on total population size ( $POP$ ) and number of employed persons ( $POP^{emp}$ ), the total value of leisure for all citizens of county  $c$  is thus calculated as:

$$VL_c = VL_c^{emp} \cdot POP^{emp} + VL_c^{uemp} \cdot (POP - POP^{emp}) \quad [3]$$

In analogy to the firm case, we can determine the ratio of this value to total electricity consumption of households at county level and interpret this as a Value of Lost Load for households ( $h$ ) in county  $c$ :

$$VoLL_c^h = \frac{VL_c}{EC_c^h} \quad [4]$$

This measure represents the value of leisure attributable to the consumption of one kWh of electricity. To determine outage costs, information on the time profiles of electricity use has to be added, similar to the firm level. In order to attain the losses resulting from a blackout during time span  $t$ , the VoLL is multiplied by electricity consumption of households during that period:

$$O_{c,t}^h = VoLL_c^h \cdot EC_{c,t}^h \quad [5]$$

Our strategy of applying this framework to derive estimates for household losses in German counties is outlined in Appendix A1.

### 2.3 | Time profiles of electricity use

To determine the absolute costs resulting from blackouts at particular moments in time, information on time patterns of electricity usage has to be added. So-called **load profiles** can inform about the characteristic distribution of annual, monthly and daily electricity consumption. In their rationing analysis for the Netherlands, de Nooij et al. (2009) construct artificial time profiles by postulating certain sectors to be active or inactive during certain time spans. For Germany, we can obtain a more detailed picture. Among the German network operators, E.ON publishes synthetic load profiles derived from its customer data. In these profiles, the given year is split into intervals with lengths of 15 minutes. For each interval, loads are reported in terms of shares in

annual electricity consumption. This allows constructing time patterns of electricity use across months, days and even single hours. Unfortunately, no regional differentiation is provided. We therefore stick to national data for all types of profiles. Regional variation in the time paths of total outage costs is thus purely driven by differences in annual sectoral consumption between regions. To achieve consistency with our data on production and value of leisure time, we choose profiles for the year 2010 for our analysis (E.ON, 2013). The remaining task is to assign sectors to profiles of certain user groups. For households and agricultural production, specific profiles are available. For manufacturing, construction and services, we make use of a non-sector-specific standard commercial profile.

By means of these profiles, formulae [2] and [5] can be applied to compute time-specific blackout costs for the four production sectors and the households in each county. Figure 1 depicts the simulated pattern of total costs for a one hour blackout starting at 12h (with day given as annual average). In addition, the ratio of these total outage costs to total electricity use in a county can be defined as the total VoLL of a county. It represents a weighted average of sectoral and household VoLLs with weights given as sectoral shares in energy consumption. Similar to absolute costs, this value varies over time due to differences in sectoral load profiles. Based on these measures, we are able to estimate the costs of implementing specific rationing schemes in the following section.

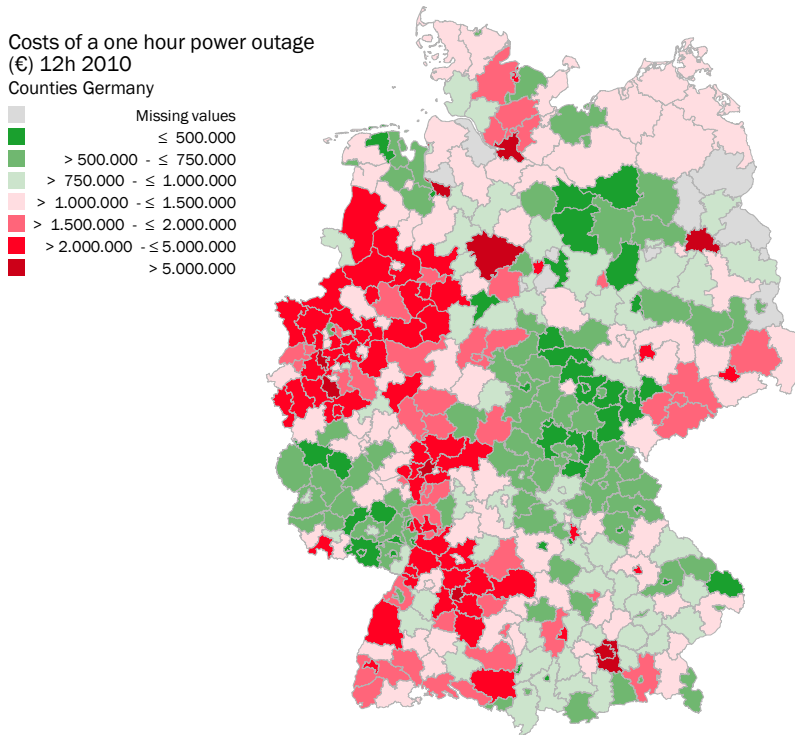
## 3 | Cost assessment of different rationing regimes

### 3.1 | Minimizing total damage

When facing an imbalance in electricity provision in the form of a supply shortage, the last resort for network operators to maintain system stability is to implement a rationing scheme. Load shedding agreements with private enterprises are encouraged, but may prove insufficient. In such a situation, a regional rationing scheme may be implemented to prevent the entire system from shutting down. Most provisions for this scenario date back to the oil crises in the 1970's and aim to implement random rationing or rolling blackouts. Therein regional entities are switched off in a rotating succession in order to evade the massive damages from system collapse.

Figure 1

### Spatial distribution of costs from a one hour blackout at 12pm in German counties



Source: HWWI, own calculations.

Since blackout costs differ significantly between regions, this implies that total costs of this procedure as well as the number of people affected are random variables of considerable range. To achieve better control of costs, a deterministic rationing rule has to be proposed as an alternative. One intuitive goal suggested by de Nooij et al. (2009) would be to minimize the sum of damages over all regions caused by saving a certain amount of electricity. They title this efficient rationing. To avoid confusion with latter welfare concepts for rationing, we refer to it as *de Nooij rationing*. According to this criterion, the order at which regions are switched-off is simply determined by the reverse ranking of Volls. Regions with lowest Volls are switched off first; regions with second-lowest Volls are switched off second etc. until the savings goal is achieved. Absolute electricity use is relevant only insofar as it determines the number of regions to be cut off.

For a comparison of the two criteria, a shortage scenario has to be defined. In Germany, the national electricity grid for long-distance transmission is divided into four network areas operated by different companies. These transmission network operators have the prime responsibility for maintaining system stability. In the case of

serious regional imbalances due to excess demand, it would be their task to implement a spatial rationing scheme provided that all alternative measures (use of balancing energy, demand-side management or voltage reduction) have failed. To evaluate consequences across German regions, this paper considers a nation-wide scenario. Hence, the imposed shortage has to represent a threat that requires a coordinated attempt across transmission grid areas. We therefore consider a fairly high supply shortage of 10 GWh, which roughly amounts to 10 percent of the average nation-wide electricity consumption between 12h and 13h in 2010 (E.ON, 2013). This will also serve to emphasize the differences between rationing regimes.

Table 1

### Damages resulting from a 10 GWh Shortage under de Nooij and random rationing

	Total costs	Citizens affected	Number of interrupted counties	Relative damage
	Mio. Euro	Mio.		%
<b>06:00</b>				
de Nooij	36.9	12.9	66	55.2
Random	66.8	20.0	101	
<b>12:00</b>				
de Nooij	24.4	3.4	15	37.8
Random	64.5	8.3	43	
<b>18:00</b>				
de Nooij	29.8	5.3	26	44.2
Random	67.5	10.9	54	

Source: own calculations; costs of random rationing are calculated as expected damages

In practice, the decision would be whether to switch off certain distribution network areas. These network areas often comprise one municipality. Large cities can host more than one network area. Unfortunately, sector-specific data is not available at the municipal level with the exception of 107 cities that have the administrative rank of counties. In this approach, regions at the next higher level, the level of counties (including the 107 cities), are modelled as network areas. In this way, we divide the German grid into 402 districts, which allows for a sufficiently detailed picture on the distribution of electricity use and economic activity in Germany. The information on load profiles enables us to assess consequences of power rationing for different times of the day. Since the estimations of outage costs are only sensible for short-run interruptions, we consider a time window of one hour in each rationing scenario. This also reflects practical concerns related to infrastructure security in case of longer outages.<sup>2</sup> During this one hour, a set of counties has to be disconnected such that a total

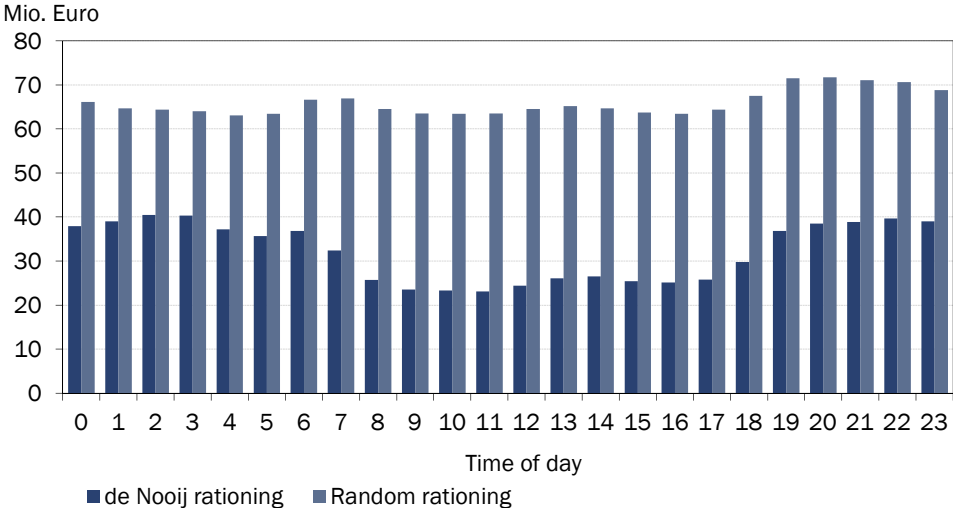
<sup>2</sup> This is different from De Nooij et al. (2010), who consider longer time frames up to 10 hours. Since they assume that a rationed region will be cut off during the full 10 hours, this implies a higher insecurity in cost estimation due to negative externalities (infrastructure, social unrest etc.) or mitigating resilience effects.

of 10 GW of electricity are rationed, i.e. the balance between supply and demand is restored. The sum of outage cost estimates in these counties is then interpreted as the costs of implementing a rationing schedule. In this way, results for each hour of the day are obtained. Table 1 lists the resulting simulation statistics for the two criteria at times 6h, 12h and 18h.

De Nooij rationing offers a considerable cost advantage compared to random blackouts. In the early morning, a cost reduction of 45 percent could be achieved, which goes up to 62 percent at noon. The daily average lies at 51 percent. At the same time, de Nooij requires to switch off a significantly lower number of counties. Around noon, it amounts to only about one third of the number of interrupted counties under a random regime. In this way, the number of citizens affected is significantly lower as well. Figure 2 documents cost levels for all hours of the day. It shows that the increase of the cost advantage in the morning hours is due to a sharp drop in the damage caused by de Nooij rationing, while costs from random rationing show no clear downward trend. This results from the increase in electricity use during this time span. It allows limiting rationing to just a few spots, which in case of de Nooij implies an even better selection of counties and thus lower losses per kWh. These gains could not be realized in a random-based approach, because the probability of a county to be rationed remains constant irrespective of total electricity use.

Figure 2

**Costs from de Nooij and random rationing over the course of the day**



Source: own calculations

### 3.2 | Alternative rationing regimes

The de Nooij criterion judges the desirability of a rationing scheme according to the sum of all resulting production and leisure costs regardless of their distribution among regions or groups of people. In this sense, it represents a strictly utilitarian view. Cost levels of different regions are considered perfect substitutes in welfare terms. This can lead this criterion to favor plans where single regions are strongly burdened. In the simulations, some counties with highly energy-intensive industries were switched off because of their low losses per kWh electricity. Given a high level of industrial activity, total costs for these counties can nevertheless be substantial, where further capital and longer-term damage can add to the immediate production losses (see sensitivity analysis). This might conflict with existing goals of economic policy.

In welfare theory, the Rawls (1971) criterion is a philosophy that rejects distributions where some agents face particularly bad outcomes. It judges a situation solely based on the well-being of the worst-off agent. A corresponding rationing rule is that those regions facing the smallest damages are switched off first, those facing the largest damages last. In this, assessing damages in terms of absolute costs would seem inappropriate: small counties would be rationed first simply because their absolute levels of population and economic activity are low. Rather, the idea of avoiding particularly high damages in single regions could be realized by switching off counties according to the ranking of costs per capita. In this way, economic centers with a high exposure relative to population size would be spared from being rationed. Formally, the welfare goal can be summarized as minimizing the highest damage per capita in a single region caused by rationing. We refer to this as the *MinMax criterion*.

If the focus of policy-makers is on reducing costs for households, a fourth criterion might be preferred: minimizing the number of citizens affected. Accordingly, the optimal way of balancing out a supply shortage is to ration counties with highest electricity use per capita first. In this way, the savings goal can be achieved by switching off the smallest number of residents. We refer to this as the *MinPeople criterion*.

To compare the two alternative criteria with total cost minimization, the same scenario as above is simulated, where 10 GW are to be rationed over a one hour period. Table 2 reports results in terms of total damage, highest damage per capita in a single region as well as number of interrupted counties and people.

Table 2

**Results under alternative rationing regimes**

	Total costs	Highest regional costs per capita	Number of affected citizens	Number of interrupted counties
	Mio. Euro	Euro	Mio.	
<b>06:00</b>				
de Nooij	36.9	5.9	12.9	66
MinMax	58.0	2.8	23.8	141
MinPeople	46.1	7.0	11.5	46
<b>12:00</b>				
de Nooij	24.4	14.0	3.4	15
MinMax	54.0	5.4	11.1	68
MinPeople	25.2	15.7	3.2	16
<b>18:00</b>				
de Nooij	29.8	10.9	5.3	26
MinMax	59.7	4.8	14.2	90
MinPeople	36.4	12.7	5.0	21

Source: own calculations

In line with expectation, rationing according to Rawls is associated with significantly higher total costs than rationing according to de Nooij for all periods of time considered. The MinMax criterion preferably rations counties with weak economic activity, as this means low outage costs per capita. However, this does not imply that they exhibit small losses per unit of electricity consumed. In fact, VoLLs in many of these counties are rather high, due to the absence of energy-intensive industries. The second figure in Appendix A2 maps the German counties rationed by MinMax. In our simulation scenario, large parts of East Germany would have to participate in the rationing scheme, since less productive capacity and household leisure is at stake there. As a consequence, the maximum costs per capita borne by a single region are during all three time periods less than half as large as for the other criteria. Given that these counties consume a low amount of electricity, the total number of counties that have to be interrupted is at the same time significantly higher.

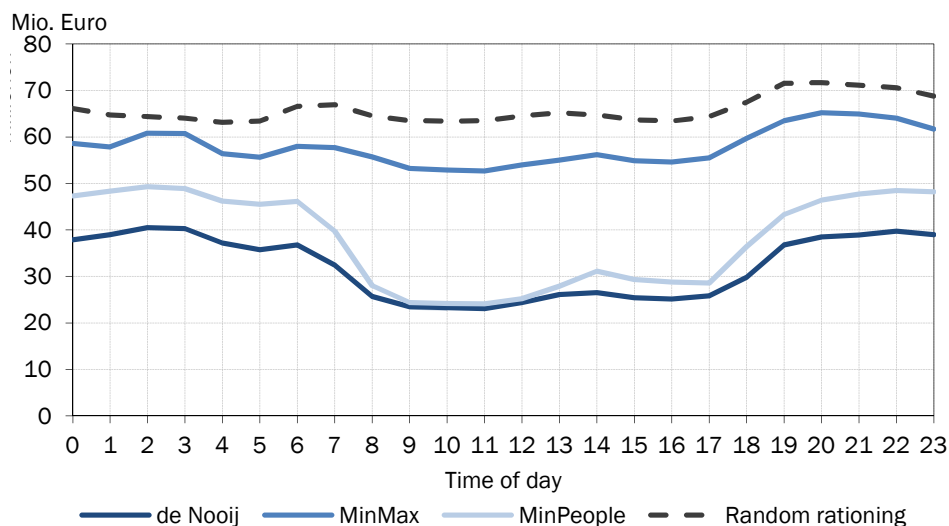
The MinPeople criterion also imposes higher total costs on society than de Nooij, as it is not focused on actual losses per kWh. At the same time, total costs are lower than for MinMax. The reason is that many of the counties with the highest levels of electricity use per capita are also characterized by low VoLLs. As a consequence, the pattern of rationed counties is similar (see figures in Appendix A2). Moreover, maximal regional damage per capita is the highest among all three criteria, given that the rationed counties also generate a high level of Gross Value Added. Since single regions contribute much to the savings goal, the number of interrupted regions is also



much lower than for MinMax. All three approaches reduce societal costs relative to random rationing.

Figure 3

### Costs of alternative rationing regimes during the day

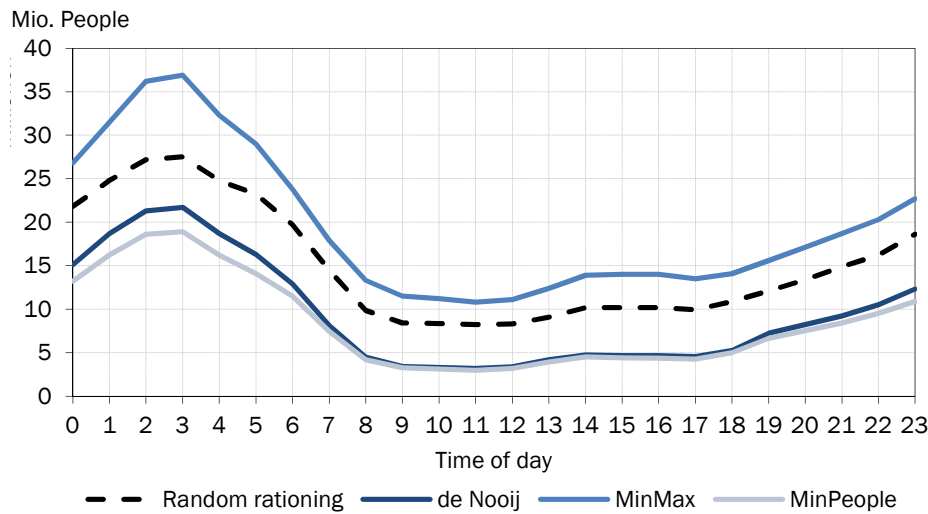


Source: own calculations

The criteria also differ concerning their sensitivity to the point in time at which a one hour rationing plan is implemented. Figure 3 shows the distribution of total costs throughout the day. While damages caused by de Nooij and MinPeople rationing diminish significantly from the period of early morning until noon, the MinMax criterion shows considerably less variation over time. This is the case even though the number of interrupted counties and affected citizens decreases during that time period for MinMax as well. The solution lies in the change of average VoLLs among the counties interrupted. For the de Nooij criterion, a reduction in the number of rationed counties implies a lower average VoLL and thus lower total costs, since counties are switched off according to the VoLL ranking. The MinPeople criterion undergoes a similar development because both criteria would focus on the same small set of highly energy-intensive counties during the morning hours. These regions, however, would never be rationed according to MinMax, as losses in single regions would prove too high.

Figure 4

### Number of people affected by various rationing regimes



Source: own calculations

## 4 | Sensitivity analysis

Given a data-scarce environment, our results are based on a range of assumptions. It is therefore important to analyze the response to changes to the most critical ones. This applies to both firm and household side. First, as discussed above, our exclusive focus on production losses as sources of outage costs at firm level neglects potential losses due to asset destruction in electricity-intensive manufacturing. To become aware of the consequences of omitting this cost category, we perform a sensitivity check by raising losses per kWh in the manufacturing sector in each county by 50 percent. Second, the electricity-dependence of leisure activities is subject to uncertainty. Some areas like social exchange are only partially reliant on electricity and their benefits could thus be maintained to some degree in the course of a blackout. An overestimation might also result from the substitutability of some activities in time. Implications of this for outage cost estimation are assessed by calculating costs under the assumption of a 50 percent lower share of electricity-dependent activities compared to the baseline scenario.

On the other hand, the assumption that the value of one hour of leisure for an unemployed person is exactly half of that for an employed person might represent an underestimation. In the terminology of the production function approach, leisure does not only encompass recreational activities, but also electricity-dependent chores like washing clothes and cooking, which are of equal importance for any self-reliant individual independent of employment status. Delays in these activities due to power

outages should thus cause similar declines in well-being. In the following, we examine the sensitivity of our calculations in this direction by assuming unemployed persons to receive 75 percent (instead of only 50 percent) of the utility employed persons receive from one hour of leisure. Hence, we implement the following three modifications:

*Modification 1: 50% higher losses per kWh in manufacturing in each county*

*Modification 2: 50% lower losses per kWh for households in each county*

*Modification 3: 50% higher losses for unemployed persons in each county*

Table 3

**Counties with highest and lowest outage costs per capita for base case and two modified scenarios**

12:00	Total costs	Highest regional costs per capita	Citizens affected	Number of interrupted counties
	Mio Euro	Euro	Mio.	
<b>Base case</b>				
Random	64.5	-	8.3	43
de Nooij	24.4	14.0	3.4	15
MaxMin	54.0	5.4	11.1	68
MinPeople	25.2	15.8	3.2	16
<b>Alternative 1</b>				
Random	69.1	-	8.3	43
de Nooij	26.9	17.5	3.5	17
MaxMin	60.1	5.8	11.6	74
MinPeople	28.2	19.2	3.2	16
<b>Alternative 2</b>				
Random	53.0	-	8.3	43
de Nooij	19.7	12.2	3.5	17
MaxMin	43.0	4.3	11.2	70
MinPeople	20.6	14.1	3.2	16
<b>Alternative 3</b>				
Random	75.3	-	8.3	43
de Nooij	28.8	15.6	3.4	16
MaxMin	63.7	6.4	10.9	67
MinPeople	29.8	17.3	3.2	16

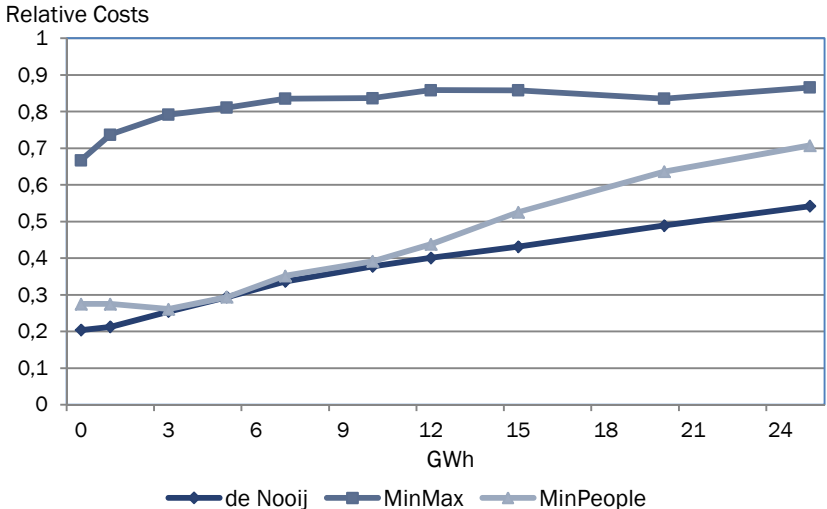
Source: own calculations

Table 3 documents responses to the modifications for the exemplary case of rationing at 12h. Modification 1 implies that the number of regions to be switched off slightly increases for de Nooij and MaxMin compared to the base case. The reason is that, due to an increase in their VoLLs, some highly energy-intensive counties are now spared from being rationed, requiring their replacement by a larger amount of counties

with lower levels of electricity use. Modification 2 is similarly associated with a small rise in the number of rationed counties for basically the same reason: the weights of household losses in total damage estimation shrink compared to production losses. Apart from these, the three modifications do not entail notable changes to the prevailing differences.

Furthermore, the results presented in section 3 depend strongly on the amount of electricity to be saved. This is most apparent for de Nooij rationing, where a smaller amount would decrease the average VoLLs of the counties to be switched off. Conversely, following a more ambitious savings goal would mean that counties with relatively high VoLLs have to be switched off additionally. In contrast, as the selection under random rationing is unaffected, cost increases are proportional there. To illustrate this phenomenon, Figure 5 plots the costs of rationing regimes across a spectrum of amounts to be saved between 12h and 13h. The costs are listed relative to random rationing.

Figure 5  
**Costs of alternative rationing regimes relative to random rationing between 12h and 13h**



Source: own calculations

All three approaches are the most effective the smaller the amount to be rationed. De Nooij rationing provides as much as an 80 percent advantage over random rationing when 1 GW needs to be rationed for the hour. This value drops to below 50 percent as the amount to be rationed is expanded to 25 GWh. MinPeople follows a similar pattern and actually comes quite close to de Nooij between 3 and 10 GWh. However, it does worse before and after that range. The MinMax regime allows for as much as 30 percent gain over random rationing, when little electricity is to be rationed. This gain becomes little more than 15 percent when rationing exceeds 10 GWh.

## 5 | Discussion

Our results indicate considerable savings potentials from applying purposeful instead of purely random-based rationing plans in case of temporary power shortages. However, pure knowledge of this fact will not suffice to get them implemented. Potential obstacles both relate to feasibility and political enforceability. Practical implementation can impose considerable information and coordination costs on transmission network operators. From a societal perspective, a critical task is to agree on a rationing criterion. There will be disagreement about the fairness of concepts. On a practical level, the task is rendered difficult because regions are affected very differently by different criteria. Hence, there will always be people from certain regions who oppose a certain criterion particularly strongly.

In this regard, the criterion of total cost minimization proposed by de Nooij (2010) seems promising. Its principle is intuitive and thus easy to communicate. At the same time, opposition in the population might be weaker than against the Rawls criterion, as the savings goal could be achieved by switching-off considerably less people. This second aspect of course holds for the MinPeople-criterion as well. In fact, results for both criteria are in our scenario of a country-wide allocation of savings quite similar. A likely issue with both criteria is that they might be considered unfair, especially by those rationed. As discussed above, while they seek to mitigate the consequences of power shortages for society as a whole, they set no limit to the potential damage done to single regions or certain groups of people.

This is different with the Rawls criterion. Even though it proposes to switch off significantly more regions, opposition among public representatives and lobbyists might be weaker for two reasons. First, maximal damage in the single regions is smaller (both in per capita and absolute terms), implying lower incentives to invest into lobbying. Second, in contrast to the other criteria, Rawls rationing exhibits a strong spatial concentration in our simulation scenario, implying that large parts of the country are exempt from participation. However, the strong spatial divide would certainly provoke allegations of a systematic discrimination of the East, which are likely to obscure any objective debate on the desirability of rationing plans.

## 6 | Conclusion

This study sets out to explore various regimes of power rationing and assess their societal impacts with random-based rationing as a benchmark. The assessment is based on hourly outage costs of firms and households, which are used to estimate the damages resulting from saving a given amount of electricity. The significant dispersion

in outage costs and VoLLs across counties suggests that there is an economic case to be made for rational rationing, i.e. a non-randomized allocation of scarce electricity in times of high loads. Clearly, counties with higher VoLLs are able to yield a higher societal return from a given unit of electricity, both in terms of output and consumption-related leisure. Even for the large shortage in electricity in our scenario, average gains of 51 percent against random rationing are found for de Nooij rationing. At noon, these savings are as large as 62 percent. Cost reductions over random rationing would be even larger if less electricity had to be saved. The alternative MinPeople criterion performs nearly as well in terms of damages and slightly better in terms of people affected. MinMax rationing appears to be the most contentious scheme investigated. Here, the number of people affected exceeds random rationing. Furthermore, strong regional clustering results, while the outage costs are only slightly lower than for random rationing.

The results presented open up various avenues for further research. Variations on the duration of blackouts might be of interest, in particular, when a rotation schedule is included to prevent the same county from being switched off for extended periods at once. Additionally, a separation of households and firms might prove insightful, for example in a scenario where only firms or only households ought to be taken off the grid.

Concerning the policy conclusions, it has to be stressed that a successful energy policy would render such extreme measures obsolete. Under extreme conditions, rationing is nonetheless preferable to a system collapse. It is hence worthwhile to contemplate various approaches. In practice, however, it will be difficult to agree upon a non-random approach, as resistance from affected regions is to be expected. Furthermore, the criterion by which to ration would have to be formalized and a methodology for its determination established. The de Nooij criterion represents an intuitive starting point, but is not without flaws. Capital damages and knock-on effects are abstracted from, but might be substantial. Furthermore, calculations have to rely on past data. Notwithstanding these issues of practicability, our simulations offer some interesting insights against the background of current concerns on energy security in Germany. Given the volatility of renewables and the ongoing shut-down of conventional power plants, these concerns are understandable. Clearly, the German electricity grid faces unprecedented, but not insurmountable, challenges.

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## 8 | Appendix

### A1: Derivation of outage cost estimates

The Federal Statistical Office (2013) in Germany regularly publishes county-level data on annual Gross Value Added and annual electricity consumption in the manufacturing sector. Based on this data, we start with calculating county-specific VoLLs for the year 2010 for this sector. This enables us to account for regional differences in energy intensity, which are partly due to specialization in certain subsectors. For all remaining sectors, the lack of data on electricity consumption implies that county-specific values cannot be created. To arrive at an aggregate cost measure for the regional economy, we therefore resort to the strategy applied by Bliem (2005) and Nick et al. (2013) at federal state level and adopt national VoLLs for the regional analysis. Remaining activities are split into three sectors: agriculture, construction and services. For these aggregations, annual electricity consumption at national level is published in the national energy balances. We use this information together with national data on GVA to calculate national VoLLs for 2010, resulting in values of 1.98 €/kWh for agriculture, 118.15 €/kWh for construction and 10.16 €/kWh for services. As should be expected, ranges of these measures are all in line with the results of Nick et al. (2013) for 2007. Regional economies with a focus on service-related activities are thus likely to exhibit higher VoLLs for production in total, as an immediate implication of their lower energy intensities.

Transferring national VoLLs for the non-manufacturing sectors to the regional level can be expected to cause only minor biases: differences in energy intensities between subsectors are considerably lower than within manufacturing and their overall shares in electricity consumption tend to be smaller as well. Dividing sectoral production at county level by national VoLLs provides us with estimates on sectoral electricity consumption at county level (see formula [2]). For each county, these estimates then enter the calculation of a weighted mean of the sectoral VoLLs as sectoral weights. In this way, we obtain county-specific measures of the average monetary loss resulting from the withdrawal of one kWh of electricity from production.

To determine the household VoLLs, estimates of the individual benefits from leisure have to be added. The amount of available hours  $T$  is also taken from the time use study. It estimates the average time needed for essential activities like sleeping and eating to comprise about 12 hours a day, leaving average consumers an amount of  $T = 12 \cdot 365 = 4380$  hours per year to allocate between work and leisure. Applying formula [3] requires additional information on numbers of employed persons as well as on average values for hourly net wages and working hours. In drawing these figures from official statistics, we have to be aware that information is required according to place of residence, not place of work: the focus is on persons actually living in a region,

since they enjoy their leisure time there. Data on the number of employed persons is readily available from the regional database of the Federal Statistical Office. The number of unemployed persons is thus also easily gained by figures on population size.

Still missing are numbers for average wages and working hours by place of residence. This data would require perfect information on bilateral commuter flows between all counties in Germany. With respect to wages, we consider this only a minor problem, since commuters do not tend to travel long distances and wage differences between neighboring counties are generally low. Therefore, we choose the average hourly net wage paid within a county in 2010 as a measure of the opportunity costs of one hour leisure time for all employed residents of that county. Since tax payments and social insurance contributions made up about 50 percent of gross labor income in Germany, this value is approximated as one half of the average hourly gross wages reported in the regional database.

#### *Estimation of electricity-dependent leisure time*

Table A1

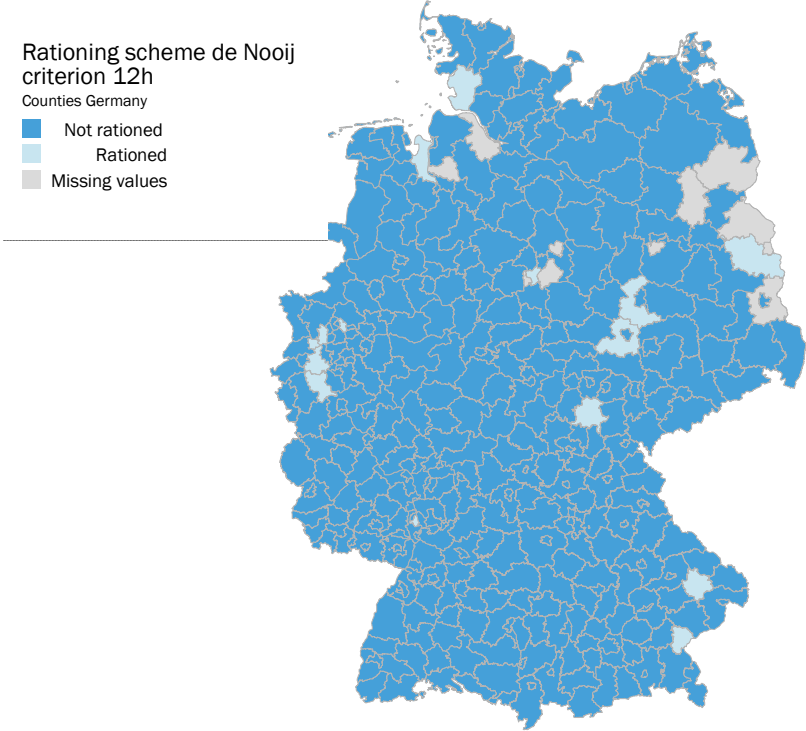
#### **Duration of leisure activities per day as reported in the time use study for Germany**

Field of activity	Subfield	Average duration (h)	classified as electricity-depende
<b>Housekeeping</b>	Preparation of meals	0:45	yes
	House cleaning	0:36	yes
	Washing clothes	0:15	yes
	Garden work and construction	0:30	no
	Household organization	0:37	no
	Caretaking of family members	0:39	no
<b>Social life</b>	Voluntary work	0:24	yes
	Social exchange and culture	2:00	yes
	Sports	0:34	no
<b>Hobbies and media</b>	TV, radio and computer	2:17	yes
	Reading	0:37	no
	Hobbies	0:23	no
<b>Sum</b>	<i>Total</i>	<i>9:37</i>	
	<i>Electricity-dependent</i>	<i>6:17</i>	
	<b>Share</b>	<b>0.65</b>	

Source: Federal Statistical Office (2003)

Concerning the number of working hours per resident, differences between neighboring counties are more pronounced as a consequence of commuter flows. Applying data on working hours by place of work would thus clearly understate the performance of persons residing in counties with a net outflow of commuters. To avoid this, we approximate the number of working hours of residents in 2010 by computing the ratio of total working hours over number of employed persons **working** in a county and multiply this ratio by the number of employed persons **living** in that county (with data again taken from the regional database). The underlying assumption is that a commuting resident works on average approximately the same amount of hours as a local worker. Finally, these estimates allow us to compute the Value of Lost Loads at household level according to formulae [3] and [4].

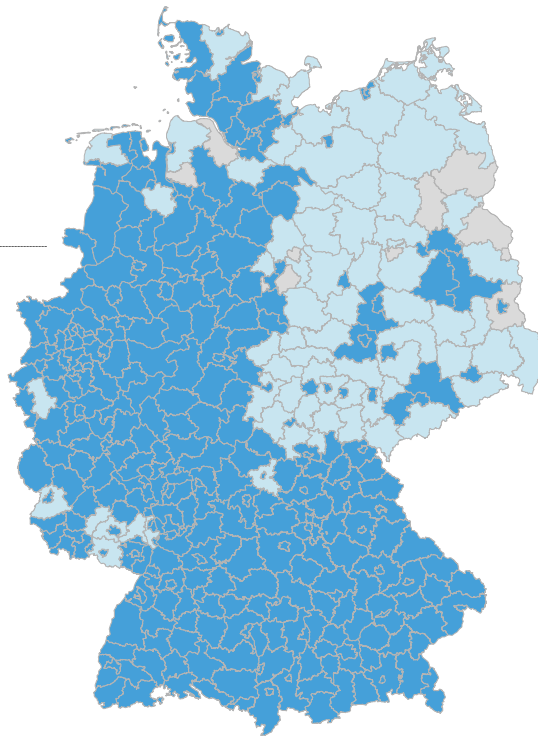
A2: Alternative rationing criteria



Source: HWWI.

Rationing scheme  
Minmax criterion 12h  
Counties Germany

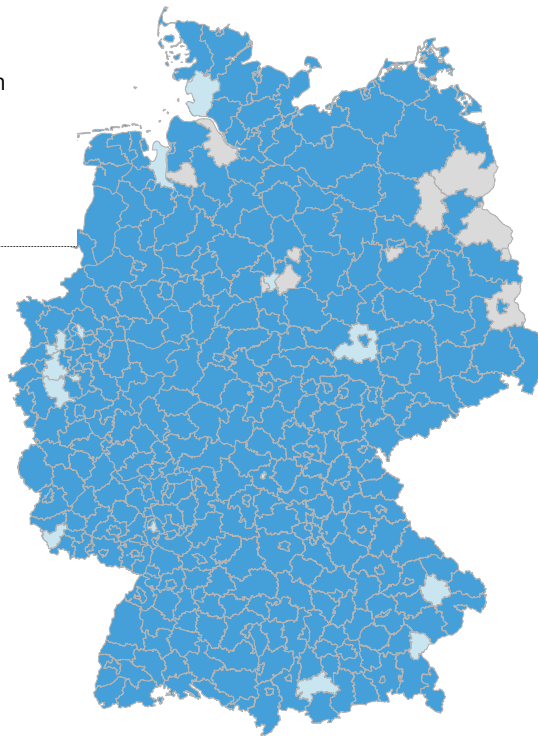
- Not rationed
- Rationed
- Missing values



Source: HWWI.

Rationing scheme  
MinPeople criterion 12h  
Counties Germany

- Not rationed
- Rationed
- Missing values



Source: HWWI.

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