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Welfare implications of power rationing: An application to Germany

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ABSTRACT

This study analyzes the economic consequences of power rationing at the level of German counties. Based on a common production function approach, it estimates the costs of power outages for firms and households in all counties and uses these estimates to derive hypothetical rationing plans for the scenario of a country-wide shortage of power supply. Rationing plans are introduced according to several criteria: a random-based approach, a criterion of total cost minimization, a criterion minimizing costs of the most affected region as well as a criterion minimizing the number of people affected. The implementation of each criterion is simulated for different times of the day. The spatial patterns of rationing prove to be heterogenous. Estimated cost structures differ to some extent as well. The results are discussed with regard to their enforceability in the context of the German energy transition.

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 percent of Gross Electricity Production through renewable resources. 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. 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. [1] 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 60–90 percent compared to a random-based

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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. [1] 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).

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. Evaluation method

To assess the welfare consequences of power cuts, researchers have applied a variety of methods. They can be categorized into survey-based approaches [2–4], market-based approaches [5–7] and production function approaches [8–10]. The first two intend to determine the willingness to pay of electricity users to avoid the occurrence of blackouts. Survey-based attempts seek to ascertain this willingness in a direct manner by means of questionnaires. Market-based approaches instead judge the value of supply security based on actual market behavior. Brown and Johnson [5] were the first to suggest an estimate of consumer surplus on the electricity market as a proxy for outage costs. This requires estimating demand functions by observing demand sensitivities in response to changes in electricity prices. However, in addition to problems of data availability and estimation techniques, this approach has also been criticized on conceptual grounds. The observed willingness-to-pay for electricity does not capture the pleasure received from all the activities complementary to electricity use, therefore tends to underestimate welfare losses from power outages [11].

In contrast, production function approaches do not directly deduce outage costs from revealed preferences, but from linkages between macroeconomic figures. 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 Munasinghe and Gellerson [8], 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.

2.2. Cost estimates at firm level

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. [9] have implemented this approach for municipalities in the Netherlands and Nick et al. [12] 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)**:

$$\mathrm{VoLL}_c^s = \mathrm{GVA}_c^s / \mathrm{EC}_c^s\ ,$$

where GVA_c^s denotes annual Gross Value Added (in Euros) of sector s in county c and 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):

$$\mathrm{O}_{c,t}^s = \mathrm{VoLL}_c^s \cdot \mathrm{EC}_{c,\,t}^s \tag{1}$$

As discussed by de Nooij et al. [1], 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 1 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 1 h (see e.g. Refs. [13,14]). A detailed explanation of the estimation approach and the data sources used is given in Appendix A.

2.3. 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