Energy Economics 43 (2014) 63–71

Contents lists available at ScienceDirect

Energy Economics

journal homepage: www.elsevier.com/locate/eneco

The impact of heat waves on electricity spot markets

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ARTICLE INFO

Article history:
Received 5 July 2013
Received in revised form 10 February 2014
Accepted 16 February 2014
Available online 24 February 2014

JEL classification:
Q41
Q54

Keywords:
Electricity market
Heat wave
Germany
Climate change

ABSTRACT

Thermoelectric power plants depend on cooling water drawn from water bodies. Low river run-off and/or high water temperatures limit a plant's production capacity. This problem may intensify with climate change. Our study quantifies the impact of forced capacity reductions on market prices, production costs, consumer and producer surplus, as well as emissions by means of a bottom-up power generation system model. First, we simulate the German electricity spot market during the heat wave of 2006. Then we conduct a sensitivity study that accounts for future climatic and technological conditions.

We find an average price increase of 11% during the heat wave 2006, which is even more pronounced during times of peak demand. Production costs accumulate to an additional but moderate 16 m. Due to the price increase, producers gain from the heat wave, whereas consumers disproportionately bear the costs. Carbon emissions in the German electricity sector increase during the heat wave. The price and cost effects are more pronounced and increase significantly if assumptions on heat-sensitive demand, hydropower capacity, net exports, and capacity reductions are tightened. These are potential additional effects of climate change. Hence, if mitigation fails or is postponed globally, the impacts on the current energy system are very likely to rise. Increases in feed-in from renewable resources and demand-side management can counter the effects to a considerable degree. Countries with a shift toward a renewable energy supply can be expected to be much less susceptible to cooling water scarcity than those with a high share of nuclear and coal-fired power plants.

1. Introduction

The role of fossil-fuel power plants in causing climate change has been investigated and discussed in-depth. The repercussions of a changing climate on electricity production and markets have, however, received less attention in the research to date. Owing to the dependency of steam power plants on cooling water, an increasing frequency or intensity of heat waves can have significant effects on the electricity sector. During hot periods, not only does the cooling water drawn from freshwater reservoirs become physically scarce; the discharge and temperature of effluent water also fall under legal restrictions protecting aquatic ecosystems (e.g., EU Freshwater Fish Directive, 78/659/EEC). Under heat wave conditions, many of these legal standards mandate a reduction in power generation. This was the case during the European heat waves of 2003 and 2006 (Strauch, 2011). The forced capacity reductions affect a range of key variables, from electricity prices to production costs, and may have different impacts on consumers and producers. During the 2006 heat wave, electricity spot market prices reached € 2000 per megawatt hour (MWh) at the European Energy Exchange (EEX), compared to their usual price of € 50 per MWh (EEX, 2012). Past heat wave impacts have not been quantified in the literature to date, except in studies of the European agricultural sector (Eisenreich et al., 2005). Yet evaluation of the impacts and resulting costs is crucial for informed decision-making in both industry and politics, especially against the backdrop of accelerating climate change.

The impact of increasing river temperatures and of decreasing water flows on electricity production has been analyzed in numerous studies of recent years (Koch and Vögele, 2009; Linnerud et al., 2011; Mideksa and Kallbekken, 2010; Pechan et al., 2011; Rübbelke and Vögele, 2011; van Vliet et al., 2012). Efforts to quantify the economic effects of forced capacity reductions on individual power plants have produced wide-ranging estimates: Förster and Lilliestam (2010) found annual income losses between 5.2 m and 81 m for a (nuclear) power plant; Koch et al. (2012) reported cumulative losses of between 15 m and approximately 60 m for all power plants in Berlin between 2010 and 2050. Most of the existing studies do not endogenize electricity market prices. Exceptions are Golombek et al. (2012), van Vliet et al. (2013) and Rübbelke and Vögele (2013), who simulated climate change impacts based on energy system scenarios, finding only minor price effects for Germany. These studies, however, focused on future average temperatures and not on weather extremes. To our knowledge, the relation between river temperatures and base load prices has only been investigated in one econometric analysis up to now (McDermott and Nilsen, 2011). A reference case based on historic data that also provides insights into the cost incidence of heat waves for producers and consumers is therefore missing. Furthermore, with the exception of Golombek et al.

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http://dx.doi.org/10.1016/j.eneco.2014.02.006
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(2012), additional heat wave impacts on the electricity sector such as reduced hydropower availability or effect on imports and exports have not been tested for or analyzed separately. Finally, to our knowledge the effect of forced capacity reductions due to heat waves on carbon dioxide emissions has not been examined in the literature so far.

In this paper, we try to fill these gaps. We apply a bottom-up simulation model of the German electricity wholesale market to examine the effect of forced capacity reductions. We start from historic data on the German heat wave of July 2006, and perform an extensive sensitivity study (i) to validate the robustness of the results and (ii) to determine how market impacts may depend on climate change and on a transformation of the energy system.

Our simulation results show that forced capacity reductions have a substantial impact on prices, which rose on average by 11% during the heat wave. As a consequence, total producer surplus increased, whereas consumer surplus decreased notedly. Production costs and carbon dioxide emissions in the German electricity sector increased moderately during the heat wave. The sensitivity analyses show that if further heat-induced effects are taken into account, e.g., increased electricity demand, or if heat waves become more intense in the future due to climate change, these impacts are more pronounced. Rising feed-in from renewable resources and improved demand-side management can counter the effects to a considerable degree.

In Section 2, we introduce the model and give an overview of the data used and scenarios applied. In Section 3, we show the results of the 2006 heat wave. The results of the sensitivity analyses are presented in Section 4. In Section 5, we discuss the results and conclude.

2. The model and data

2.1. Theoretical model

In the following, we present a theoretical model illustrating the main effects of reduced thermal capacity on the electricity market. We assume a market with perfect competition where producers bid at variable production costs. Each producer operates only one power plant. The market price is determined by the marginal costs of the most expensive power plant necessary to cover demand. Producers are able to make profits when the market price exceeds their variable costs. Profits are used to cover capacity costs.[1] Fig. 1 gives a stylized overview of the effects.

The inverse demand for electricity is denoted by $D(q)$, where q is the quantity of power. Demand is assumed to be price-inelastic in the short term. $S_{nhw}(q)$ is the domestic electricity supply without capacity reductions, $S_{hw}(q)$ is the supply with capacity reductions. The suffix *hw* denotes the heat wave situation, while *nhw* signifies the undisrupted situation without a heat wave. The market price is represented by p. Power plants are denoted $i = 1,\ldots,N$ and produce a power output q_i each, subject to a capacity constraint, $q_i \leq q_i^{max}$, with variable production costs c_i. The sum of generation costs is represented by C. All these variables are positive.

Under undisturbed conditions, the market equilibrium leads to the electricity price p_{nhw}. Due to the scarcity of cooling water, the capacity of several plants is temporarily reduced, causing a supply gap of Δq. This gap has to be closed by power plants located further to the right in the supply curve, i.e., plants with higher production costs.[2]

Power plant operators maximize profits, regarding fixed costs as sunk. The sum of producer surplus, PS, is given by

$$PS = \sum_{i=1,\ldots,N} (p - c_i) q_i. \tag{1}$$

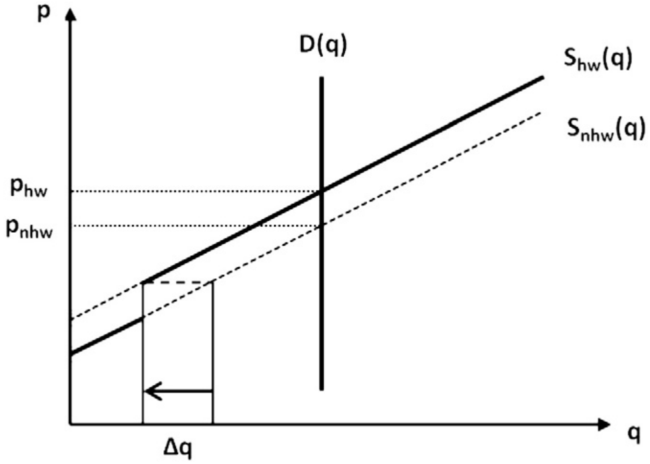

Fig. 1. Effects of capacity reductions on market equilibrium and prices.

The sum of generation costs, C, is

$$C = \sum_{i=1,\ldots,N} c_i q_i \tag{2}$$

The total of consumer surplus, CS, is defined as the difference between willingness to pay, represented in the demand curve, and the market price. Since demand is inelastic, CS changes during the heat wave by

$$\Delta CS = p_{nhw} \sum_{i=1,\ldots,N} q_{i,nhw} - p_{hw} \sum_{i=1,\ldots,N} q_{i,hw} \tag{3}$$

It is evident from the partial equilibrium analysis that the electricity price increases due to the capacity reductions. With increasing prices, consumer surplus decreases, since $\sum_i q_{i,nhw} = D = \sum_i q_{i,hw}$. Since the supply gap is closed by plants that have higher variable production costs c_i, the sum of generation costs C unambiguously increases by

$$\Delta C = \sum_{i=1,\ldots,N} c_i q_{i,hw} - \sum_{i=1,\ldots,N} c_i q_{i,nhw}. \tag{4}$$

The effect on the surplus of a single power plant is generally ambiguous. It changes during the heat wave by

$$\Delta PS_i = (p_{hw} - c_i) q_{i,hw} - (p_{nhw} - c_i) q_{i,nhw}. \tag{5}$$

If production q_i were identical in both situations, then ΔPS_i would be positive: the producer can sell the same quantity at higher prices. Yet in cases where $0 < q_{i,hw} < q_{i,nhw}$, the effect on the producer surplus earned by a single power plant could be either positive or negative. The direction of the overall effect depends on the magnitude of the price and the quantity effect. The smaller the difference in production and the higher the price increase, the more likely it is that ΔPS_i is positive. Two extreme cases have straightforward effects on a single power plant's producer: if $q_{i,hw}$ is zero (positive) and $q_{i,nhw}$ positive (zero), then ΔPS_i is negative (positive).

The effect on total producer surplus PS does not depend on the quantity effect since the total amount of energy remains unchanged when demand is price inelastic. Given a linear supply curve as depicted in Fig. 1, total producer surplus increases or at least remains unchanged in any case. However, the real supply curve or merit order is not a linear but a step function with a roughly convex shape at medium to high demand. Therefore, the total effect on PS can be either positive or negative. Total producer surplus clearly increases when only the marginal power plant has to reduce production and is replaced by a plant with substantially higher costs, e.g. in times of high demand. Then the price increases

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[1] Capacity costs are not considered here.

[2] These considerations also hold if multiple power plants are curtailed, no matter whether they are adjacent in the merit order.