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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. To what extent do such capacity reductions affect electricity spot markets? Who bears the consequent costs? How is this influenced by climate change and a change in the electricity generation system? We quantify these effects by means of a bottom-up power generation system model. First, we simulate the German electricity spot market during the heat wave in 2006, and then conduct a sensitivity study that accounts for future climatic and technological conditions.

We find an average price increase of 11%, which is even more pronounced during times of peak demand. Production costs accumulate to additional but moderate €15.9 m during the two week period. Due to the price increase producers gain from the heat wave and consumers disproportionately bear the costs. Carbon emissions increase during the heat wave. The price and cost effects are more pronounced and significantly increase if assumptions on heat-sensitive demand, hydro power 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 to renewable energy supply can be expected to be much less susceptible to water scarcity than those with a high share of nuclear and coal-fired power plants.

Keywords: Electricity Market, Heat Wave, Germany, Climate Change

JEL: Q41, Q54

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1 Introduction

The role of fossil power plants in causing and mitigating climate change has been elaborated in depth. But how are electricity production and markets affected by a changing climate? In particular, the effects of an increasing frequency or intensity of heat waves for the electricity sector can be remarkable. For example, already during the European heat waves in the summers of 2003 and 2006, several power producers had to cut their production (Strauch, 2011). This was caused by legal water use restrictions and/or scarce cooling water. Thermoelectric power plants that are located inland depend on cooling water for production drawn from rivers, nearby lakes or other freshwater reservoirs. To protect aquatic ecosystems from thermal pressure, standards have been established that restrict the discharge and temperature of the effluent water (e.g. EU Freshwater Fish Directive, 78/659/EEC). Under heat wave conditions, these standards can require to reduce power production. During the 2006 heat wave, record electricity spot market prices of € 2,000 per megawatt hour (MWh) were registered at the European Energy Exchange (EEX), which are usually about € 50 per MWh (EEX, 2012). Climate projections for Germany show that water scarcity and high river temperatures will most likely intensify in the future (Deutschländer and Dalelane, 2012). This is also projected for other European and international locations.

This paper seeks to quantify the impact of capacity reductions of thermal power plants on the electricity market with an energy system simulation model. We aim at shedding more light on how heat waves affect prices, consumer and producer surplus, as well as carbon dioxide (CO_2) emissions. We start from historic data of the heat wave in Germany in July 2006, and perform an extensive sensitivity study to determine how market impacts may depend on climate change and on a transformation of the energy system. The evaluation of impacts and the incidence of its costs are crucial for informed decision making both in industry and politics, especially against the backdrop of climate change.

The impact of both increasing river temperatures and decreasing flows on electricity production has been analyzed in recent years (Koch and Vögele, 2009; van Vliet et al., 2012; Linnerud et al., 2011; Rübbelke and Vögele, 2011; Mideksa and Kallbekken, 2010). Van Vliet et al. (2012) and Hoffmann et al. (2013) show that especially thermoelectric power plants with once-through cooling systems are susceptible to cooling water scarcity. In particular nuclear power plants will face serious reductions in electricity production due to upcoming cooling problems (Rübbelke and Vögele, 2011; Förster and Lilliestam, 2010; Linnerud et al., 2011). In economic terms, the effect of forced capacity reductions has been quantified for single power plants with wide ranges (Förster and Lilliestam, 2010; Koch et al., 2012). Förster and Lilliestam find annual income losses between €5.2 m and €81 m for a (nuclear) power plant; Koch et al. find accumulated losses from 2010 until 2050 between €15 m and approx. €60 m for all power plants in Berlin. Most studies do not endogenize electricity market prices. Exceptions are Golombek et al. (2012) and Rübbelke and Vögele (2013) that simulate climate change impacts based on energy system scenarios. They find only minor price effects. These studies, however, do focus on future average temperatures and not on weather extremes. Depending on the amount of capacity reductions, the partial equilibrium effect of heat waves on producer surplus is ambiguous. While, at the one hand, there are losses from foregone production, producers can also gain from price spikes. Our paper contributes to resolving this ambiguity. For the past, the relation between river temperatures and base load prices has, to our knowledge, only been investigated in an econometric analysis by McDermott and Nilsen (2011). A reference case based on historic data, which also provides insights to the cost incidence of heat waves for producers and consumers, is thus missing. Furthermore, with the exception of Golombek et al. (2012), additional heat wave impacts on the electricity sector such as reduced hydro power availability or affected im- and exports have not been tested for and displayed separately. Finally, The effect of capacity reductions on carbon dioxide emissions has not been examined so far.

We develop and employ a bottom-up model of the German electricity wholesale market in this paper. This allows us to separate the capacity reduction from other price driving effects. The model is run for a 2006 heat wave scenario and compared with a counterfactual scenario with an absent heat wave. We can thus determine the change in prices, generation costs and producer surplus. The robustness of the results is validated in a sensitivity study. To estimate the consequences of climate change, we particularly explore further heat-induced effects on the energy sector. In addition the influence of renewable energy supply on these effects is systematically investigated.

We find that capacity reductions have a substantial impact on prices even with relatively moderate capacity reductions of up to 2,830 MW. Production costs are moderately affected. Producers mostly profit from the price increase unless they face substantial reductions in plant capacity and/or are bound to long-term contracts. Consumers bear a burden that is several times larger than the total cost increase. The reductions in 2006 led to an increase of carbon dioxide emissions. If further heat-induced effects are taken into account, e.g. on electricity demand or hydro-power, or if heat waves become more intense in the future, all these effect are more pronounced and costs increase. Rising feed-in from renewable resources and improved demand-side management counter the effects to a considerable degree.

2 The Model

2.1 Theoretical Model

This study quantifies the effect of reduced thermal capacity on the electricity market price and on surplus in the short-term partial equilibrium. In the following we outline the basic effects with a theoretical model. We assume a market with perfect competition. Figure 1 gives a stylized overview of the effect.

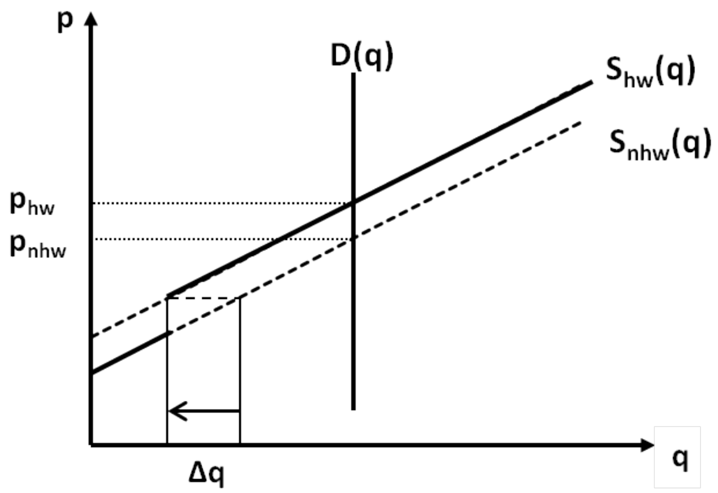

Figure 1: Effect of capacity reductions on market equilibrium and prices

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 $i = 1, ..., N$ 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 cooling water scarcity, 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 right in the supply curve, i.e. with higher production costs.

Power plant operators maximize profits, regarding fixed costs as sunk. The producer surplus from a single plant is given by

$$PS_i = pq_i - c_i q_i = (p - c_i)q_i, \tag{1}$$

so that the sum of producer surplus is

$$PS_{tot} = \sum_{i=1,...,N} (p - c_i)q_i. \tag{2}$$

The sum of generation costs C is

$$C = \sum_{i=1,...,N} c_i q_i \tag{3}$$

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 elastic, CS changes during the heat wave by

$$\Delta CS = p_{nhw} \sum_{i=1,...,N} q_{i,nhw} - p_{hw} \sum_{i=1,...,N} q_{i,hw} \tag{4}$$

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 with plans that have higher variable production costs c_i, the sum of generation costs C unambiguously increases by

$$\Delta C = \sum_{i=1,\dots,N} c_i q_{i,hw} - \sum_{i=1,\dots,N} c_i q_{i,nhw}. \tag{5}$$

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

$$\Delta PS_i = (p_{hw} - c_i) q_{i,hw} - (p_{nhw} - c_i) q_{i,nhw}. \tag{6}$$

If production q_i was identical in both situations then ΔPS_i would be positive: the producer can sell the same quantity at higher prices. Yet, in case where $q_{i,hw} < q_{i,nhw}$, the effect on producer surplus could be both 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 the single producer surplus: if $q_{i,hw}$ is zero (positive) and $q_{i,nhw}$ positive (zero), then ΔPS_i is negative (positive).

The effect on PS_{tot} does not depend on the quantity effect since the total amount of energy remains unchanged. Total producer surplus increases with higher prices and decreases with higher generation costs. If the price effect outweighs the cost effect, the protection of the freshwater ecosystems would be realized almost exclusively at the consumers expense and incentives to overcome the cooling problems, e.g. by use of a different cooling technique, would be low for producers.

While the direction of the effect on CS can easily be deducted theoretically, the magnitude of the effect cannot be determined per se. The same is true for the impact on C: It is obvious that the generation costs will increase, but is this effect relevant? And do producers gain or lose? To resolve these questions, we develop a numerical energy system model that also considers effects not included in the theoretical analysis of this subsection.

2.2 Model Implementation

Beyond the theoretical setting, several characteristics of electricity markets have a significant influence on prices. The supply curve or merit order, for instance, is not a linear but a step function with a close to convex shape at medium to high quantity. The effect of capacity reductions on the variables of interest thus depends on the level of demand. Furthermore some inter-temporal aspects are considered. In the following we outline the amendments made to the theoretical model, which closely follows the approach of Schwarz and Lang (2006), Weigt and Hirschhausen (2008) and Leuthold et al. (2012).

The model is based on real data on all German thermal power plant units exceeding 20 MW net capacity. The calculations for the 2006 heat wave are based on historic demand and historic feed-in from renewable energies (excluding hydro power). One component that determines the supply curve are the variable production costs c_i, which entail fuel costs and certificate prices for carbon in the European Union's Emission Trading System (EU ETS). In addition, start-up and abrasion costs, sc_i, influence supply and hence prices. They occur only during the time when the plant unit is started up and comprise technology specific fuel and abrasion costs. Since they are de facto fixed costs, a successive run of a mixed integer (MIP) and a linear program (LP) is needed, to convert them into time-specific mark-ups. The hourly price is computed in the second step by minimizing the costs in each time-step, i.e. with a temporal resolution of one hour.

In the first step, the so called unit commitment problem, production costs are minimized with start-up costs included as fixed cost components. The objective is to minimize the production costs

$$min\ C = \sum_{i,t} c_{i,t} q_{i,t} + sc_{i,t}, \tag{7}$$

subject to the technical constraints of electricity generation [1] and demand. Here $c_{i,t}$ are the variable generation costs of power plant unit *i* in hour *t*. The start-up costs $sc_{i,t}$ occur if the plant unit is started up in hour t. The production of the plant unit is restricted upwards by its installed net capacity, q_i^{max} and downwards by a minimum necessary amount of production, q_i^{min}.

The model is further adjusted by considering start-up constraints. When a power plant unit is switched off it has to remain off for a certain period of time before it can be restarted (Takriti et al., 2000). Likewise, some units have a minimum operation period. If a plant unit is started up in one period, it cannot be shut off

[1] Constraints due to transmission are neglected in this approach.

earlier than the minimum on period has passed (ibid.).

Additionally the optimal operation of pumped-storage power plants (PSPs) is simulated. They are included as an aggregate in the model. Again technical restrictions apply: The sum of the energy withdrawn from the grid, psp_t^{up}, and of the energy fed in to the grid, psp_t^{down}, cannot exceed the bottleneck capacity of the PSPs. In addition, the power generated by PSPs cannot exceed the capacity stored.

The hourly load data available is not to be confused with the load that has to be matched by domestic thermal power plants and PSPs. Feed-in from renewable energy supply (RES-E) has to be subtracted from hourly load. In addition, plants titled as industrial power plant (IPP) (approx. 3 GW), plants fueled by waste or landfill gas (approx. 1 GW) and heat-led combined heat and power (CHP) plants (approx. 13 GW) are considered as must-run capacity. The residual load, D_t, to be met is hence constructed as the sum of hourly load and net exports to neighboring countries net of RES-E, heat-lead CHP and IPP feed-in.

Supply has to match D_t net of the difference of energy stored and produced by the PSPs at every point in time:

$$\sum_i q_{i,t} = D_t + psp_t^{up} - psp_t^{down}. \tag{8}$$

It is assumed that all electricity is traded on one (day ahead) wholesale market. Although only about 20 to 30% of the power is traded via the EEX, the day ahead spot market price still plays a significant role also for other ways of trading. Due to arbitrage opportunities it serves as point of reference for forward markets and over-the-counter trade (Judith et al., 2011; Ockenfels et al., 2008)[2]. This modelling assumption is common practice in other studies (e.g.Sensfuß et al. 2008; Rübbelke and Vögele 2013). Note that the changes in the model concern wholesale market prices and are not to be confused with end user prices.

[2]Prices in forward markets or in long-term bilateral contracts, which are based on expected exchange prices, may vary from the exchange price but not in a systematic way (Ockenfels et al., 2008).

2.3 Data

The supply curve (merit order) was estimated based on data from the German Federal Network Agency (Bundesnetzagentur) containing information (age, fuel type, net bottleneck capacity and existence of combined heat production) on all conventional and renewable power units with an installed capacity greater than 20 MW by unit (Bundesnetzagentur, 2012), adjusted for changes since 2006. Data on RES-E was retrieved from the transmission system operators (Amprion, 2013; Tennet, 2013; TransnetBW, 2013; 50Hertz, 2013). Since the production of heat-led CHP mainly covers space heat demand which is insignificant in summer, we assume that in this period their production is 20% of the net installed capacity (cf. Weigt and Hirschhausen, 2008). Operators of power-led CHP plants can offer electricity below marginal costs, because part of the costs are recovered by the sale of heat. The amount of this effect is calculated with the net realizable-value method (Frank, 2003; Cornehl, 2008). Net electricity exports that reduce or increase domestic production is provided by the European Network of Transmission System Operators for Electricity (ENTSO-E) [3].

To estimate the marginal cost curve the following cost components are taken into account: efficiency factor, fuel price, emission factor, certificate price for carbon, variable operating expenses (e.g. taxes, charges, fuel transportation) and start-up costs. An overview of the data origin is given in Table 1.

The demand data for 2006 was obtained from ENTSO-E.[4]. As mentioned above, the data is corrected for factors such as RES-E feed-in, heat-led CHP production, im- and exports.

We fit the model to historic EEX prices. By adequate choice of PSP availability and input of real data, the model explains 85% of the variation in the real electricity price data. The model mean price is 7.3% lower than the mean of real prices. The model produces a lower electricity price volatility (-10.2%) than seen in the real prices. During almost all night times real prices are below model prices, es-

[3]ENTSO-E only provides the data for the past two years. For 2006 data was kindly provided for this period by Hannes Weigt, which had been retrieved from ENTSO-E in previous years.

[4]Load is not identical to consumption data. The first is given in MW for a single moment, while the latter is given in MWh for a certain period. The load data is provided as average values for every hour and are therefore less precise than consumption values. ENTSO-E only provides load data on an hourly basis, while consumption data are given as a monthly aggregate only. We take hourly load data as an approximation for the power demand. The data represents only 91% of the total demand since it lacks e.g. demand of industry and railway companies. It is scaled up to represent 100% of the hourly electricity load in Germany

Component	Source
Efficiency factor	Nuclear: Förster and Lilliestam (2010) Hard coal, lignite, gas/ oil-fired, gas-steam (age dependent): BMWi (2006) Pump-Storage: Weigt and Hirschhausen (2008)
Fuel price (monthly prices)	Crude oil (UK Brent): Mineraloelwirtschaftsverband (2012) Hard coal (cif-NW Europe): EURACOAL (2012) Uranium: IndexMundi (2012) Fuel oil: StatistischesBundesamt (2011) Natural gas: BAFA (2013) Lignite: Jansen et al. (2005)
Emission factor	BMU (2003)
Emission certificate price	EEX (2012)
Additional variable costs	Ellersdorfer et al. (2008)
Start-up costs	Jansen et al. (2005)
Start-up and minimum down times	Steck and Mauch (2008)

Table 1: Variable cost components

pecially at the weekends. This may be explained by the fact that power suppliers do accept a price below variable costs in order to save start-up costs (Ellersdorfer et al., 2008). The opportunity gains of avoided start-up costs are not reproduced by the model. In addition, some price peaks in the model do not match the real data. These occur particularly where plants with high start-up costs are run for a very short time (e.g. 1 hour). In sum, the results of the model are satisfactory and reliable.

2.4 Heatwave Data and Counterfactual

The aim of this paper is to analyze the impact of heat waves on the electricity prices. In order to do so, two scenarios have to be constructed for the model runs that describe the energy system with and without heat wave effects. The two scenarios are outlined in the following.

In the *heat wave scenario* the maximum capacity of these thermoelectric power plants is restricted that in fact experienced problems during the heat wave 2006. The information on the forced capacity restrictions in Germany is based on Strauch (2011). Strauch collected data from several sources including interviews, literature and media analysis. In total, thirteen coal-fired and seven nuclear power plants had to reduce their production (mostly at the end of July). Of these 20 power units, 40% are equipped with a cooling tower. With regard to the capacity reductions of nuclear power plants we cross-checked with monthly data from the International Atomic Energy Agency (IAEA, 2007). Based on this information the highest reductions found by Strauch, which are applied here, can be assumed to be a conservative approximation. For those coal-fired power plants where the capacity reduction was only specified as small, we assume 10% reductions. The reductions in the model all occur during the last fortnight (18th-31st) in July 2006, yet not all constantly and simultaneously. On average, the concurrent reductions amount to 1,946 MW, which corresponds to the capacity of approx. two nuclear power stations. At a minimum 338 MW and at a maximum 2,830 MW were simultaneously not available.

In addition, the heat wave might have effected other sources of electricity supply. To the authors knowledge, the impact of climate change on renewable supply is little researched to date (Mideksa and Kallbekken, 2010). While it is known that a rise in winter temperatures increases efficiency due to decreased atmospheric icing (Laakso et al., 2003), little is known about the effect of heat waves especially for wind power. Solar power output might increase and hydro power might decrease due to water scarcity. For the former, the effect has not been quantified so far. The latter is treated in the sensitivity analysis below. As stated above, heat-led CHP and IPP are assumed to run independent of outside temperatures in summer. While a decrease in productivity and also production shifts have been registered in some enterprises during heat waves (PWC, 2010), there is no reliable data on changes in power production and consumption of the industry in Germany. Most of the listed IPPs are gas-fired and thus less susceptible to water scarcity.

The main difference in the *counterfactual scenario* is the assumption of an absence of forced capacity reductions. Hence the upper limit of production is the net installed capacity for all power plant units. We assume that the residual load data used remains unaffected. Potential additional heat wave impacts such as on electricity demand, e.g. due to cooling needs, and on im- and exports will be discussed in the sensitivity analysis.

Since we first only vary the scenarios in presence or absence of forced capacity reductions, it is likely that we underestimate the heat wave impact on the electricity market. To cover additional heat wave impacts an extensive sensitivity analysis is carried out.

3 Results and Sensitivity Analysis

3.1 Impacts of Capacity Reductions

The following results cover the fortnight in July 2006 during which the capacity reductions took place. Our simulation results show that the wholesale electricity price increased on average by €4.14/MWh (11.2%) during these 14 days. In times of peak demand (8 am until 8 pm on weekdays) the increase is even more pronounced, i.e. €8.29/MWh (17.3%), than during off-peak times (€2.07/MWh or 6.5%). The rise in production costs is not as distinct: On average production costs increased by 5.9% (€1.04/MWh). The increase is only slightly higher during peak times than off-peak (see Figure 2).

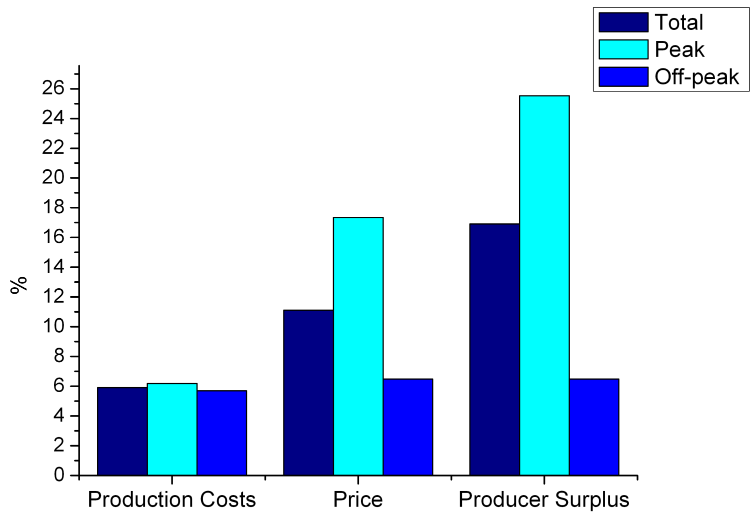

Figure 2: Effect of capacity reductions on production costs, price and producer surplus (mean values per MWh)

The price increase is relatively high and relevant. The difference in impact between peak and off-peak times can be explained by the shape of the merit order. Reduced capacity has greater effects the higher the level of demand.

Most of the costs of the heat wave are borne by the consumers. Production costs moderately increase in total by € 16 m during the fortnight. Producer surplus rises simultaneously by approx. € 53 m (see Figure 3). To put into relation, the producer surplus increase corresponds to approximately 1% of the annual turnover of the largest power producer RWE Power in Germany in 2006 (RWE, 2007). At the same time the consumer surplus decreases by € 69.9 m. More than 70% of these gains or losses are realized in times of peak demand. This shows that indeed a relevant shift of wealth from consumers to producers is caused by the capacity reductions.

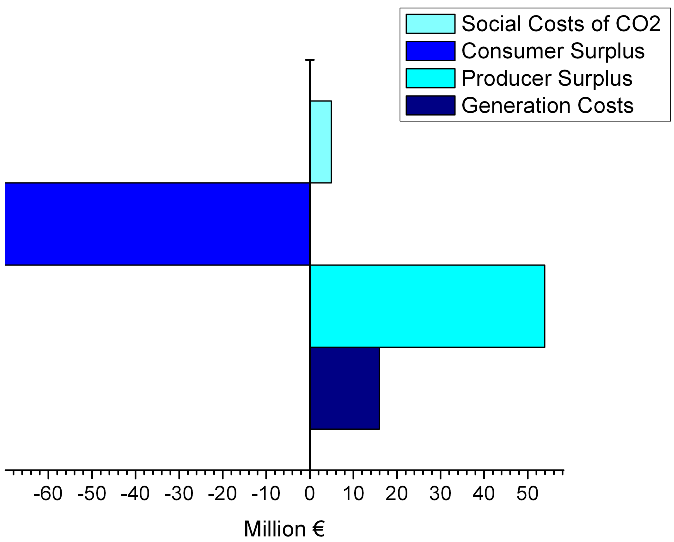

Figure 3: Impact of capacity reductions on producer surplus, consumer surplus, production costs and social costs of CO_2 emissions

The great decrease of consumer surplus and high increase of producer surplus is in part due to the assumed inelasticity of demand. Still it is interesting to see that the overall effect on producer surplus is positive even in off-peak times with lower price effects. Another reason for the great difference between consumer and producer surplus is the assumption of short-term trading. In the case of long-term and less flexible contracts, producers would not be able to pass through the additional costs to this extend.

Another effect that has not been examined before in the literature is the change in carbon dioxide emissions during a heat wave. It can be observed that emissions increase by about 5% per MWh. During the heat wave it sums up to an additional emission of approx. 150,000 tons CO_2. This is due to the fact that the supply gap caused by the reduced capacity of some power plant units has to be closed by power plant units located further right in the merit order. In our case, mostly carbon-neutral nuclear plants were temporarely replaced by carbon intensive plants, which explains the rise in emissions. If we assume social costs of € 50 per ton CO_2 (IPCC, 2007), and subtract the already priced-in costs from emission certificates, additional social costs of approx. € 5 m result (see Figure 3).

Since obviously not all producers gain from the price increase, it is useful to take a closer look at the situation of single power units to identify where losses are made. An operator of a power unit *A* with 1,345 MW net installed capacity that has to reduce capacity by 65% during a period of 9 days produces approx. 180 GWh less in sum. At the same time, power is sold at higher prices. As a consequence the operator loses € 4.85 m of producer surplus during these 9 days. In addition, the producer is able to profit slightly from the price increase in the remaining three days with normal operation. During these days the loss of surplus is compensated by about € 160,000 additional income (see Figure 4). If prices remained uneffected, the producer would have gained € 6.93 m less during the heat wave compared to regular capacity limits. This shows that the price effect is not negligible and can lead to positive effects on producer surplus despite capacity reductions.

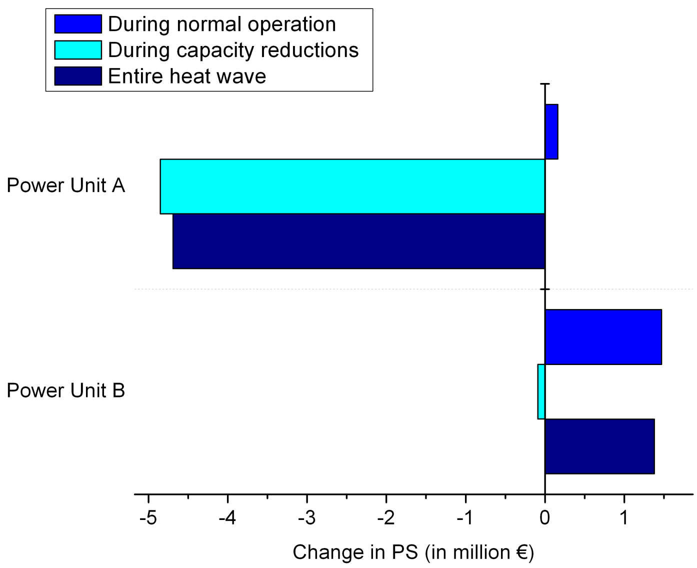

Figure 4: Impact on producer surplus from two representative power plant units during hours of normal operation, hours with capacity reductions and the sum of both (power plant unit A has a reduced production of a total 180 GWh during 9 days; unit B has a reduced production of 7.8 GWh during 4 days.)

In another case, a similar sized power unit B is forced to reduce production by less (10%) and for a shorter period of time (4 days). In total, only 7.8 GWh are produced less in this case. During the time of reduced capacity, the effect on producer surplus is indeed negative but moderate (- €88,000). In sum the producer profits from the heat wave price increase: Net of the losses she gains almost €1.4 m (see Figure 4). The results thus confirm the previous considerations: The smaller the capacity reductions, the more likely does the price effect outweigh the quantity effect.

3.2 Additional Heat Wave Impacts and Climate Change

In 2006 both demand and supply could have been more affected by the extreme temperatures than assumed above and/or additional impacts could occur in the future with more climate change. To test the simulation results and to discuss implications of the situation under climate change, a series of sensitivity analyses is carried out. The focus is on changes in demand, capacity of run-off river power plants, net exports, demand elasticity and more severe forced reductions of power plants. A change in one of these factors leads to variations in residual load of either the heat wave or the counterfactual scenario as illustrated in Figure 5 and Figure 6 (see below).

First, the assumptions for the counterfactual residual load are relaxed. So far we have not accounted for differences in the counterfactual apart from the presence/ absence of forced capacity reductions. Yet, in a situation without a heat wave, demand and net exports could differ from the historic heat wave data. Taken such changes into account, the counterfactual residual load values would be lower than in the runs above. We vary the residual load values of the counterfactual between 0 and -6% of the historical data, to cover the plausible changes as discussed in the following.

If electricity demand rose by 2% in July 2006, as reported by the German Association of the Electricity Industry for the summer of 2003 (VDEW, 2003), residual load would have been on average 1,125 MW (2.5%) lower in the counterfactual scenario. In this case, the price would rise by 19% and the increase in producer surplus would amount to €95.4 m. Line B in Figure 5 represents this situation. Hence even considerably small differences in demand exacerbate the effect on prices and costs.

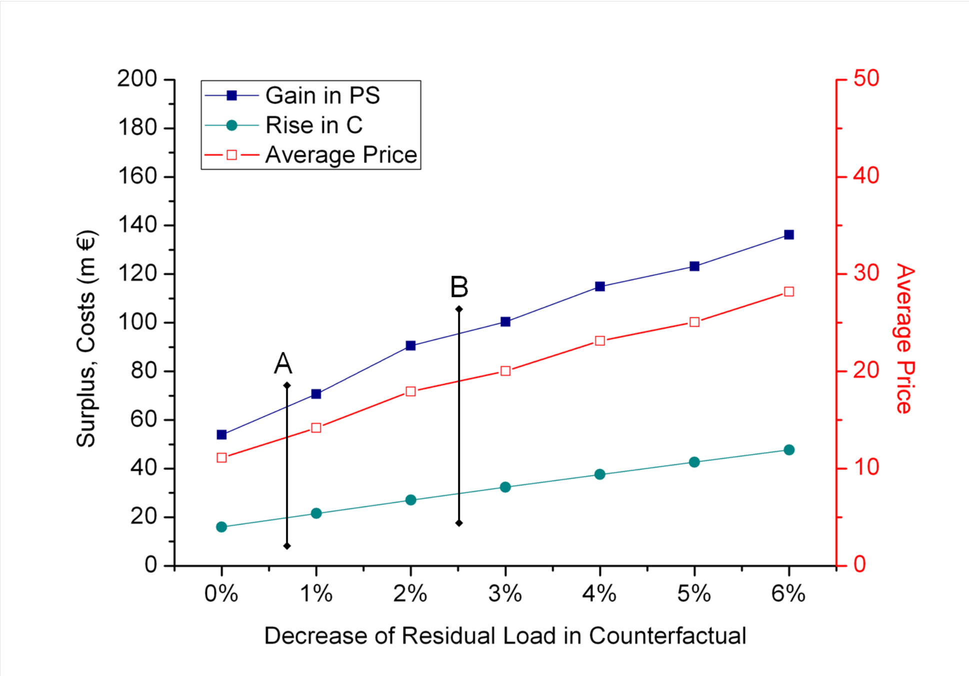

Figure 5: Effect of changes in residual load during counterfactual on mean price, producer surplus (PS) and production costs (C). Line A represents a decrease of residual load of 0.7% due to more imports in absence of a heat wave; line B represents a decrease of residual load of 2.5% due to less demand without a heat wave.

If we assume greater water scarcity and/or greater heat wave impacts for 2006 also in neighboring countries, the net exports would have been greater in the counterfactual than in the heat wave scenario. In absence of a heat wave, Germany would have received more power imports and would have had to cover less supply by domestic plants. Based on the calculations by Rübbelke and Vögele (2011) for greater water scarcity we decrease the net exports by 30% in the counterfactual. This corresponds to a decrease of residual load on average by 327 MW (0.7%), which is represented in line A in Figure 5. The average price would increase by additional 9 percentage points during the heat wave. Since more demand has to be covered by domestic power plants, domestic producers profit from the constraint of power exchange: Producer surplus would rise by approx. € 66 m in this case, which equals a total increase of about 17.6% compared to the situation without a heat wave.

Second, we study the effect of a change in the price elasticity of demand. We apply demand elasticities of -0.1, -0.25 and -0.4. Though still relatively low, these elasticities are significant for short-term demand. Leuthold et al. (2012), for instance, apply a price elasticity of -0.25. It can be seen that the results are very sensitive to a rise in price elasticity of demand: In the first case, the average price increases by 4.4%, in the second by 2.6% and in the third case prices increase on average by 1.9% during the heat wave. Producer surplus increases by 3.5% in the first case, by 0.01% in the second and even decreases by 1.3% in the third case. Production costs increase by 4.7%, 4.2% and 4%, respectively. The results show that current technological developments as the introduction of smart metering and demand response programs could be very effective in reducing costs in extreme situations such as heat waves.

Third, we determine the sensitivity of the costs and the cost incidence of heat waves to a changing climate. Projections for Germany show that the frequency of temperature anomalies in the summer months is likely to increase drastically until the end of the century, especially in the south (Deutschländer and Dalelane, 2012). As a consequence, residual load may increase more during future heat waves, e.g. due to increased cooling demand, lower availability of hydro power plants or more severe capacity reductions of thermal power plants. We thus vary the residual load values in the heat wave scenario between 0 and 6% of the historical data.

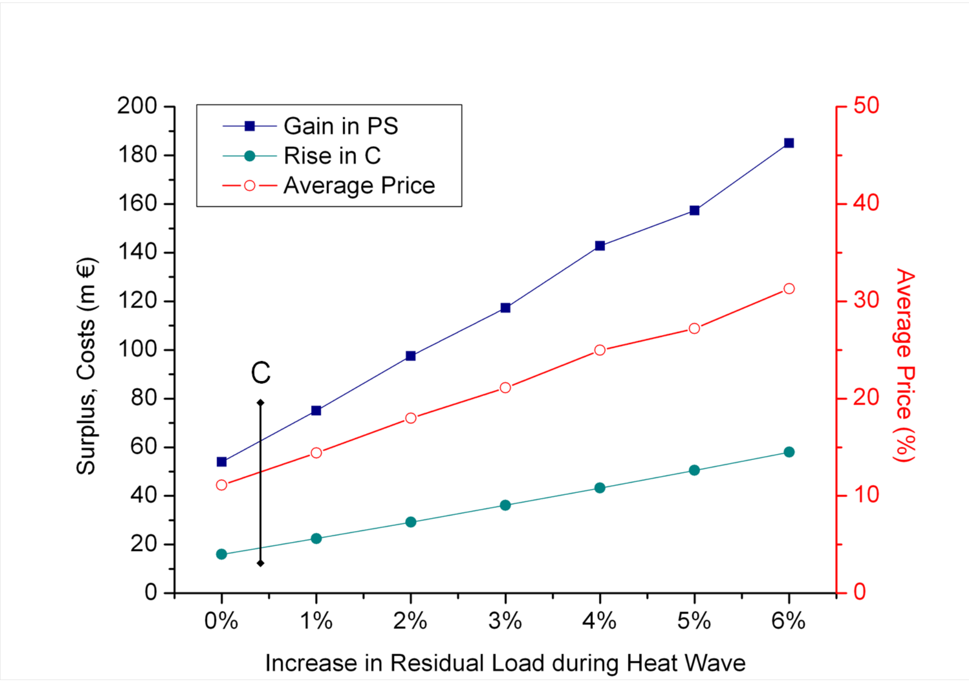

Figure 6: Effect of changes in residual load during the heat wave on mean price, producer surplus (PS) and production costs (C). Line C represents an increase of residual load of 0.4% due to additional hydro power contraints during the heat wave.

If the capacity of run-off river power plants decreases by 10%, which is in line with summer run-off projections until 2020 (Zebisch et al., 2005), residual load increases on average by 180 MW (0.4%) accordingly. The average price increase would be only slightly higher, approx. 12.3%, in this case, which corresponds to situation C in Figure 6. The gain in producer surplus would amount to € 62.4 m.

A more intensive heat wave might also result in greater capacity reductions. To get a better idea of this effect, we test the sensitivity of the results to greater capacity reductions of the previously affected power units. In two additional runs we limit the capacities of those power plants that had to reduce production in the 2006 heat wave scenario (i) to their minimum necessary amount of production and (ii) to zero for the same time periods as in 2006. On average, reductions are (i) 2,090 MW (107%) and (ii) 4,890 MW (251%) greater than before. As a result, the average price increases by approx. 24% in the first case and almost 50% in the second (compared to the counterfactual). Production costs increase by € 35 m (13%) and € 71 m (26%), respectively, and producer surplus rises by even (i) € 113 m (35%) and (ii) by € 237 m (74%) (see Figure 7). Consumer surplus decreases by (i) € 148 m and (ii) € 308 m. This shows that the results are very sensitive to the extent of capacity reductions. The risk of blackouts also rises with higher capacity reductions, which is not considered here.

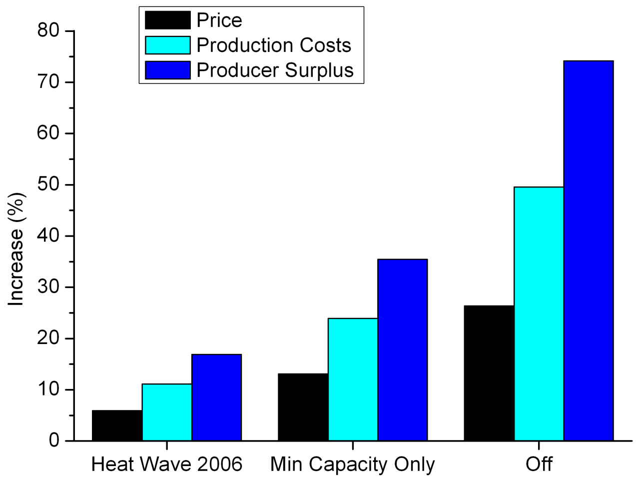

Figure 7: Effect of different capacity reductions on average prices, production costs and producer surplus. In the *Heat Wave 2006* run, 1,946 MW capacity were reduced on average, in the *Min Capacity Only* run 4,036 MW, and in the *Off* run average 6,837 MW were reduced.

In brief, the sensitivity analysis shows robust results with regard to additional heat wave impacts. Before drawing more general conclusions, the sensitivity to a change in the energy mix is analyzed.

3.3 Change in Energy Generation System

In Germany, the generation system has undergone some substantial changes in the past, e.g. with regard to the energy mix, and is planned to transform even more in the future. To make some tentative statements about the impacts on heat waves in a future generation systems, we determine the sensitivity of the results to an increase in RES-E. We simulate a coverage of RES-E (excluding hydro power) of domestic production between 2.2 and 30%, i.e. the amount in 2006 and the amount projected for 2030 (Schlesinger et al., 2011).

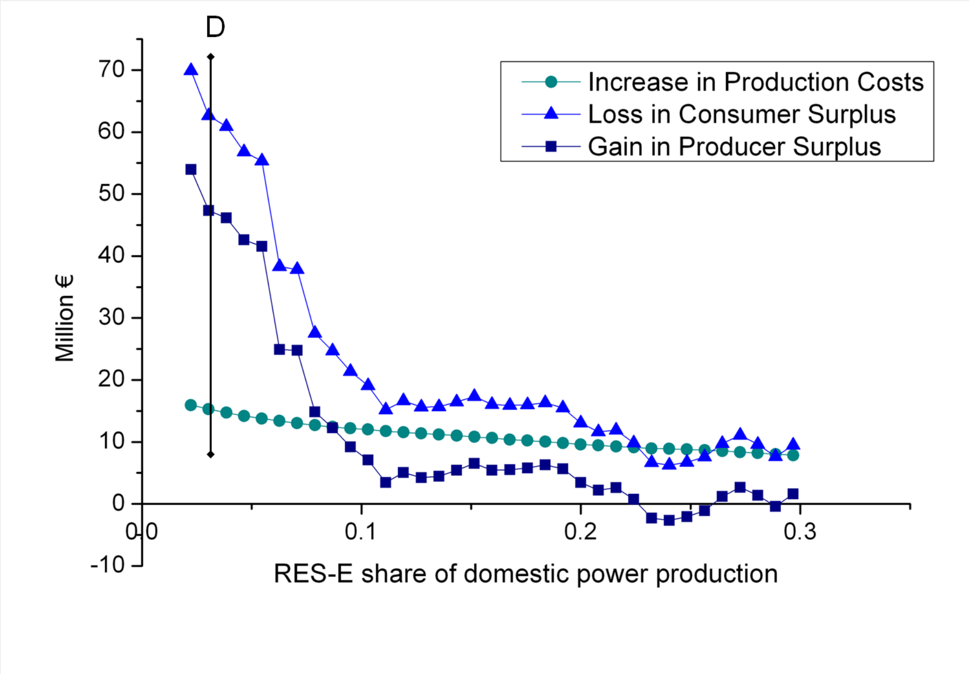

Figure 8: Effect of changes in RES-E (excluding hydro power) on production costs, producer and consumer surplus; line D represents an RES-E share of domestic production of 3%.

As can be seen in Figure 8, the sensitivity is not negligible. Already with an increase of 0.8 percentage points of the RES-E share in domestic production, the sum of generation costs would drop by 4% compared to the heat wave situation

2006.[5] This corresponds to situation D in Figure 8. In case of a 30% coverage of domestic production by wind, solar and biomass, the increase in generation costs during the heat wave would be reduced by 51% to € 7.8 m, see Figure 8. Producer surplus would only vary by € 1.6 m from the counterfactual scenario. The precipitous drop in the consumer and producer surplus can be explained by the shape of the merit order. The step course of the merit order as well as varying start-up costs and constraints account for the fluctuations in consumer and producer surplus as the RES-E share increases.

In summary, the sensitivity analyses underline the robustness of our results. The effects on prices, costs and producer gains aggravate, if additional heat wave impacts like increased electricity demand, reduced hydro power capacity, reduced net exports and more strict capacity reductions are introduced. The disproportionate relation between additional generation costs and additional producer surplus slightly increase. An increase in both, price elasticity of demand and RES-E share of domestic production reduces these effects substantially. In both cases production costs increase less and the change in producer surplus can become negative during a heat wave.

4 Conclusion and Discussion

Most thermoelectric power plants depend on nearby freshwater for cooling. Due to water scarcity and/or legal restrictions, several power plants had to reduce production during a heat wave in July 2006 in Germany. We quantify the electricity price changes and the cost incidence of this heat wave. We also determine whether electricity producers might have gained additional profits, as the theory is indecisive about this effect in the partial equilibrium. Due to global warming, the electricity market impact of heat waves might considerably change in the future, but also due to the transformation of the German energy system. This paper addresses both questions with an extensive sensitivity study.

The 2006 heat wave had (ceteris paribus) considerable effects on electricity prices, costs and profits. Our simulations show that prices increased by about 11% during this time. This ledadditional production costs of about € 16 m. On the consumer side, however, surplus decreased by about € 70 m. Note that, in our set-

[5]Decreases of net exports, which have to be considered due to the sensitive data situation, would affect the results in the same way.

ting, consumers do not coincide with the end users, but with retail companies and large customers. The aggreate of all electricity producers profits from the price increase: foregone production is overcompensated by the price effect. We further find that the heat wave led to increasing carbon emissions, since CO_2 neutral nuclear power plants were substituted by emission intensive plants.

The effects of climate change and a transformed energy system are simulated by modifying assumptions on forced capacity reductions, electricity demand, hydro power capacity, net electricity exports, and renewable feed-in. These parameter variations also underpin the robustness of our results. Consequences of more intense heat waves like increased electricity demand, reduced hydro power capacity, reduced net exports and more strict capacity reductions all exacerbate the effects on prices, costs and producer gains. The disproportionate relation between additional generation costs increases a little. On the other hand, a slightly increased price elasticity of demand already reduces these effects substantially. Also an increased renewable feed-in in a future generation system reduces costs. With a 30% RES-E share of inland electricity production, the mean price increase would be (ceteris paribus) approx. 4% instead of 11%. The increase in production costs would halved.

It is yet not straightforward to extrapolate our findings to a dynamic setting under climate change or an energy system transformation. Our paper models spot-market prices, but producers are also bound to longer-term contracts. Thus, when forced to reduce production, they may have to cover additional costs themselves. But still, over-the-counter (OTC) trading and futures are based on expected prices on the spot market. If heat wave induced capacity reductions become more frequent, this will be reflected in other electricity markets, e.g. in forward markets. With more price elastic demand the price would increase significantly less, as seen in the sensitivity analysis, and producer surplus would be attenuated. On the other hand, a rise in electricity demand for air conditioning during heat waves might counterbalance or even outweigh this effect.

Also for spot-markets, simulation models have their limits. We can only partially explain the historic record prices of up to € 2,000 per MWh during the 2006 heat wave. Market power might be one reason for prices exceeding marginal cost on average by more than 55%. On the other hand, the study of McDermott and Nilsen (2011) associates our price increase of 11% with river water temperatures of up to 32-35° Celsius, while 29° C were metered for the river Rhine (the most important cooling water body in Germany) during the 2006 heat wave (IKSR, 2006). McDermott and Nilsen (2011) might hence underestimate the heat wave price effect since they focus on base load prices.

The works of Golombek et al. (2012) and Rübbelke and Vögele (2013) determine climate change costs and price effects for the electricity sector by assuming scenarios for 2030. Rübbelke and Vögele (2013) find a remarkable 9% increase of producer surplus during peak load in summer. Even with a comparable increase of net exports as in Rübbelke and Vögele (2013), our model shows a much lower effect on domestic producer surplus (2.8%). This difference is mainly due to absence of heat-sensitive nuclear power plants in the generation system of Rübbelke and Vögele (2013). It may also be due to the difference in temperature extremes, since Rübbelke and Vögele (2013) do assume average temperatures, but not a heat wave situation. The effect on prices found by Golombek et al. (2012) are comparable to our model when there is a RES-E share of 30% of inland electricity production.

Compared to the range of losses for a single power plant found by Förster and Lilliestam (2010), our results are at the lower end, even for plants with tight capacity reductions. This may be due to two reasons: First, Förster and Lilliestam assume a relatively high average EEX price compared to our simulation; and second, they do not take the effect on equilibrium market prices into account. Neither do Koch et al. (2012), who find relatively low economic losses for all power plants in Berlin until 2050.[6]

In this respect, we contribute to the literature with a quantification of the effects of the 2006 heat wave from an energy system perspective with endogenous prices. Our detailed model allows to computing variations of many parameters that are indicative for the impacts of climate change and the consequences of a restructured energy system. While the former increases costs, that latter leads to cost reductions. In any case, surpluses react more sensitively than prices, consumers disproportionately bear the costs, and producers gain.

The model results demonstrate two new relations between adaptation and mitigation in the energy sector: (i) Emissions increase during heat waves when nuclear capacities have to be reduced. The emission of greenhouse gases leads to an increase in global temperatures and summer anomalies, forcing some power plants

[6]The comparability of our results with the work of Koch et al. is limited, since they publish accumulated losses only.

to reduce production. In turn, this leads to an increase in emissions. (ii) Climate change mitigation policies that alter the energy mix away from large scale thermoelectric power plants can lead to a reduction in water withdrawal and thus render the generation system less sensitive to heat waves.

Climate change impacts in an industry that provides basic public services can lead to crucial political repercussions. First, the cost incidence found in the model points towards distributional conflicts and should be carefully considered by policy makers. It could lead to situations where the protection of freshwater ecosystems under climate change is predominantly at the expense of power consumers. This cost incidence yet crucially depends on the elasticity of demand and the institutional settings of electricity trading. Second, current political and technological developments such as the transformation of the German energy system towards renewable energies and an increase of demand flexibility can counter the impact of water scarcity on the energy markets. Without a shift towards carbon-neutral and water independent power plants, the resource use conflict between ecosystem protection and energy security will intensify.

Our results thus emphasize the interrelation between mitigation and adaptation to climate change. If mitigation fails or is postponed, the impacts of heat waves on the energy system and their costs will rise. This said, more research is needed on the climate change sensitivity and cooling water dependency of the alternative renewable energy technologies.

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