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Thinking ahead for Europe

Distributional Consequences of Climate Change Impacts on the Power Sector: Who gains and who loses?

Dirk Rübbelke and Stefan Vögele*

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Abstract

Climate change tends to negatively affect the power sector, inter alia, by causing cooling problems in power plants and impairing the water supply required for hydro-power generation. In future, when global warming is expected to increase, autonomous adaptation to climate change via international electricity markets inducing reallocations of power generation may not be sufficient to prevent supply disruptions. Furthermore, the consequent changes of supply patterns and electricity prices might cause an undesirable redistribution of wealth both between individual power suppliers and between suppliers and consumers. This study ascertains changes in European power supply patterns and electricity prices caused by ongoing global warming as well as related redistribution of wealth for different climate change scenarios. Our results confirm that autonomous adaptation in the power sector should be complemented by planned public adaptation in order to preserve energy security and to prevent undesired distributional effects.

Keywords: adaptation, climate change, hydroelectric power, nuclear power, redistribution of wealth, vulnerability

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1. Introduction

The vulnerability of energy supply infrastructure to climate change is an important topic in the literature on the adaptation to climate change, since all (economic) activity requires the input of energy.[1] Consequently, this infrastructure (generation as well as distribution) is critical for the functioning of economies, and adaptation of the energy systems to climate change – in turn – is crucial for their maintenance.

In the recent past, recurring disruptions of energy supply induced by extreme weather events have been observed.[2] An obvious connection between weather extremes and energy supply is found in the hydropower sector. Hydroelectric power is the major source of electricity for 26 countries from the Sahel to southern Africa, and the secondary source for an additional 13 countries (Showers, 2002: 639). Due to drought, several areas in these countries from a wide range of climates were negatively affected by power shortages in the 1980s and 1990s.

The effect of extreme weather patterns, which are supposed to occur more frequently in future due to ongoing climate change,[3] on energy supply systems is also observable from the Brazilian blackout in 2009. Some 40% of the Brazilian National Interconnected System's load was interrupted in the course of an automatic disconnection of a transmission line as a consequence of adverse weather patterns (Ordacgi Filho, 2010). Furthermore, in 2005 Hurricane Katrina in the Gulf of Mexico caused a gross peak oil supply loss of 1.5 mb/d (IEA, 2007: 37). Due to shortages in oil supply, the US Environmental Protection Agency even relaxed pollution standards nationwide, so that lower grades of gasoline were allowed to be used. This gasoline was expected to be imported from Europe (Mouawad et al., 2005).

Extreme weather patterns can also negatively affect the power generation in fossil fuel and nuclear power plants (see e.g. Koch & Vögele, 2009; Kopytko & Perkins, 2011; Mideksa & Kallbekken, 2010; Flörke et al., 2011). Such plants require water for cooling processes; about 43% of the EU's water demand is used as cooling water by power authorities (EUREAU, 2009: 21). The availability of cooling water is sharply reduced during heat waves and droughts. As Förster & Lilliestam (2010) show, power generation could be severely constrained by typical climate impacts such as increasing river temperatures and decreasing

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[1] "From a thermodynamic point of view, energy and matter are the fundamental factors of production. Every process of production is, at root, a transformation of these factors" (Baumgärtner et al., 2001: 366).

[2] "The relevance of adding extreme events to the analysis is almost trivial: our serious worry about climate change is entirely based upon their possible occurrence" (van den Bergh, 2004: 392).

[3] Itteilag (2008) states that peak electricity demand in the US, typically for summertime air conditioning, is growing at 2.6% per year and he discusses available energy technologies and programmatic procedures to reduce electricity peaks and to prevent a peak electricity shortfall.

stream flow. According to the IPCC (2008), the frequency of periods characterized by water shortages and by high water temperatures will increase in Europe and other parts of the world in future. Although all thermal power plants are negatively affected by high ambient temperatures, nuclear power plants are especially vulnerable (Linnerud et al., 2011: 150).[4]

Yet, the problem of cooling water shortage is not only to be expected in future, since such shortcomings have already occurred in the past. During recent years, the rivers that supply the water used to cool many of Europe's nuclear plants warmed up so often during summer heat waves that plant managers had to cut back power output and/or to release damagingly hot water back into the rivers. A severe heat wave in 2003, for example, which raised summer temperatures by 3 to 5°C in most of southern and central European countries and which was accompanied by significant annual precipitation deficits (IPCC, 2008: 845), impaired the generation of electricity in more than 30 nuclear power plant units in Europe because of resulting limitations in the possibilities to discharge cooling water (IAEA, 2004). Some nuclear power plants got exemptions from legal requirements to be able to continue their operating activities. As a result of the cooling problems of the nuclear power plants in 2003, France as the biggest electricity exporter had to import electricity from Great Britain to be able to supply enough electricity to Italy and other countries (UCTE, 2004). In 2006, a nuclear power plant in Spain had to shut down due to rising temperatures in the river supplying the plant's cooling water and in France the government approved requests to allow plants to discharge cooling water at above normal temperatures. Also in 2009 a summer heat wave caused cooling water shortages in France. As a consequence the French nuclear power generation level dropped significantly. France had – as in the heat wave in 2003 – to import electricity from the UK during the 2009-summer. Altogether a third of the nuclear power stations of the biggest European electricity exporter France was put out of action (Pagnamenta, 2009). Some German nuclear power plants had to reduce their electricity generation due to a summer heat wave in 2010. In order to protect the stability of the power grid, a concept for preventing the breakdown of the power supply and for limiting negative impacts on the environment was elaborated.

Currently nuclear power has a share of about 28% in the electricity supply of the EU, while the respective share of hydro power is about 12% (EUROSTAT, 2010). So disruptions in the use of both nuclear and hydro-power plants may have significant impacts on the electricity supply system. In our analysis of the potential impacts of ongoing climate change on power supply in Europe, we will focus on these two important subsectors of energy generation. As the aforementioned negative climate-induced impacts on power supply imply, the adaptation to these impacts took place autonomously via the European electricity market (for different types of adaptation, see e.g. Fankhauser, Smith & Tol, 1999). International trade of electricity made it possible that the loss of power-generation capacity in one subsector or plant location of the European energy system was replaced by an increase in generation capacity in another sector/location, e.g. a decline in French nuclear power generation was compensated for by a rise in British supply of electricity. Yet, due to ongoing climate change, such autonomous adaptation might not be sufficient anymore in the future and advance strategic policy intervention might be required to reduce vulnerabilities of the European energy system. Yet, as Seo (2011: 825) stresses, "[a]daptation measures that should be publicly coordinated for the provision have not received a proper attention up until now." Due to the long lifetime of infrastructures and the magnitude of investments in the electricity

[4] Greis et al. (2009) investigate a specific conventional steam/gas power plant site in Germany and find that rising average air and water temperature levels will cause only very small changes in gross power output until 2050.

sector, especially in this sector, public adaptation strategies should be developed at an early stage.[5]

In order to demonstrate the potential necessity for public adaptation strategies in the European electricity sector, we conduct an analysis of the autonomous short-term adaptation of this sector, i.e. we investigate short-term and temporary changes in power generation and national import-export balances for electricity induced by extreme climatic conditions. Yet beyond, we analyse distributional impacts of such autonomous adaptation, i.e. we also regard redistribution of consumer and producer rents in order to identify the main losers and potential beneficiaries of climate change-induced energy insecurity. Potentially undesired redistribution of wealth, either between consumers and producers or between individual countries, can be identified and public adaptation strategies to prevent such adverse developments can be launched in advance.

In detail we proceed as follows. In section 2, we discuss different aspects of energy security that will be relevant for our subsequent analysis of the consequences of future power supply disruptions and explain, from an *ex-post* perspective (see Löschel et al., 2010 for a discussion of *ex-post* and *ex-ante* perspectives on energy security), how disruptions in energy supply might affect rents of agents acting on the markets for energy. In section 3, we present the methodology of and the scenarios regarded in our analysis. In section 4, the results concerning electricity generation, trade and distributional effects are displayed and discussed. Section 5 puts these results in a broader context and draws some conclusions.

2. Climate Change and Energy Security

According to the IEA (2007: 12), energy insecurity "stems from the welfare impact of either the physical unavailability of energy, or prices that are not competitive or overly volatile." Conveying this idea inversely, Bohi & Toman (1996: 1) state that "[e]nergy security refers to the loss of economic welfare that may occur as a result of a change in the price or availability of energy." In general, the change in availability of energy influences the price of energy via market interaction and vice versa, i.e. price and availability changes are interrelated. Via the price mechanism demand (supply) for energy is equalized to the supply (demand), except for extraordinary and rare cases where energy is indeed physically unavailable (e.g. due to embargos or wars). If we therefore focus on the normal cases, energy (in-)security is mostly an issue of price changes and not of complete unavailability of energy. As Helm (2002: 176) points out: "The complementarity of energy with the rest of the economy means that customers will typically want stable and predictable prices, in line with their investments in durables, housing and capital stock at a point in time".[6] Expressed in welfare terms, which is of major importance in both definitions of energy (in-)security above, *consumers* of energy perceive energy insecurity because they suffer welfare losses which might be either due to 1) higher total energy expenses caused by rising energy prices, 2) sharp rises in energy prices (volatility) or, in some rare cases, 3) the unavailability of energy supply.

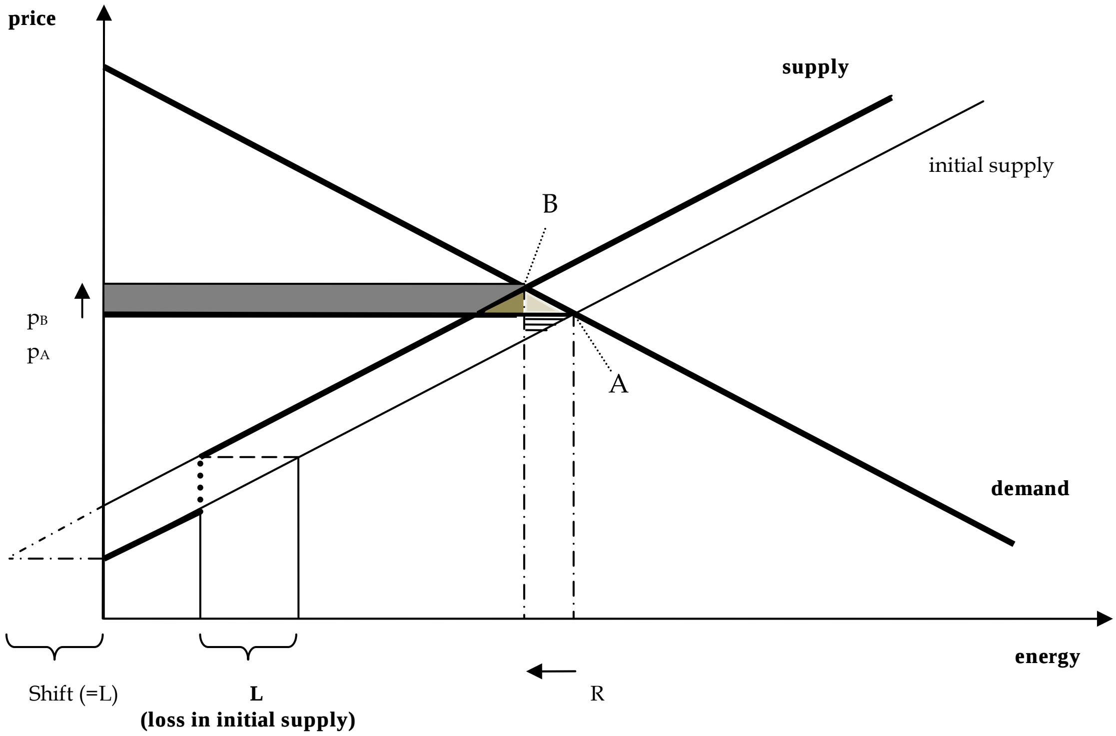
The consequences of energy (in-)security on the utility levels of energy *suppliers* is more complex. Let us consider the change in their rents from an ex-post perspective and by

[5] See, e.g. Guthrie (2006) for the influence of public regulations on investment behaviour in the electricity sector.

[6] According to the findings of choice experiments conducted by Longo et al. (2008), consumers are willing to pay a higher price for electricity in order to internalize the external costs of energy insecurity.

focusing on price level aspects (ignoring the influence of price volatility itself on welfare) in the simplified illustration of Figure 1.

Figure 1. Change in rents and market equilibrium induced by a shock on the supply side



We assume that there is a temporary loss in energy supply by the amount L caused, e.g. by extreme-event-related problems in the generation process. Let us temporarily suppose that there are linear energy demand and supply functions for the regarded economy. Initially, i.e. before there is this supply side shock, the initial supply curve (thin line fading to the short bold line intersecting the axis of ordinates) and the demand curve intersect in A. The loss in energy supply by L (see the associated marginal prices in this supply range) causes a modification of the supply curve. Since the cheapest supply options still prevail (left hand side of the lost supply range), the new supply curve coincides with the old one in the respective supply range. Beyond this low-cost range, the new supply curve is located above the old one; it is depicted by the bold line passing through the new market equilibrium B.

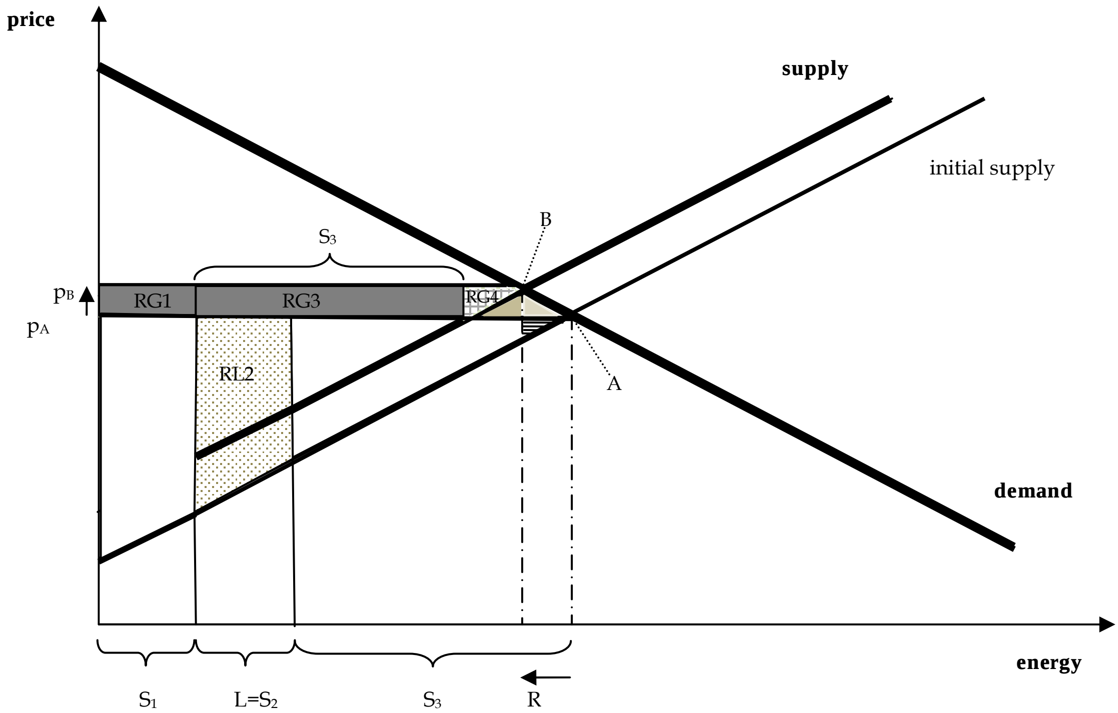
The decline in consumer-rent, due to higher market prices for energy and the cutback in energy consumption, is depicted by the (light, medium and dark) grey shaded area. The medium and dark grey areas reflect the loss in consumer rents caused by the increase in the market price for energy. The light grey area stands for the loss resulting from the shrinking of the level of consumed energy.

In contrast the suppliers obtain additional rents due to the increase in the market price for energy and these additional rents are depicted by the dark grey shaded area. The medium-grey triangle also depicts additional revenues due to higher energy prices, but these are immediately sapped by higher supply cost: the loss L in supply has to be partly replaced by alternative supply at higher cost. This loss due to higher supply cost is depicted by the area between the new and the initial supply curve up to the new quantity (associated with B) of energy sold on the market. Finally, below the light grey shaded triangle, there is a striped area, which depicts supplier rent losses due to the decline in energy sold on the market. The overall change of supplier rents depends on the slope of the supply function.

Let us next have a closer look at the distribution of supplier rents and how they might become affected by energy supply disruptions causing energy insecurity to rise. We now assume that, before the shock, energy had been supplied by three companies. An individual energy providing company i (i=1,2,3) had initially a supply S_i (see Figure 2). Let us furthermore assume that only the supply of the second company collapses, while the other two companies' supply remains unchanged (it is neither reduced nor can it be augmented; their marginal supply cost will neither change). Let us further assume that, due to the loss in the second company's supply, a fourth company will enter the market and will supply additional energy, but at higher marginal costs than the other companies on the market.

As we can observe from Figure 2, the first and third company will obtain a gain in their rents by the dark grey areas RG1 and RG3, respectively. RG1 and RG3 are equal to the rise in the market price (p_B-p_A) multiplied by supplied quantities S_1 and S_3, respectively.

Figure 2. Changes in individual suppliers' rents



The entrant to the market, i.e. the fourth company, will now supply the amount L-R=S_2-R, i.e. it will sell an amount of energy that is equal to the difference between the second supplier's former supply S_2=L minus the reduction R in total sales on the market. Of course, by entering the market the entrant gains additional rents (grided area RG4) which he could not materialize in the initial situation when competitor 2, who could supply energy at a lower price before, was still on the market. Consequently, the only energy supplier suffering from the loss of low-cost energy supply capacity is supplier 2, whose own supply and rents cease to exist. Supplier 2's loss in rents is equal to the dotted area RL2 in Figure 2. The other suppliers take advantage at the expense of the consumers who have to pay a higher energy price. The sum of total supplier rents and total consumer rents declines after the break-down of company 2's supply, since supply cost of energy have been increased and energy sales shrank.

In contrast to this case, there may be situations without real impairments of energy supply but where rumours about crises or shortages are spread in order to induce a price increase on the energy markets while supply cost remain actually unaffected. Then suppliers' profits tend to be augmented (as long as price-elasticities of demand are moderate), while the consumers will lose consumer rents. Consequently, the suppliers acquire additional rents at the expense of the consumers, while total rents (sum of supplier and consumer rents) decline as the consumption of energy shrinks due to rising market prices.

A national government might try to reduce vulnerability of its economy with respect to international energy supply disruptions (e.g. stop in the delivery of gas via international pipelines for political reasons) by supporting domestic energy supply. This could be done by raising the price of imported energy via a tax which will encourage domestic supply and mitigate dependency on foreign supply. "The difference between the domestic price and the expected price of imports reflects the risk premium - the greater this risk or the greater the risk aversion, the greater will be this premium" (Markandya & Pemberton, 2010: 1611). Of course, such policies would also affect consumer rents as well as domestic and foreign energy suppliers' profits in different ways.

From this discussion we can observe that the consumers of energy always suffer from energy-insecurity related price effects, while individual suppliers might take advantage of partial shortages or even from rumours about shortages in the short-run. Therefore, from the consumers' point of view energy security with respect to certain forms of energy like oil might even be considered as a global or international public good.[7] From an economic perspective it is irrelevant where a country's consumers acquire their oil which is due to its fungibility. As Crane et al. (2009: 14) point out, "[d]isruptions of supplies or jumps in demand anywhere in the world will be distributed across the world market." Yet, with respect to electricity supply interrelations between regional shortages, price effects and redistribution of rents are different from those related to oil supply, amongst other things because electricity is not traded in global but in regional networks, i.e. there is a limited fungibility of electricity.

Since energy is used in every process within an economy, energy prices will cause the prices of all commodities and services to increase. "Price shocks may prevent the economy from performing to its full potential, the reason being that the sudden change of relative prices of production input factors may lead to temporarily increased unemployment or the obsolescence of production capital" (Löschel et al., 2010: 1666). Possible macroeconomic effects of energy price shocks are discussed, e.g. by Bohi & Toman (1993), and they may negatively affect both consumers and suppliers of energy.

After this rather general description of changes in consumer and producer rents caused by supply side shocks, we more specifically consider rent redistributions in Europe, which are caused by electricity shocks exerted by climate change-related extreme weather events, in the subsequent sections.

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[7] Egenhofer (2007) discusses the EU's 'trilemma' in the shape of potentially conflicting objectives for energy security, market liberalization and environmental protection. He points out that the "concern about security of supply in liberalized markets is connected to viewing security as a public good or externality" (Egenhofer, 2007: 88).

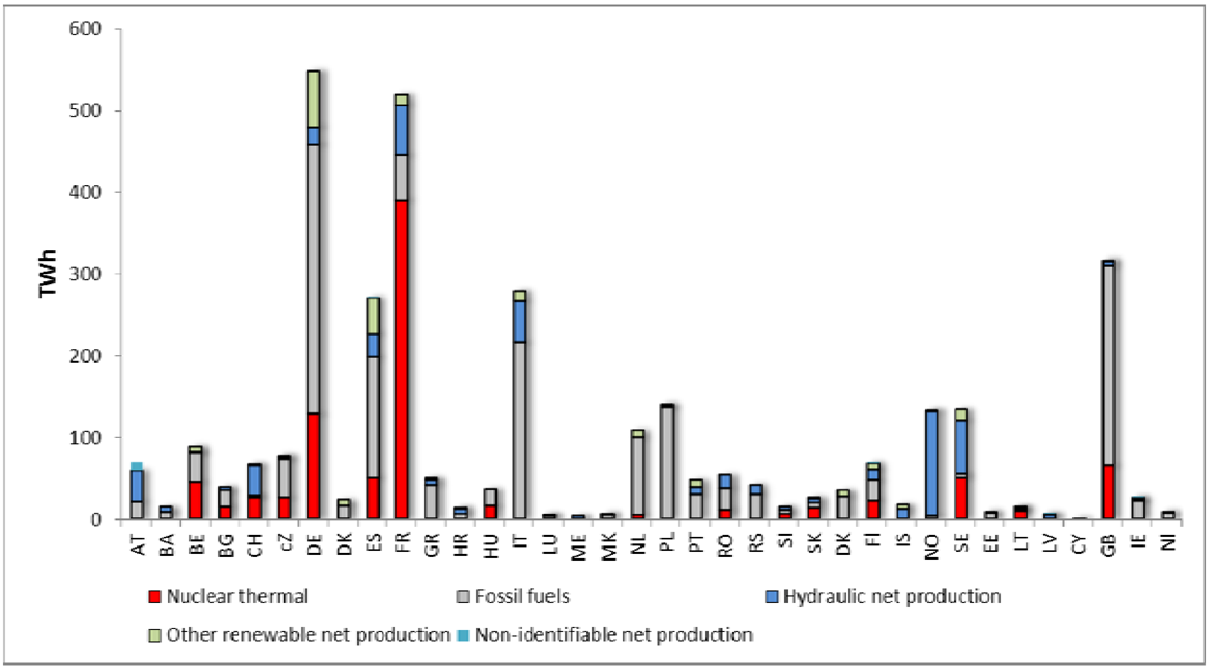
3. Methodology and Scenarios

In our analysis, the impacts of global warming on European electricity supply are supposed to arise from changes in air and water temperature as well as changes in water availability. We focus on electricity supply stemming from nuclear and hydro-power plants because they are major electricity sources in Europe and because they revealed a high vulnerability to changes in air/water temperature and water availability in the past. In the case of nuclear power the vulnerability of each power plant to climate change can be assessed by using statistics of the IAEA (2008). In the case of hydro power there is a very strong correlation between water availability and electricity production. Therefore the vulnerability of hydro-power plants to climate change can be assessed quite well. In contrast, for other power plants (e.g. gas and coal-power plants) specific information about their vulnerability to climate change is usually not available.

Figure 3 gives an overview of the structure of electricity production in Europe. Currently, France, Spain, Germany and UK are European countries where the electricity production is strongly based on nuclear power generation. In countries like Austria, Switzerland and France hydro power is one of the main pillars of the electricity supply system.

In recent years, nuclear power in France, Germany and Spain faced cooling problems caused by water scarcity and increases in the temperature of rivers used for cooling. Water scarcity was also the reason why the electricity production of hydro-power plants was reduced. To take the different characteristics of rivers regarding water availability into account we evaluate the situation at the different power plant sites using data of the IAEA (2008). The sites where power plant had cooling problem in recent years are identified as critical ones and analyzed in more detail.

Figure 3. Electricity generation in Europe



Remarks: AT: Austria, BE: Belgium, CH: Switzerland, CZ: Czech Republic, DE: Germany, DK: Denmark, ES: Spain, FR: France, GB: United Kingdom, HR: Croatia, IT: Italy, LU: Luxembourg, NL: Netherlands, PL: Poland, SI: Slovenia, SK: Slovakia, HU: Hungary, BA: Bosnia/Herzegovina, ME: Montenegro, RS: Serbia, MK: The former Yugoslav Republic of Macedonia, AL: Albania, GR: Greece, BG: Bulgaria, RO: Romania, SE: Sweden, NO: Norway, PT: Portugal, IE: Ireland.

Source: Entso-E (2011).

In order to assess the impacts of climate change on nuclear power plants in Europe we use an approach introduced by Koch & Vögele (2009) (see also Rübbelke & Vögele, 2011). Like in other thermal power plants, in nuclear power plants only a part of the energy input is converted to electricity. The rest of the energy is transformed to heat. That part of heat which is not used for district heating has to be disposed either to the air or by using cooling water. As shown in Koch & Vögele (2009) and Rübbelke & Vögele (2011), the demand for freshwater of a thermal power plant can be assessed by

$$Q^F = \frac{KW \cdot h \cdot 3.6 \cdot \frac{1-\eta_{total}}{\eta_{elec}} \cdot (1-\alpha) \cdot (1-\beta) \cdot \omega}{\vartheta \cdot c \cdot AS} \cdot EZ \qquad (1)$$

where Q^F: cooling water demand [m^3]

KW: installed capacity [kW]

h: operation hours [hours]

3.6 factor to convert kWh to megajoules

η_{total}: total efficiency [%]

η_{elec}: electric efficiency [%]

□: share of waste heat not discharged by cooling water [%]

□: share of waste heat released into air [%]

□□: correction factor accounting for the effects of changes in air temperature and humidity within a year [–]

□: water density [t/m3]

c: specific heat capacity of water [MJ/t K].

AS: permissible temperature increase of the cooling water [K]

EZ: densification factor [–]

Equation (1) describes the links between use of fuels, energy conversion, production of waste heat and demand for cooling water. Based on information on the electricity produced in a period ($KW{\cdot}h$) and data on efficiencies, the amount of total waste heat can be calculated. In Equation (1) the amount of waste heat that has to be removed by using cooling water results from total waste heat ($KW{\cdot}h\cdot$ 3.6.(1-η_{total})/η_{elec}) multiplied by different correction factors accounting for, e.g., the share of waste heat released into the air. The first part of the denominator in Equation (1) describes how much energy is absorbed if one m^3 of water is heated up by one degree centigrade and the second part (AS) of the denominator depicts the degrees centigrade the water is heated. The return water results from waste heat divided by the heating up potential of the water which is calculated by multiplying heat capacity and permissible temperature increase. For the calculation of the freshwater demand it has to be taken into account that, if a cooling tower is used, additional water will be necessary to avoid an increase in salinity caused by water evaporation. By using EZ as densification factor we take this aspect into account.

If no cooling tower is used, the waste heat will be released into the receiving surface water. Using a cooling tower, the waste heat will be released mainly into the air. In the latter case, the demand for cooling water results from losses of water evaporated in the cooling tower. The amount of evaporated water depends on air temperature and humidity as well as on the freshwater which is needed to prevent the build-up of minerals and sediments in the cooling cycle.

The impacts of cooling water shortages and limitations on the increase in water temperature can be assessed by transforming equation (1) to

$$KW = \frac{Q^F \cdot \vartheta \cdot c \cdot AS}{h \cdot 3.6 \cdot \frac{1-\eta_{total}}{\eta_{elec}} \cdot \lambda \cdot (1-\alpha) \cdot (1-\beta) \cdot \varpi \cdot EZ} \quad (2)$$

Assuming limitations in the available amount of cooling water ($Q^F_{\max}$) and a lower permissible temperature increase of the cooling water (AS_{max}), the capacity has to be reduced to

$$KW_{\max} = \frac{Q^F_{\max} \cdot \vartheta \cdot c \cdot AS_{\max}}{h \cdot 3.6 \cdot \frac{1-\eta_{total}}{\eta_{elec}} \cdot \lambda \cdot (1-\alpha) \cdot (1-\beta) \cdot \varpi \cdot EZ} \quad (3)$$

where KW_{max}: usable capacity [kW]

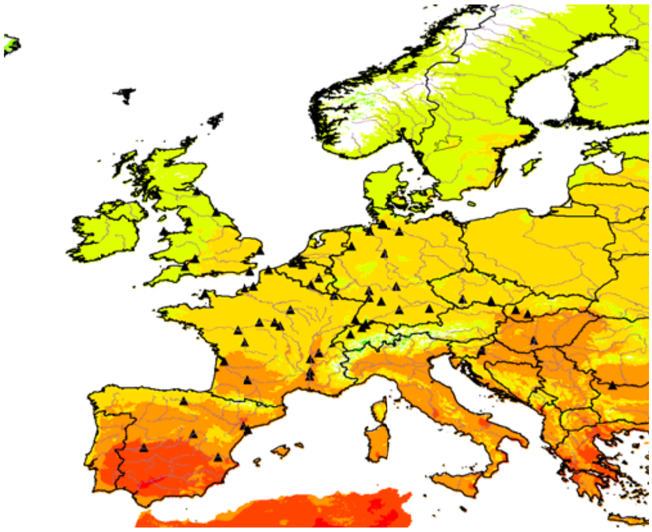
For the scenarios we consider, information on installed power plant capacities, electricity exchange capacities, cost figures and the demand for electricity at a given point in time are needed. For the analysis of the impacts of climate change on the electricity supply also changes in air and water temperature as well as the availability of water have to be specified.

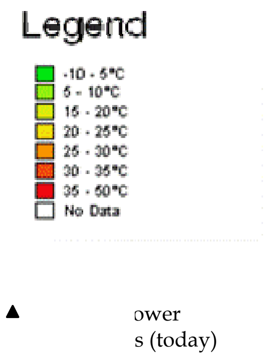
In our study we use figures provided by the Union of the Electricity Industry (EURELECTRIC, 2009) for the description of the power plant stock in 2030. Information on the electricity exchange capacities and on load figures is extracted from a publication of the European Network of Transmission System Operators for Electricity (ENTSO-E, 2011). In addition, we use data of the IAEA (2008) to assess the possibilities to postpone inspections and maintenance periods of nuclear power plants to periods in the summer when plants' cooling systems tend to be at high risk. The employed climate change scenario corresponds to a projection of the Canadian Centre for Climate Modeling and Analysis (CCCMA) for the "A1" emission storyline of the IPCC. The projection is provided with a spatial resolution of a square kilometer which makes it possible to extract power plant site specific data (Govindasamy et al., 2003; WORLDCLIM, 2010); see Figure 4 for respective air temperature data and projections for Europe.

Figure 4. Air temperature in Europe

Average max. air temperature (t_{max}) in Europe

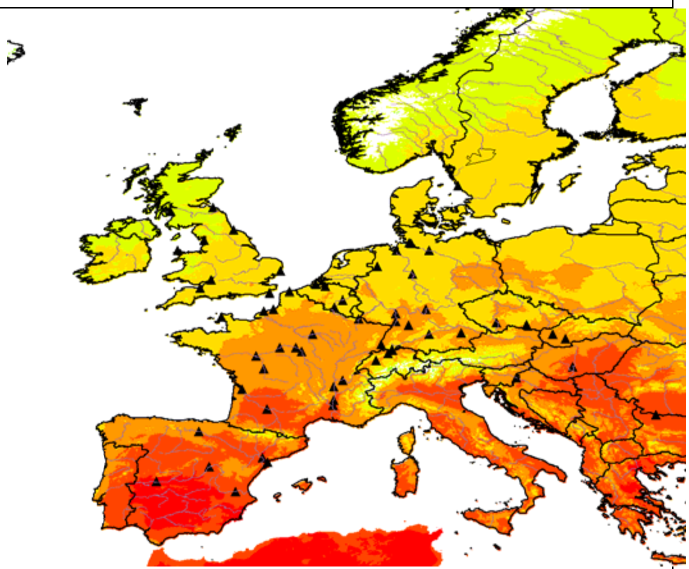
1950-2000 (August)





Air temperature (t_{max}) in Europe

2050 (August)



Source: Govindasamy et al. (2003) and WORLDCLIM (2010).

The data of the climate scenario are used to assess the impacts of higher evaporation rates (caused by changes in air temperature) on the water demand of power plants and to assess increases in the water temperature for individual power plant sites. The interaction between air and water temperature is assessed by using following equation:

$$T_s = \mu + \frac{\alpha - \mu}{1 + e^{\gamma(\beta - T_\alpha)}} \qquad (4)$$

where T_s: stream water temperature [°C]

T_α: air temperature [°C]

μ: estimated minimum stream temperature [°C]

α: maximum stream temperature [°C]

γ: steepest slope of the function [°]

β: air temperature at the inflection point [°C] (see Mohseni et al., 1998; Webb et al., 2003; Morrill et al., 2005; Pedersen & Sand-Jensen, 2007 and WWF, 2009).

The parameters for the air/water temperature relationship are derived from the literature (Morrill et al., 2005 and WWF, 2009): The minimum stream temperature is assessed to be 0°C, the maximum stream temperature 29°C, the steepest slope 0.14 and the air temperature at the inflection point 16.5°C. For each power plant site, specific data on air temperature is extracted from the climate model. The data are inserted in equation (4) in order to calculate the power plant site specific water temperatures.

Due to a lack of data and in order to limit the complexity of our study, we assume that all nuclear power plants have the same efficiency. In addition, we assume a densification factor of 3 for all power plants with closed-circuit cooling system. These assumptions have been chosen in accordance with DOE/NETL (2007) and World Nuclear Association (2010).

The 'Reference' scenario describes the situation without climate change and the scenario 'Climate Change/Slight Water Scarcity' refers to the situation with changes in air and water temperature. In accordance with Umweltbundesamt (2008), we assumed for this scenario a reduction in runoff of rivers of up to 10%. The impacts on the electricity supply of a more serious water scarcity are analyzed in the third scenario ("Climate Change/More Serious Water Scarcity"). Here we assumed a reduction runoff of rivers of up to 25%.

With an optimization approach implemented in GAMS, we assess the cost-optimal use of the existing power plants for each country in Europe taking electricity import and export capacities into account. Based on electricity prices calculated for each country and information on the variable costs of the different power plants (including fuel costs), country-specific producer surpluses are identified. The producer surpluses are used as indicators identifying those countries where the electricity suppliers will benefit or suffer from climate change.

4. Results

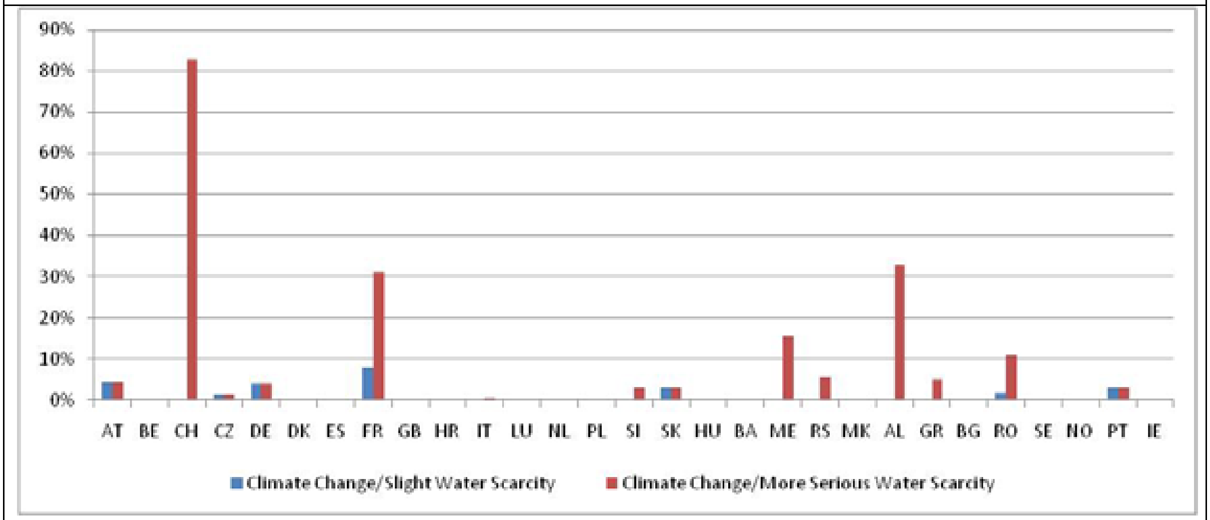
In our calculations, in the "Climate Change/Slight Water Scarcity" scenario during the peak load time in summer, the available capacity of nuclear power plants will be reduced by 6 GW and the available capacity of hydro-power plants by 12 GW due to the assumed increases in air and water temperature and decreases in water availability. In the scenario "Climate Change/More Serious Water Scarcity", the capacity that is unavailable will rise in total by another 19 GW.

Climate change will have impacts not only on the production levels but also on the electricity prices. Gas and coal power plants will be used to compensate supply gaps. Because the production cost of these power plants are higher than the ones of nuclear and hydro-power plants, electricity prices will increase. In the "Climate Change/Slight Water Scarcity" scenario, the prices for electricity increase in Belgium, France, Germany, Great Britain, Hungary, Portugal, Romania and Slovakia. The price effects in this scenario are relatively small. The changes in prices are significantly higher in the climate change scenario with higher water scarcity. In this scenario, the electricity prices in Switzerland, for example, rise by 80% because expensive gas-fired power plants would be put into operation. In the reference scenario, only 'cheap' hydro and nuclear-power plants were employed in this country. With the need to raise the use of gas-fired power plants, also in other European countries the electricity prices are expected to increase significantly (Figure 5).

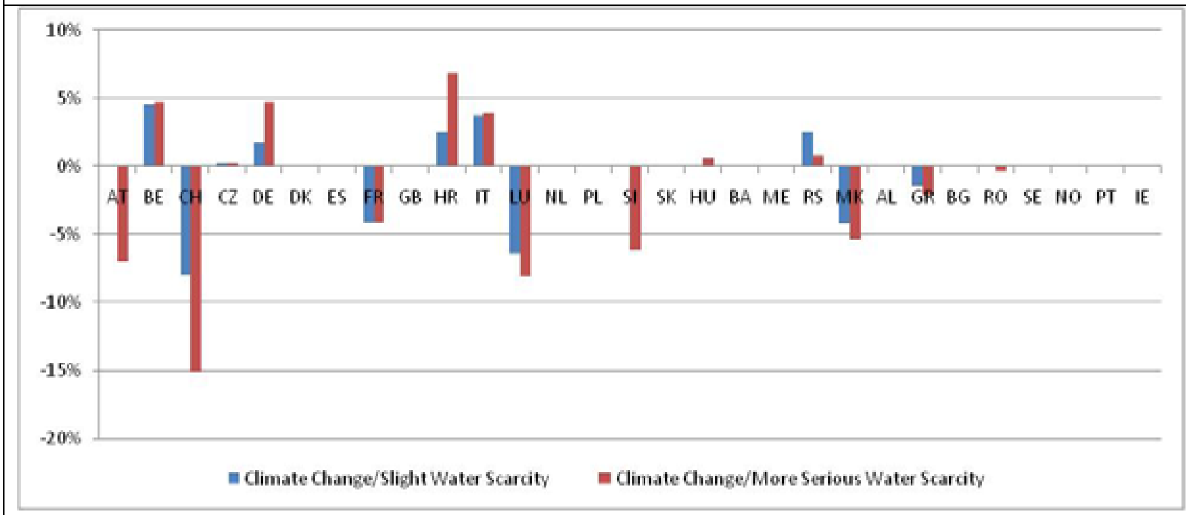
In both climate change scenarios, the use of domestic power plants is extended in countries like Belgium, Germany, Hungary, Italy and Spain. In other countries domestic electricity production decreases because of limitations in the use of nuclear and hydro-power plants caused by limitations in their availability and the induced increases in domestic electricity generation costs. These countries will tend to augment their imports of electricity or reduce their exports.

Figure 5. Changes in electricity prices and generation

Changes in prices



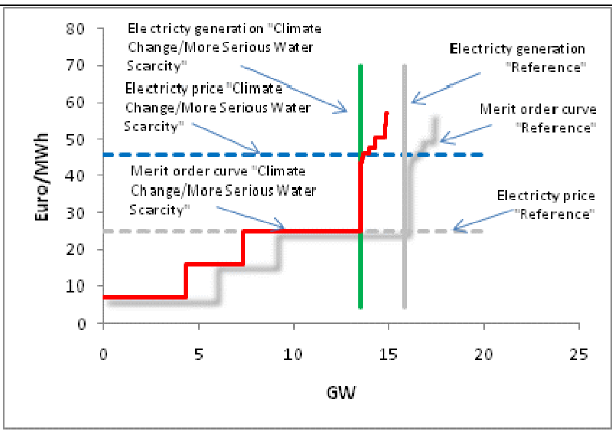
Changes in production



Examples for the potential impacts of climate change on suppliers' rents are presented in Figure 6. This figure shows the electricity supply of Switzerland and Germany with and without climate change. In the reference scenario, power plants with an overall capacity of 16 GW are in use in Switzerland and with an overall capacity of 72 GW in Germany. Assuming that electricity prices correspond to the marginal generation cost at that deployed power plant which exhibits the highest marginal cost, the electricity prices will reach €25/MWh in Switzerland and €53/MWh in Germany. In the "Climate Change/More Serious Water Scarcity" scenario, less hydro and nuclear power plants will be available. Therefore, the merit order curves (reflecting supply curves as those used in simplified ways in Figures 1 and 2) move to the left and consequently the electricity prices increase. The increase in the prices induces a lower demand of other countries for electricity produced in Switzerland as well as France, because other countries can supply additional electricity in a cheaper way. Germany will import less electricity from France and Switzerland and will extend the use of domestic power plants.

Figure 6. Electricity production in Switzerland and Germany (2030)

Switzerland



Germany

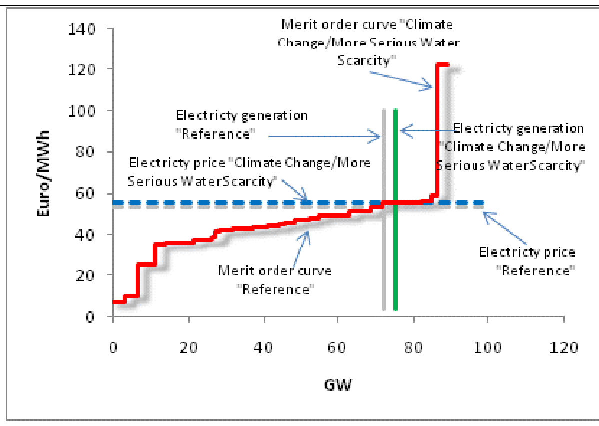
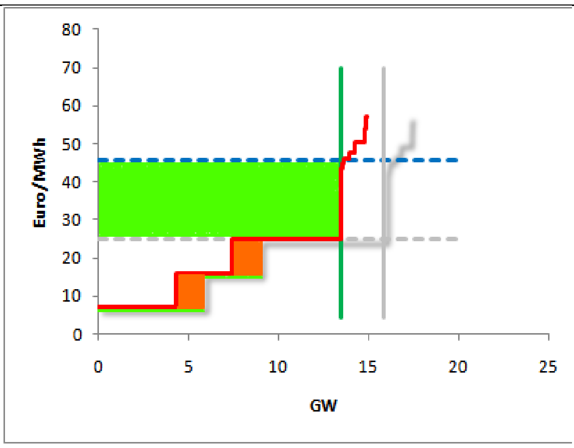


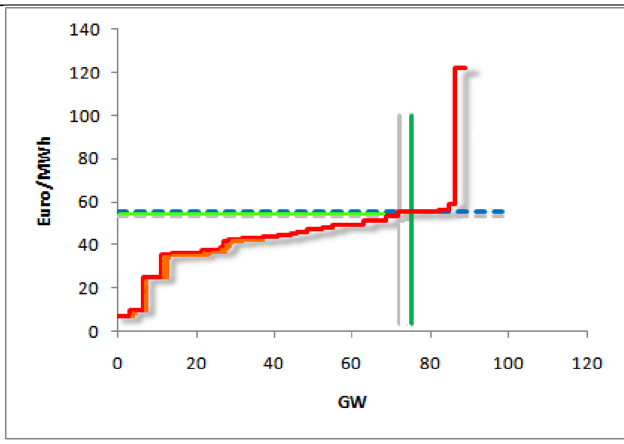
Figure 7 shows the changes in the suppliers' rents in Switzerland and Germany. On the one hand, the increase in prices causes an augmentation of suppliers' rents. On the other hand, the reduction in domestic supply diminishes suppliers' rents. All in all the changes in the suppliers' rents in Switzerland will increase by 190% and the rents in Germany by 9%.

Figure 7. Changes in the suppliers' rents of Switzerland and Germany

Switzerland



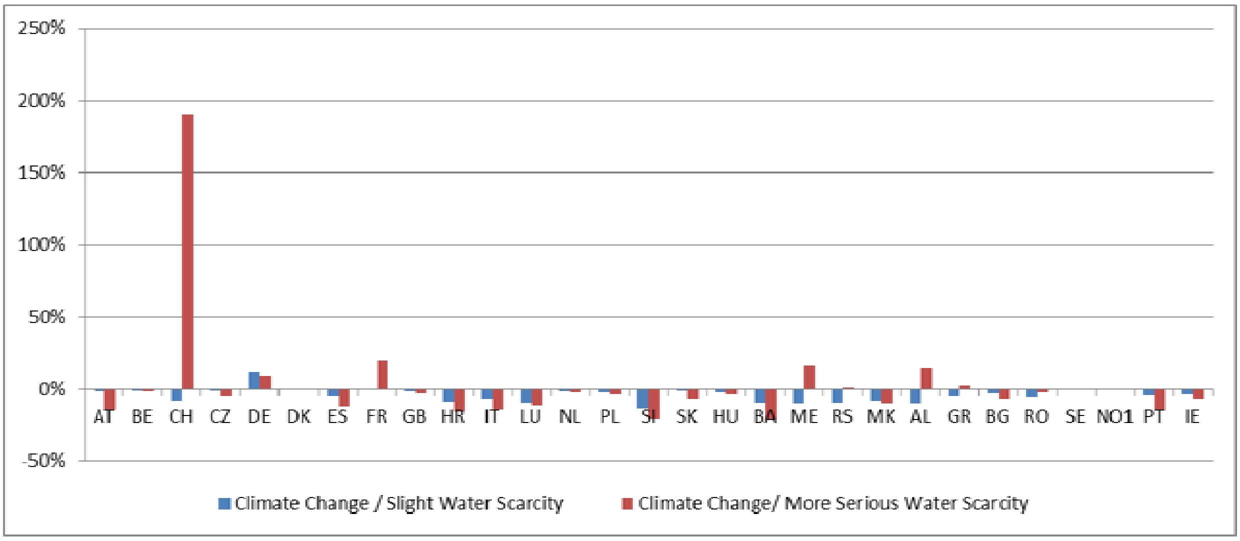
Germany



Remarks: Green: increases in suppliers' rents; orange: decreases in suppliers' rents.

Figure 8 gives an overview of the suppliers' rents in the individual European countries. In our scenario the electricity suppliers in Germany will belong to the beneficiaries of climate change. In contrast, the suppliers' rents of e.g. Austrian, British and Spanish suppliers, will decrease due to changes in the electricity supply curve and a decline in the capacity for electricity exports. In Switzerland the change in suppliers' rents depends on the extent of climate change-related water scarcity. They only decline in the climate change scenario with slight water scarcity, because in this scenario the Swiss production will be reduced whereas the electricity price will remain almost on the level of the reference scenario.

Figure 8. Impacts of climate change on suppliers' rents



5. Conclusions

Nuclear energy is frequently regarded as a vehicle to reduce CO_2 emissions and thus to combat global warming (see e.g. Apergis et al., 2010). Yet, there is also a reverse interrelation: the nuclear power sector is negatively affected by climate change, since cooling processes of power plants are likely to be impaired by climate change-related extreme weather events like drought and heat waves. Such incidences also interfere with hydro-power generation. Consequently, while representing options for climate change mitigation, these two energy sources – which were in the focus of our analysis – at the same time require adaptation to ongoing climate change.

Autonomous adaptation in the energy sector takes place via international electricity markets inducing a temporary reallocation of power generation among different sectors and plant locations. In order to assess climate change impacts on power supply patterns in Europe and to ascertain induced rent redistributions both between power suppliers and between suppliers and consumers, we considered temporary autonomous adaptation in response to extreme weather patterns (heat waves and drought) for different climate change scenarios. We found that strong declines in electricity generation due to climate change tend to occur, e.g. in Austria, France and Switzerland. By means of changes in European power generation patterns as well as in import and export balances, local electricity shortages can be overcome, but prices tend to rise significantly in some European countries, e.g. in Switzerland by more than 80% and in France by more than 30% in one of our scenarios. However, depending on the degree of global warming, the real effects might be even stronger.

While European consumers will throughout lose welfare due to the rise in electricity prices, some European suppliers might gain from the climate-change induced disruptions of hydro and nuclear power. The change in suppliers' rents depends on the severity of global warming, as can be easily observed from the Swiss case, where a moderate climate change scenario implies a decline in respective rents, while stronger global warming tends to augment these rents. The latter is due to the fact that electricity prices will increase much more in the case of strong global warming and the Swiss suppliers can therefore usurp additional rents at the expense of the consumers of electricity.

Hence, besides the possibility that solely autonomous adaptation via reallocation of power generation might become insufficient to prevent power supply disruptions caused by ongoing climate change and rising severity of associated extreme events in future, there is a second reason for also executing advance strategic public policy intervention concerning adaptation (which complements autonomous adaptation) in the electricity sector: the short-term, temporary reallocation of power generation might cause an undesired redistribution of wealth.

Such strategic public policy intervention concerning adaptation could either target the affected power sector itself or it may (also) address the upstream water supply sector. In the latter case, an improvement of the management of water supply is an option. Yet, many European river basins supplying cooling water are transnational and therefore an international coordination is required in many cases. Improvements in the power sector itself could be attained, e.g. by increasing power plant efficiencies. These measures (improvement in the management of water supply and augmentation of power plant efficiencies) tend to have positive consequences for the hydro and nuclear-power supply and consequently may help to prevent both power supply disruptions as well as potentially undesired welfare redistributions (which could be perceived to arise e.g. if large rents are redistributed from consumers to individual suppliers whose supply cost have not or only slightly increased).

Another option to prevent power supply disruptions is the diversification of the sources of supply. The augmentation of the use of such power plants that do not require cooling systems (e.g. photovoltaic installations) could contribute to the mitigation of adverse effects of climate change on the electricity supply system. However, the option of raising the use of expensive photovoltaic installations does not prevent those undesired rent redistributions between consumers and producers we discussed in this paper. However, it might affect the redistribution of suppliers' rents among nations.

Furthermore, in order to mitigate unfairness perception *ex post*, those rents which governmental decision-makers consider to be unfairly usurped by the suppliers at the expense of consumers could be (partly) taxed away and the revenues could be employed for public measures mitigating global warming or helping to adapt to it. In this manner, beneficiaries of (higher electricity prices induced by) climate change could take their share in financing climate policies.

Yet, such a tax scheme should be designed with care, because it may adversely as well as positively affect suppliers' incentive structures. On the one hand, it should not yield disincentives for suppliers to provide sufficient power reserve capacities. The price is an indicator for scarcity and a high price provides incentives for raising investments in the supply infrastructure. On the other hand, a tax levied on rents acquired only due to temporary climate change effects provides disincentives for suppliers to usurp additional rents by manipulating prices via strategically reducing power supply in summer peak-load periods.

Although we did not discuss the potential impact of the design of network infrastructures on rent distribution, the related effects might be significant and seem to provide some scope for future research.

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