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Impacts of climate change on European critical infrastructures: The case of the power sector

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ABSTRACT

Climate change induces various direct and indirect impacts. Among the direct effects are the likely rise in the frequency of heat waves and droughts in Europe. These immediate effects of climate change, in turn, cause downstream effects. Drought-induced water scarcity and lack in water supply affect further sectors and critical infrastructures. A lack in water supply for cooling purposes, for example, will negatively affect the electricity generation in power plants.

In this paper we analyze the consequences of climate-change related impacts on such interplays between climate-change affected sectors. More specifically, we investigate how electricity exchanges between countries in Europe are affected and threatened by climate change because of the higher risk of water supply shortages due to more frequent drought and heat-wave incidences.

1. Introduction: climate change and critical infrastructures

In 2009, a summer heat wave caused cooling water shortages in France. As a consequence the French nuclear power generation level dropped significantly. France even had 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 were put out of action (Pagnamenta, 2009).

The positive aspect of this specific incidence was that national shortages of electricity could be compensated for by the European electricity exchange system. Yet, according to the IPCC (2008a), because of global warming the frequency of periods characterized by water shortages and by high water temperatures will increase in Europe in future. Therefore, a crucial question is whether the European electricity (exchange) system will be able to cope with these aggravating threats in future. About 43% of the European Union's water demand is used as cooling water by power authorities (EUREAU, 2009: 21) and hence especially these authorities tend to be seriously challenged and affected by climate change in future.

Periods in which cooling water shortages occurred have been experienced in Europe not only in 2009, but recurrently in the recent years. Already in the summer of 2003 more than 30 nuclear power plant units in Europe had to reduce their

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production because of limitations in the possibilities to discharge cooling water (IAEA, 2004). Although some nuclear power plants got exemptions from legal requirements to be able to continue their operating activities, the whole electricity exchange system was affected by the limitations in the production possibilities of the power plants: As a result of the cooling problems of the nuclear power plants and like in the summer of 2009, the electricity exporting France had to import electricity from Great Britain in the summer of 2003 to be able to supply enough electricity to Italy and other countries (UCTE, 2004). Since European countries are interconnected by the European electricity grid, regional power supply shortages exert spillovers beyond the directly drought-affected European regions. Hence, the functioning of the power supply and exchange infrastructures is critical for all European countries attached to the grid.

In order to preserve the functioning of the European power sector by adequately adapting it to ongoing climate change,[1] information about the impacts of climate change on the European electricity exchange system and its capability for compensating for national or regional power supply shortages are required. Due to the long lifetime of infrastructures and the magnitude of investments in the electricity sector, adaptation options should be included already in today's planning and strategies (BMU, 2007: 2–3).

The protection of critical infrastructures, like the electricity sector, has indeed become a major concern in the European Union (EU) in recent years. In 2004, the European Commission adopted a Communication with the title ''Critical Infrastructure Protection in the Fight against Terrorism'' (EC, 2004) and, thereafter, in 2005, the Commission adopted a Green Paper (EC, 2005) on a European Programme for Critical Infrastructure Protection (EPCIP). In the Green Paper, the need to help reducing vulnerabilities concerning critical infrastructures was acknowledged. The threats are seen in terrorism, natural disasters and accidents; the risk of any disruptions or manipulations of critical infrastructures should be minimised. Consequently, while the initial focus of the emerging European Critical Infrastructure Protection (CIP) policy was on terrorism as a threat for disruptions, the policy evolved into an all-hazards approach. In December 2006, the European Commission adopted a Communication (EC, 2006) which describes the overall framework for EU-level CIP activities.

The Green Paper (EC, 2005) on the EPCIP adopts the principle of subsidiarity such that the EU would only be responsible for the CIP of those infrastructures whose disruptions would cause cross-border effects. Member States have to conduct CIP of those infrastructures whose disruptions would mainly affect the state itself, but their CIP is to be executed under a common EPCIP framework. The European Commission considers critical infrastructures (CIs) to be European CIs, if they or disruptions of them significantly affect at least two EU member states. The European Council identified energy and transport sectors as European CIs (EC, 2008). Yet, the European Council also pointed out that it pursues a step-by-step approach to identify and designate ECIs and that energy and transport sectors are those chosen in the first step. Other candidate sectors are (1) information, communication technologies, (2) water, (3) food, (4) health, (5) financial, (6) public and legal order and safety, (7) civil administration, (8) chemical and nuclear industry, and (9) space and research (Annex 2 of EC, 2005).

The relevant sectors can be split into subsectors. In this paper the energy subsector 'electricity subsector which includes infrastructures and facilities for generation and transmission of electricity in respect of supply electricity' (see Annex I of EC, 2008) is of main relevance. Currently, nuclear power has a share of 28% in the electricity supply of the EU (EUROSTAT, 2010) and thus, disruptions in the use of nuclear power plants tend to have especially significant impacts on the European electricity supply system. Consequently our analysis will focus on this important subsector of energy generation. In the water sector we are mainly interested in the subsector which is concerned with water-supply issues. In the European Union, 40 of the 110 existing river basins are international (EC, 2007: 20) and hence these 40 water supplying basins meet – like the power supply sector – the European CI criterion to concern more than one country.

More specifically, we are interested in the links between these two subsectors despite the fact that the common EPCIP framework which – according to the Green Paper (EC, 2005) – has to define competences and responsibilities of involved agents, envisages to settle CIP principles on a sector-by-sector basis. On the one hand, ''[s]uch a strategy allows for CIP to be tailored to different CI needs and varying legal competences for CIP across the policy spectrum'' (Fritzon et al., 2007: 32). Yet, on the other hand, the fragmentation of regulations must not go so far that spillovers and synergies between different sectors become disregarded and will not be exploited. ''Assessing the impact of systemic interactions is one of the most important but least understood aspects of modern risk assessment'' (IRGC, 2009: 25).

There are many examples of close relationships and interdependencies between different CIs. As Watts (2003: 559–560) explains, power grids might be affected by communication system disruptions (e.g., caused by terrorist attacks). Little (2002: 111) gives the example of failures in the communication system affecting the health sector. Svendsen and Wolthusen (2007: 44) refer to interactions between electric power grid and the telecommunications sector. De Bruijne and van Eeten (2007: 19) even stress that CIs ''are becoming more dependent on each other's 'always on' availability'' and as a consequence these infrastructures have ''become increasingly vulnerable to large-scale, cascading disruptions across sectoral boundaries''. Or as Kröger (2008: 1781) puts it: ''recent decades have witnessed on the one hand a development towards a highly integrated system of interdependent systems, and on the other hand an increased social vulnerability in the face of loss of continuous operation''. He stresses that additional hazards and threats to CIs have also arisen. By investigating the consequences of climate-change induced shortage of water supply (droughts), we follow the advice given by the OECD (2003: 50): ''Attention has to be less focused on the occurrence and direct consequences of a hazard, and be more geared towards indirect cause-effect relationships,

[1] Of course, climate change may affect the energy supply in various ways. Potentially rising frequency and intensity of storms may increase the frequency and duration of power system blackouts, for example.

diffusion, and long-term effects''. While climate change is the initial effect induced by anthropogenic emissions of greenhouse gases, droughts are a successive indirect consequence which in turn generates another sequence of problems (disruptions in the generation of power). In contrast to other papers analyzing possible effects of climate change on power plants and other water users (see e.g., DOE/NETL, 2007; EPRI, 1995; Förster and Lilliestam, 2010; Hurd and Harrod, 2001; Koch and Vögele, 2009; Müller et al., 2007), we present an approach that does not analyze the effects on individual power plant sites or the overall economy but impacts on transnational electricity exchanges. This allows considering the spillovers of regional shocks in electricity generation to other regions of the European Union.

The main objective of our analysis is to determine the effects of global warming on the European supply structure of nuclear power and the national effects of induced changes in the exchange of power via the European grid. For three different scenarios threats of electricity-supply shortages to individual European countries are elaborated and potential future bottlenecks are identified. These findings will help to adapt the European electricity supply scheme adequately to the global warming threat and due to the illustrated interrelations between the two considered European CI we challenge the sector-by-sector approach favoured by the European Union in its European CI protection strategies.

The analysis is structured as follows. In Section 2, we will assess the impacts of climate change on the electricity system taking into account country-specific shares of nuclear power in the electricity system and the exchanges of electricity between the countries. More specifically, Section 2.1 specifies our model and describes the three considered scenarios. In Section 2.2, we outline our theoretical approach on which our analysis is based. In Section 2.3 the results are presented and discussed. Section 3 provides a critical discussion of the results in view of the context of the paper as well as a short outlook.

2. Impacts of climate change on nuclear power plants and electricity supply in Europe

Before we develop our model and turn to the analysis, a short description of the locations of the considered European nuclear power plants is provided in order to illustrate the heterogeneity of the significance of the cooling problems among different European regions. Although droughts and cooling problems are more pressing in some specific European regions than in others, all European regions are affected by deteriorations in regional energy supply since they are all connected to the European electricity grid and transfer electricity via it.

Most of the nuclear power plants in Europe are located in France, but Germany, the UK and Spain also have a large number of such plants. In contrast to the UK, which was exporting electricity to France during the heat waves in 2003 and 2009, in other European regions nuclear power plants are mainly located at rivers inland, where cooling water shortages are especially pressing during heat waves (in contrast to areas which are located at the sea coast). Fig. 1 gives an overview of the distribution of nuclear power plants in Europe and those plants which had cooling problems in the past are highlighted. The nuclear power plants with cooling problems in summer are mainly located in the south of Europe and onshore near big rivers. The nuclear power plants in the UK did not face cooling problems in recent years and this explains why the British electricity exports could help to compensate for supply shortages in France.

In the next subsection, we specify the scenarios that we will employ for a closer analysis of the potential future impacts of climate change on the European electricity system.

2.1. *Specification of the scenarios*

In order to analyze what will happen to electricity production and exchange if air temperature rises due to global warming, we consider a situation that comprises the following two components: (1) the investigated scenarios are based on the electricity supply and exchange situation of August 2007 (IAEA, 2004; UCTE, 2008) and (2) 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 and is provided with a spatial resolution of a square kilometer. Let us have a closer look at these components.

(1) In 2007, Germany, France, Great Britain, Spain and Italy had the highest shares of electricity generation in Europe. In Germany, Italy and Great Britain the demand for electricity was higher than the domestic production in the summer months. So they had to import electricity. Most of the electricity that these countries needed was provided by France (see Fig. 2).

    Usually nuclear power plants are inspected, maintained and refueled each year. If the power plant companies choose July or August to do this, they can avoid cooling problems. According to data of IAEA, we assess the potential to do this for France with 8 GW, for Germany with 3.5 GW and 0.5 for Switzerland, Spain, Czech Republic and Hungary (IAEA, 2008).

(2) The climate change scenario we employ is provided with a spatial resolution of a square kilometer. In this storyline a rapid economic development with strong attitudes to market-based solution is assumed. As one result of the increase in CO_2 emissions, the air temperature in Europe in the summer will rise by 3 K on average (see Govindasamy et al., 2003; WORLDCLIM, 2010). If the climate changes as Govindasamy et al. (2003) expect, especially in the south of Europe air and therefore also water temperatures will increase significantly (see Fig. 3). We selected this scenario because of its high resolution. Because of the resolution power plant site specific data can be extracted. Comparing the scenario with the situation in Europe in summer of 2003, the scenario seems to be very realistic. In our analysis the data of the climate scenario is used not only to assess increases in the water demand of power plants caused by higher evaporation rates (due to the changes in air temperature) but also to calculate increases in the water temperature for each power plant site.

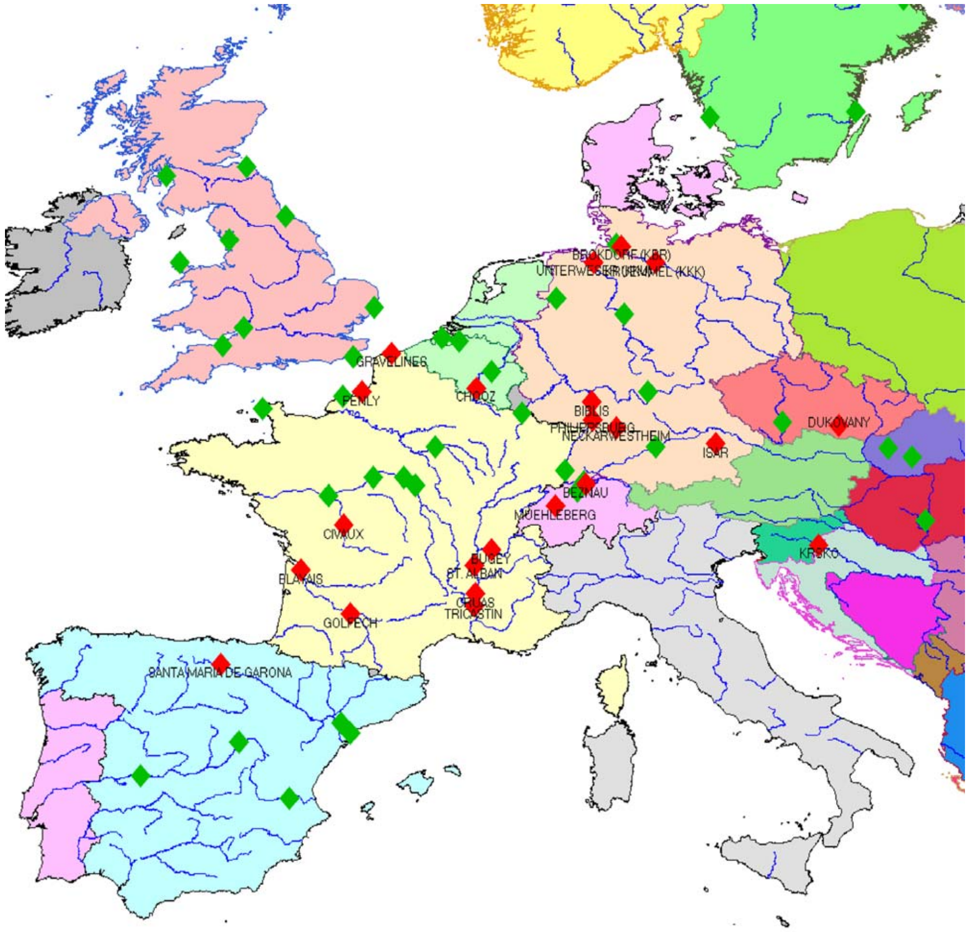

Fig. 1 – Nuclear power plants in Europe. Remarks: Red: Nuclear power plants with cooling problems in recent; green: nuclear power plants without cooling problems in recent years. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.) Source: IAEA (2004, 2008)

Because data on the future of the water availability is not available for each of the critical power plant sites we analyze three different specific scenarios distinguishing different water availability levels: the first one reflects the situation of August 2007. In the second one (scenario ''climate change + slight water scarcity'') we assume an increase in air and water temperatures with no extension of the water intake. Increase in air and water temperature result in higher demand for fresh water.[2] Without the possibility to increase the water intake the power plants have to reduce their production. In the third scenario (scenario ''climate change + more serious water scarcity'') we assume that 10% less water than in the second scenario will be available.

2.2. *Description of the theoretical approach*

To be able to assess the impacts of changes in humidity, air and water temperatures as well as in the availability of freshwater on production processes in thermal power plants it is necessary to analyze the freshwater demand of the power station that is needed to run the station without cooling constraints. The demand for freshwater of a thermal power plant can be calculated by

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

where Q^F: cooling water demand [m^3]; KW: installed capacity [kW]; h: operation hours [h]; 3.6 factor to convert kWh to megajoules; η_{total}: total efficiency [%]; η_{elec}: electric efficiency [%]; α: share of waste heat not discharged by cooling water [%]; β: share of waste heat released into air [%]; ω: correction factor accounting for the effects of changes in air temperature and humidity within a year [–]; ϑ: water density [t/m^3]; c: specific heat capacity of water [MJ/t K]; AS: permissible temperature increase of the cooling water [K]; EZ: densification factor [–]; (Koch and Vögele, 2009).

Eq. (1) describes the link 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. Usually in power plants only 30%

[2] In order to run the power plants without any limitations on the production, on average about 15% more water will be necessary.

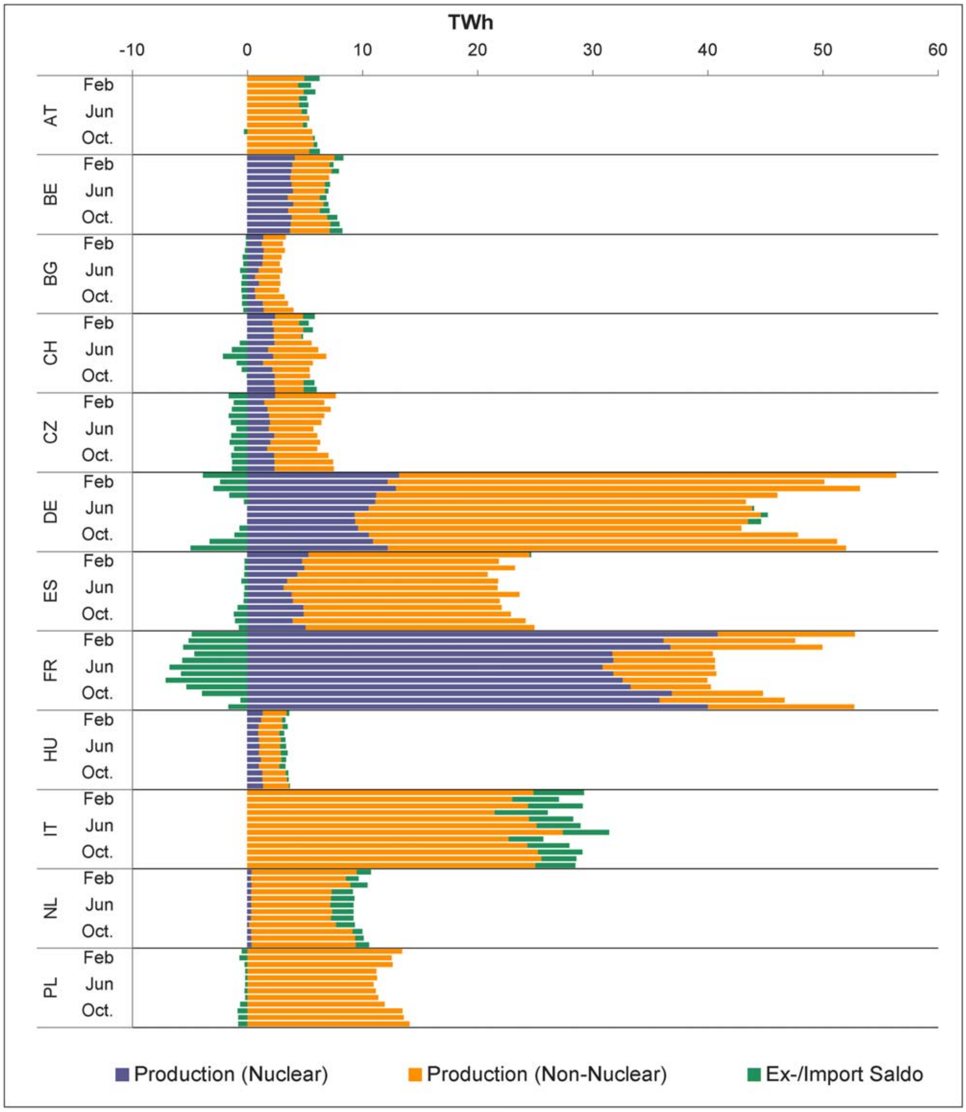

Fig. 2 – Net-electricity production and electricity im-/export in the year 2007. Source: ENTSO-E (2010)

(e.g., old coal power plants) to 55% (new gas-fired power plants) of the energy input is coverted to electricity. The rest of the energy is converted into heat. The heat which is not used for districting heating has to be taken away either to the air or by using cooling water. In Eq. (1) the amount of waste heat that has to be removed by using cooling water results from total waste heat ($KW \cdot h \cdot 3.6 \cdot (1 - \eta_{total})/\eta_{elec}$) multiplied by different correction factors taking, e.g., the share of waste heat released into air into account. The first part of the denominator in Eq. (1) describes how many 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 consideration.

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.

Cooling problems will arise if there are limitations on water temperatures and limitations on the availability of fresh water: In order to heat up one litre of water by 1 °C, there is a need of 4.2 kJ. Consequently, if it is allowed to heat up the water from 18 °C to 28 °C, there will be a need of 1 m^3 of water for disposing an amount of 42 MJ heat. If the heating-up temperature is limited to 5 °C (23–28 °C), there will be a need of 2 m^3 of water. If an extension of the water withdrawal is not

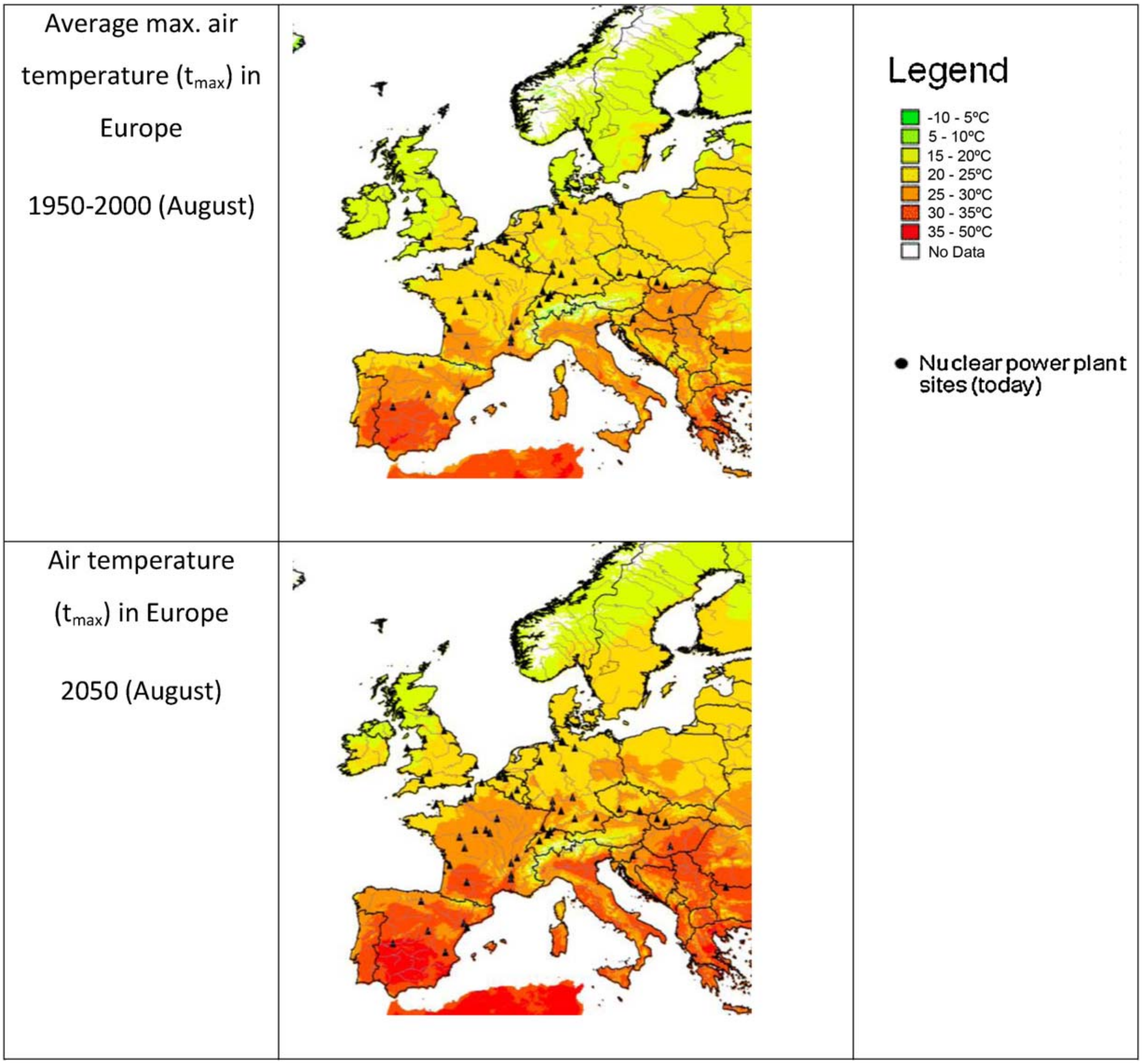

Fig. 3 – Air temperature in Europe. Source: Govindasamy et al. (2003) and WORLDCLIM (2010)

possible, production has to be reduced by 50%. Therefore, both the warming-up limitations and water availability have to be taken into account.

The impacts of cooling water shortages or limitations on the increase in water temperature and available amount of cooling water can be assessed by transforming Eq. (1) to

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

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 reduced to

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

where KW_{max}: usable capacity [kW].

Fig. 4 shows the relation between possible electricity production and permissible water intake for a 1200 MW nuclear power plant with a closed-circuit cooling and for a power plant with a once-through cooling system. Usually there are several legal constraints for power plants regarding the temperature of the discharged water. So power plant operators are not allowed to discharge water with a temperature above 28/30 °C (once-through cooling system) or 35 °C (closed-circuit cooling system) and not more than 10 °C warmer than the water temperature of the river the cooling water is discharged in (see e.g., BUND, 2009). A low permissible temperature can be compensated for with a higher volume of cooling water. If the amount of permissible water intake is constrained the power plant has to reduce its production. In the example presented in Fig. 4, a reduction of permissible temperature rise from 10 °C to 6 °C results in an increase of the freshwater demand from 52 m^3/s to 86 m^3/s.

If the possible water intake is limited to 52 m^3/s the power plant will have to decrease its production by 40%. Using a closed-circuit cooling system, significantly less water is necessary than if a once-through cooling system is used (see Fig. 4). Closed-circuit cooling systems are basically used

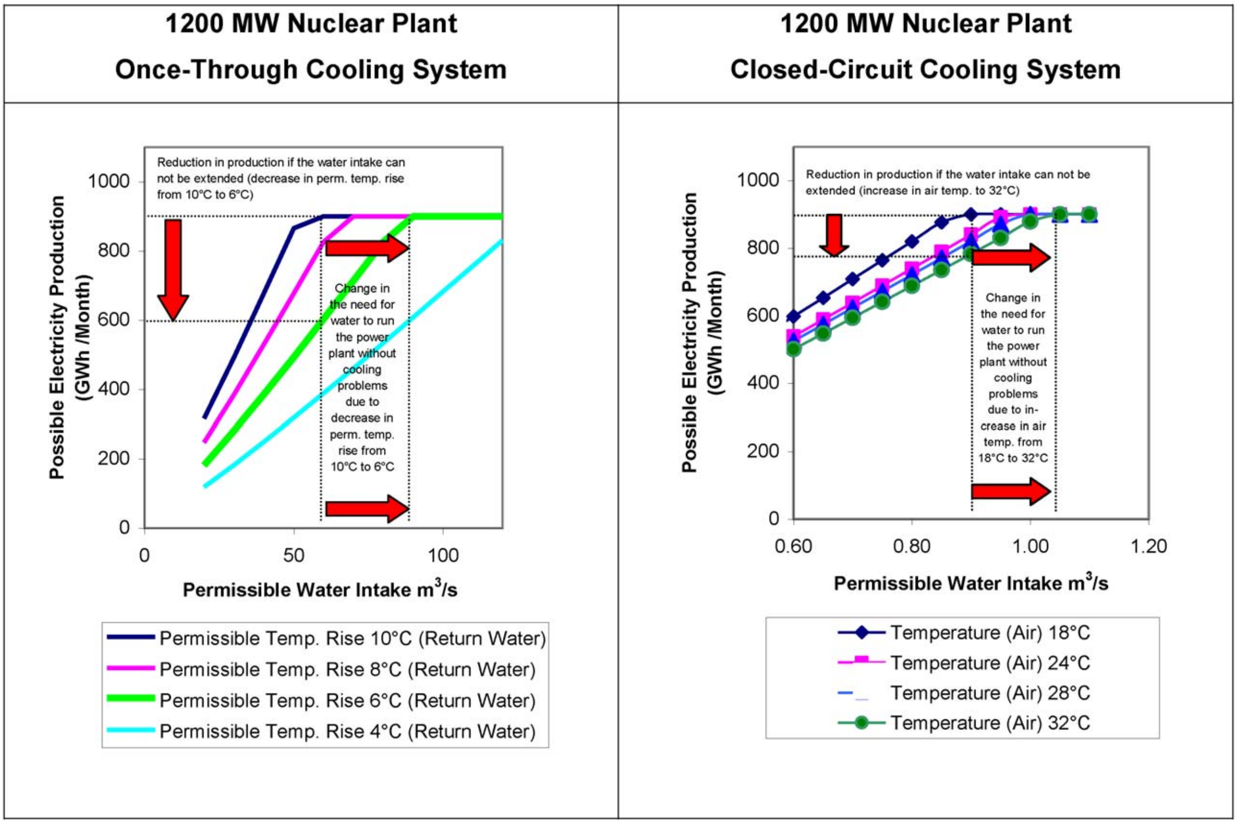

Fig. 4 – Permissible water intake and electricity production.

in combination with cooling towers. In contrast to the once-through cooling system the water demand of this kind of cooling depends also significantly on the higher air temperature. With higher air temperatures the evaporation and therefore the demand for freshwater increases. In our example the demand for freshwater will rise by 17% if the temperature increased from 18 °C to 32 °C. Again, if the permissible water intake cannot be extended, the power plant has to reduce its production (see Eq. (1)).

According to the relevant literature, the interaction between air and water temperature can be described by:

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

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 and Sand-Jensen, 2007; WWF, 2009).

Besides the analysis of the vulnerability of nuclear power plants to changes in air and water temperatures, our main concern is to investigate how climate-change induced modifications of the power plant's production affect the European electricity exchange system. Regarding the influence of changes in electricity production on ex- and imports of electricity we assume that individual countries adjust their electricity exports by the same rate at which their imports have changed.

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).

In our calculations we assume that the demand for reserve capacities and the load still remain on the level of 2007. This assumption was selected in order to identify problems in the electricity supply system in a first approximation without the need for a closer discussion of the reserve strategies of utilities and possible measures on the political level. In the reference situation enough water is available to use the power plants without any constraints. The analysis of the heat summer of 2003 shows that at a greater number of power plant sites the permissible water intakes cannot be expanded if the temperature in summer increases strongly (see IAEA, 2004). Taking this observation into account we assume that at the power plant sites where power plants had cooling problems in recent years also in the future an expansion of the permissible water intake will not be possible.

The parameters for the air/water temperature relationship are derived from the literature (Morrill et al., 2005; WWF, 2009): The minimum stream temperature is assessed to be 0 °C, the maximum stream temperature to be 29 °C, the steepest slope to be 0.14 and the air temperature at the inflection point to be 16.5 °C.

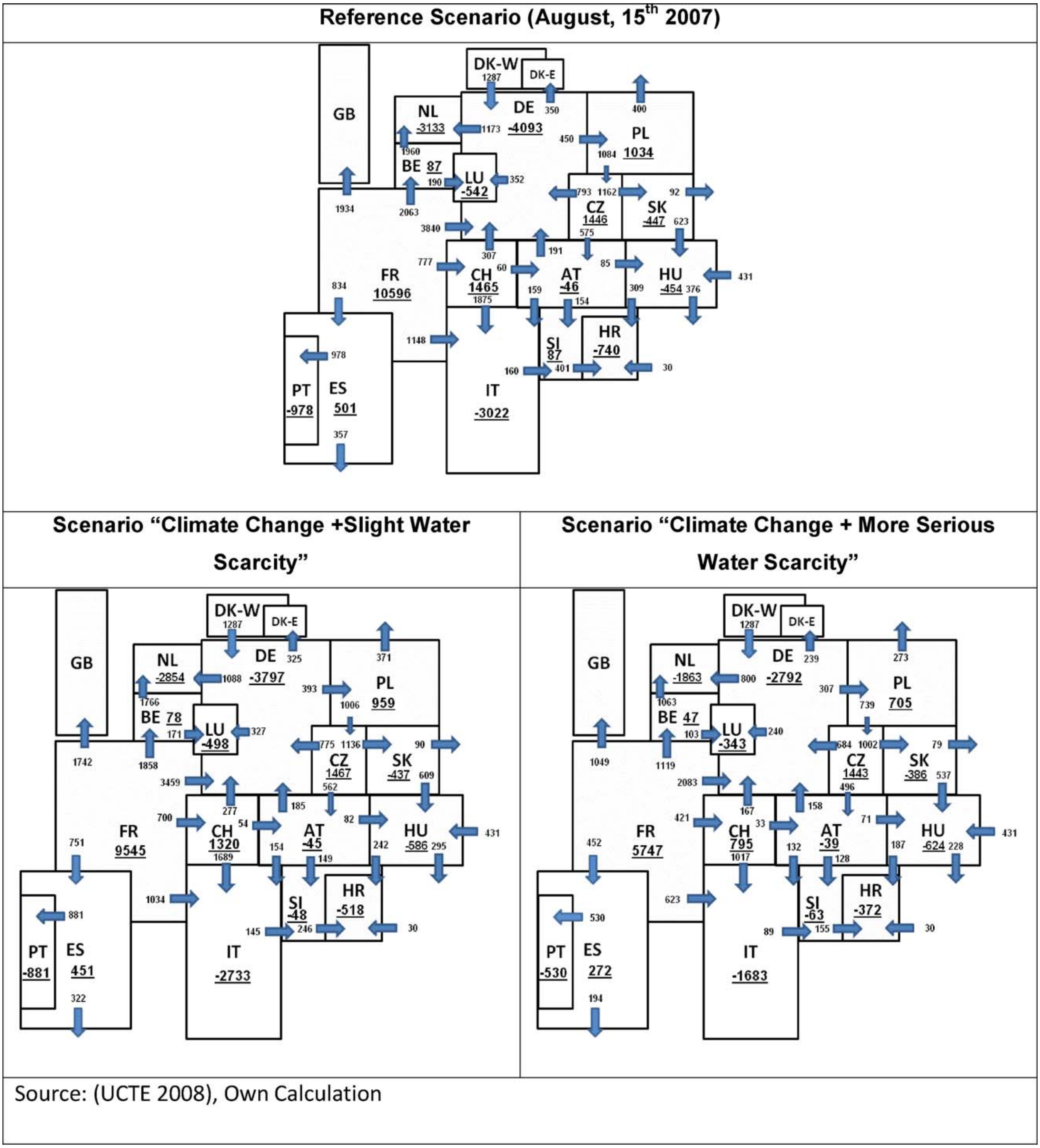

Fig. 5 – Load flows (day) on 3rd Wednesday of August at 11:00 am CET in MW. Source: UCTE (2008), own calculation

Each power plant site specific data on air temperature is extracted from the climate model. The data are inserted in Eq. (4) in order to calculate the power plant site specific water temperatures.

Besides air and water temperature data, information on the availability of freshwater is necessary to identify which power plant will get cooling problems if climate changes. 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 IAEA (2008). The sites where power plants got cooling problem in recent years are identified as critical ones and analyzed in more detail.

2.3. Results

For each of the scenarios mentioned above, the electricity production at the different nuclear power plant sites is calculated. To show to which extent countries without nuclear plants are affected by the limitation on the electricity supply in other countries (caused by climate change) we focus our presentation of results on the exchanges of power plant capacities. Fig. 5 reflects the exchanges of power plant capacities in Europe at a specific point in time. The arrows show the import/export balances of power plant capacities in Europe. They describe the net capacity a country provides for another country. The numbers underlined show total export/import balances: A negative number indicates that the country is a net importer of electricity. If the number is positive then the country will export more electricity than it imports.

The reference situation presented on the top of the figure reflects the exchanges of power plant capacities on August, 15th 2007 at 11:00 am according to data published by UCTE (2008). Assuming an increase in air temperatures as Govindasamy et al. (2003) expect, less power plant capacity will be available in France due to cooling problems. Although the vulnerability to climate change can be reduced by shifting the inspection and maintenance periods of critical power plants to summer time, France will have to reduce its exports of electricity.[3] In our calculation the (net-)exports will decrease from 10,595 MW to 9545 MW. In this second scenario, nuclear power plants in Germany and Switzerland will also face cooling problems. In contrast to France and Spain, these countries are able to postpone the inspection and maintenance periods of all critical power plants to August. So the changes in air and water temperatures will have no direct impacts on electricity exports of these countries. Switzerland as well as Germany and other countries depend more or less on electricity imports from France. Therefore these countries will also have to reduce their electricity exports to Italy, the Netherlands and other countries due to the reduction in the imports from France. All in all, in this scenario the changes in the electricity exchange system are more or less small. The situation changes significantly, if a scenario with more severe water scarcity is considered. This situation is presented in the third scenario: Besides France and Spain also Switzerland will have to limit nuclear production. Consequently the electricity supply of Switzerland is not only affected by the limitation in electricity imports from France but also due the limitations in the use of its own nuclear power plants.

Because not only France but also Switzerland will have to reduce the electricity exports significantly in countries like Italy less electricity will be available. As the example of the Netherlands shows, not only the direct neighbours of France will have to look for ways to reduce the supply gap but also countries which depend indirectly on electricity from France. Taking electricity import dependency shares into account especially Italy will have problems meeting the demand for electricity if no direct or indirect measures are taken. Other countries will have fewer problems because of their low electricity import share.

[3] We consider the electricity transfers from individual countries' point of view. Yet, it should be taken into account that the electricity sector in Europe is not consisting of state-controlled monopolies anymore, but energy companies operate in a liberalised market and make their profits by producing electricity.

3. Conclusions

Climate change does not only threaten critical infrastructures directly, but there may also be follow-up effects negatively affecting downstream infrastructures. In our analysis we regarded the follow-up consequences of climate-change induced shortages of water supply for cooling purposes in nuclear power plants. In the future, the threat of water shortages affecting the cooling processes of power plants will become a very important issue. Apart from countries with a high nuclear power production share, countries which depend on electricity imports like the Netherlands will also be affected by climate change.

In order to address the threat of a climate-change induced shortage of electricity supply, there exist two different general strategies or climate policies: "Societies can respond to climate change by adapting to its impacts and by reducing GHG emissions (mitigation), thereby reducing the rate and magnitude of change" (IPCC, 2008b: 56). In fact, on the one hand, nuclear power generation is a low carbon option for producing electricity and can hence be seen as a climate-change mitigation option if it replaces power generation options using more carbon-intensive fossil fuels like coal or oil. On the other hand, due to the ongoing climate change the European nuclear power sector necessitates adaptation policies. These adaptations have either to be placed in the sector itself or in the upstream water supply sector. Put differently, we may especially distinguish between the following two adaptation categories: (1) improving the management of the upstream critical infrastructure in the shape of water supply (many European river basins are transnational and therefore an international coordination is required in many cases), and (2) improving the management of the downstream critical infrastructure in the shape of electricity generation in power plants. Our analysis focused, in turn, mainly on the second category of adaptation options in order to prevent follow-up effects of deteriorations in water supply.

On the one hand, increases in power plant efficiencies as well as replacement of power plants with power plants which do not need a cooling system (e.g., photovoltaic installations) can contribute to reduce the effects of climate change on the electricity supply system. On the other hand, simultaneous changes in the demand for electricity, e.g., due to an increase in the use of air-conditioning, and the concurrent construction of wind-power plants on sites with poor wind conditions in summer will even worsen the situation. Yet, all in all, with coordinated measures of the partners of the electricity supply system the effects of climate change on the electricity system could be limited. These coordinated measures involve aspects of electricity supply as well as demand and water management to reduce man-made water shortages and the heating up of rivers.

It has to be taken into account that the considered climate-change induced problems involve international dimensions. A large share of European rivers, and hence water supply from these rivers, are transnational. Thus, improvements of the management of water resources necessitate to a large extent a European coordination in order to be effective and adaptation measures related to water scarcity and droughts should be discussed in a transboundary and interdisciplinary context

(EC, 2009b: 100). As a means to deal with or prevent future water scarcity, the European Commission, among other things, intends to assess the need to further regulate the standards of water using equipment and water performance in different sectors (EC, 2009a: 11). If prolonged drought occurs, a prioritisation of main uses should be established and for this objective, the EC (2007: 17) suggests employing impact indicators and among these proposed indicators are such reflecting impacts on socio-economic uses of water related to power production.

Further international aspects are associated with the European trade of electricity, since deteriorations in the production of electricity will affect a wide range of European countries. Both considered critical infrastructures, water supply and electricity production, therefore, exhibit properties of European critical infrastructures and the European Programme for Critical Infrastructure Protection may provide some assistance to protect them. Yet, overlaps of this programme with other European regulations, e.g., with the EU Water Framework Directive (WFD), should be taken into account and synergies should be exploited. One of the WFD's objectives is to contribute to mitigating the effects of floods and droughts (EC, 2000) and consequently the WFD pursues also the protection of critical infrastructures.

Finally, it has to be highlighted that our calculations are based on the assumptions of unchanged load and unchanged use of other power plants. In the past, the plant operators were able to manage disruptions of electricity supply by importing electricity from other countries or using reserve capacities. But even the association of transmission system operators for electricity, Entso-E, finds it hard to provide exact figures for each country on spare capacities (UCTE, Etso, Nordel, ATSOI, BALSTO, UKTSO, 2007).

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