Water Resour Manage (2014) 28:1767–1780
DOI 10.1007/s11269-014-0589-z

Security of Water Supply and Electricity Production: Aspects of Integrated Management

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Received: 8 April 2013 / Accepted: 12 March 2014 /
Published online: 27 March 2014

Abstract The share of renewable resources in electricity generation, e.g. in Germany, is increasing. The power sector is thus becoming more dependent on climate/weather parameters. During the summer months of the last decade, numerous thermal power plants in Europe had to be throttled due to water shortages and high water temperatures. At the same time, Europe was confronted with a reduction in hydropower production. One method of securing a future electricity supply is to increase the reliability of the water supply for power plants. In this paper, scenarios are presented for future electricity production by hydropower and thermal power plants in the Elbe river basin. Electricity production in hydropower plants will decline by approximately 13 % by 2050. This decline is due to climate change and it could be compensated for by optimizing and modernizing existing hydropower plants. Due to higher efficiencies and the conversion of plant cooling systems, no water shortages are expected in most thermal power plants. However, water shortages are expected to affect the plants in the city of Berlin. Inter- and intra-basin water transfers constitute a possible adaptation option. While the transfer of water from the river Oder would be the most cost-efficient solution from Berlin's perspective, the transfer of water from the river Elbe would have additional positive effects in the upstream Spree river sub-basin.

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Keywords Water supply · Electricity production · Integrated management · Elbe basin

1 Introduction

With an increasing share of renewable resources, the electricity supply is becoming more dependent on climate/weather parameters. For instance, the electricity generated by run-off-river hydropower plants is strongly dependent on river discharge and hence on rainfall and evapotranspiration. Thermal power plants will play an important role in generating electricity in the future, be it for base load or peak load. However, a large proportion of thermal power plants depend on water for both production and cooling processes, regardless of whether the power plant is conventionally fired, e.g. using coal or gas, or whether it uses renewable resources, e.g. biomass. In the latter case, fuel production also depends on climate/weather parameters, as do other renewable resources, such as wind and solar power. However, as electricity generation in wind and solar power plants is almost independent of water resources (Macknick et al. 2012), it is not further analysed in this paper.

Due to this strong dependency on climate/weather parameters, the future electricity supply will be much more comparable to water supply than in the past in Germany. Water supply and electricity generation are closely connected (e.g. Gleick 1994; Feeley et al. 2008). In both the water resources sector and the electricity sector, the efficient use of resources is of utmost importance. The concept of transmission, i.e. water transfers and electricity transmission, is already widely used in both sectors to balance deficits and surplus. Demand management in both sectors is in its infancy, it is even less developed in the electricity sector than in the water sector. The concept of storage has been used for water resources management for many centuries. The main problems associated with storing electricity in the past are high costs and losses during conversion and storage. However, water storage, e.g. in reservoirs, involves certain building and maintenance costs, and evaporation or seepage losses also occur.

Water management and storage can increase the reliability of hydroelectric power generation. Pumped storage hydropower plants are a means of increasing electricity supply during peak load. Water transferred to and stored in reservoirs in river basins with low water availability can safeguard the water supply to thermal power plants.

In the summer months of 2003 and 2006, thermal power plants in Europe had to be throttled due to water shortages and high water temperatures. At the same time, hydropower production was reduced due to low flows in rivers. As a result, the effects of climate change on water availability and water temperature, and their impacts on electricity generation, have received increased attention over the last few years.

According to IPCC reports (IPCC 2007), climate change is set to continue or even accelerate. However, the areal resolution of global climate models is much too coarse for climate change to be analysed on a local or regional level. Therefore, climate data must be regionalized using regional climate models. This regionalization could amplify the uncertainty because different models of regionalization can give different results. A further source of uncertainty is the development of society and the economy affected by climate change.

The possible effects of climate change on thermal power plants and other water users have been analysed by different authors. An analysis by Hurd and Harrod (2001) for the entire USA showed that there is wide scope for economic losses due to climate change depending on the region analysed. Kirshen et al. (2008) point out that the rising water demand for thermal power plants in the city of Boston will lead to rising heat loads for surface waters. Feeley et al. (2008) analysed scenarios for thermal power plants using different cooling systems and different electricity demand trends in the USA. Depending on scenario assumptions, the water demand of thermal power plants in 2030 could decline by 30 % or remain at the present level. Förster and Lilliestam (2010) and Linnerud et al. (2011) analysed the impact of climate change on nuclear plants and assessed the resulting costs.

According to Aguiar et al. (2002), hydropower plants in Portugal would be most severely affected by declining discharges as a result of climate change. For Austria, higher hydropower production due to increased precipitation is expected for the period up to 2040, while hydropower production is expected to decline thereafter (KlimAdapt 2010). For the Upper Danube basin, a decline of between 8 and 16 % is expected in hydropower generation by 2060 (Prasch and Mauser 2010). For a small catchment in the Swiss Alps, Schaefli et al. (2007) simulated a median decrease of 36 % in hydropower production for 2070–2099 compared to the control period. For parts of Norway, Seljom et al. (2011) estimated an increase of more than 20 % by 2050, while for other regions the increase was less than 10 %. Lehner et al. (2005) roughly estimated the future hydropower potential for Europe. While for northern Europe, an increase of more than 25 % was assumed by 2070, for parts of southern Europe, a decline of up to 25 % was calculated.

This paper concentrates on the water-energy nexus in the Elbe river basin with a focus on the Spree river sub-basin. The generation of electricity by hydropower plants plays an important role in renewable energy in Germany and the Elbe river basin. Although the installed hydropower capacity has increased slightly over the last few years (see Table 1), the share of hydropower generation in renewable electricity production has declined from approximately 67 % in 2000 to 19 % in 2010 (BMU 2011). This can be explained by an increase in the installed capacities of other types of renewable energy, e.g. wind and solar energy.

The installed generation capacity of thermal power plants in Germany in 2010 was approximately 91,565 MW (gross production). Of these, 22,333 MW used once-through cooling systems and 69,232 MW were equipped with cooling towers (see e.g. Strauch 2011). Thermal power plants using mine discharge water or groundwater are only slightly affected by climate parameters. Combined heat and power plants used for district heating or to supply industrial production processes with heat are also only slightly affected because they are used mainly in winter and their discharge heat is used in other processes. Therefore, approximately 36,626 MW of the installed capacity is only slightly affected by climate parameters. In addition to climate parameters, the fuels and power plant technologies used have an impact on electricity generation and its reliability.

Koch et al. (2012) analysed the effects of global change on thermal power plants in the city of Berlin. In addition to climate change, the analysis takes into account changes in electricity demand, as well as the development of power plant technologies. In spite of rising electricity

Table 1 Installed capacity, annual production, utilization ratio and share of renewable electricity generation for hydropower plants in Germany (BMU 2011)

Year	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
MW inst.	4,600	4,600	4,620	4,640	4,660	4,680	4,700	4,720	4,740	4,760	4,780
GWh/a	24,867	23,241	23,662	17,722	19,910	19,576	20,042	21,249	20,446	19,059	19,694
Utilization ratio	62 %	58 %	58 %	44 %	49 %	48 %	49 %	51 %	49 %	46 %	47 %
Share of renewables	67 %	60 %	52 %	39 %	36 %	32 %	28 %	24 %	22 %	20 %	19 %

(MW inst.: MW installed)

demand and declining water availability, electricity generation restrictions can be kept within reasonable limits by using new power plant technologies and/or adaptations of cooling systems.

This paper builds on the work of Koch et al. (2012), widens the focus to the entire Elbe river basin including the Spree river sub-basin and the water-energy nexus in general, and shows that water resources and electricity generation should be managed in an integrated way.

2 Study Area

The Elbe river basin (catchment area 150,000 km^2) is located in central Europe. Approximately two thirds of the basin is located in Germany and one third in the Czech Republic. According to Krysanova et al. (2010) declining water availability and more frequent droughts due to climate change are major concerns in the Elbe river basin. Thermoelectric generation accounts for approximately 70 % of water withdrawals. This water is mainly used as cooling water and a large proportion is discharged back into the river. Thus, thermoelectric generation only accounts for a small percentage of water consumption. According to IKSE (2005), the mean discharge at the Neu Darchau/Elbe gauge, the last gauge in the free-flowing river Elbe, is 711 m^3/s (approximately 22,500 million m^3/a). The part of the Elbe downstream of the Neu Darchau/Elbe gauge is referred to as Tidal Elbe and is strongly affected by the tide. The water withdrawn by thermal power plants up to the Neu Darchau/Elbe gauge represents 14.4 % of the mean discharge, while the water consumption, i.e. withdrawals minus return flow, is 1.1 %.

This analysis covers 31 thermal power plants, which are coal-, gas-, oil-, or nuclear-fuelled. In addition, 118 hydropower plants are included, of which 91 are run-off-river and 27 are located at reservoirs (see Fig. 1).

3 Scenario Assumptions

Scenarios with different development trends were used to account for uncertainty about future development. Two global socio-economic trends were regionalised. The term “socio-economic change” as used here includes changes in electricity demand, electricity prices, and technological progress. The first trend “globalisation” is characterised by fast global integration, higher economic growth rates, and convergence in the economic development of regions. The second trend “differentiation” is characterised by slow global integration, lower economic growth rates, and a process of stronger differentiation between regions. The underlying socio-economic scenarios are described in Blazejczak et al. (2012). These are compatible with greenhouse gas emission trends described in the IPCC scenario A1B (IPCC 2001). By the middle of this century, climate forces were assumed to vary only slightly in the two socio-economic trends because global climate reacts slowly on the differences in greenhouse gas emissions. For the region analysed, a temperature increase of approximately 2.0 °C by 2050 was assumed. Global climate data were simulated using the GCM ECHAM5/OPYC3 (Roeckner et al. 2003). Climate data were regionalised using the STAR model (Orlowsky et al. 2008). One hundred realisations (stochastically generated time series) of climate data were generated, e.g. air temperature, relative humidity, and precipitation, for the period from 2008 to 2052. The eco-hydrological model SWIM was applied to these climate realisations to simulate natural discharge time series (see Conradt et al. 2012). Natural discharges reflect changes in climate, land use and the development of groundwater drawdown in mining areas.

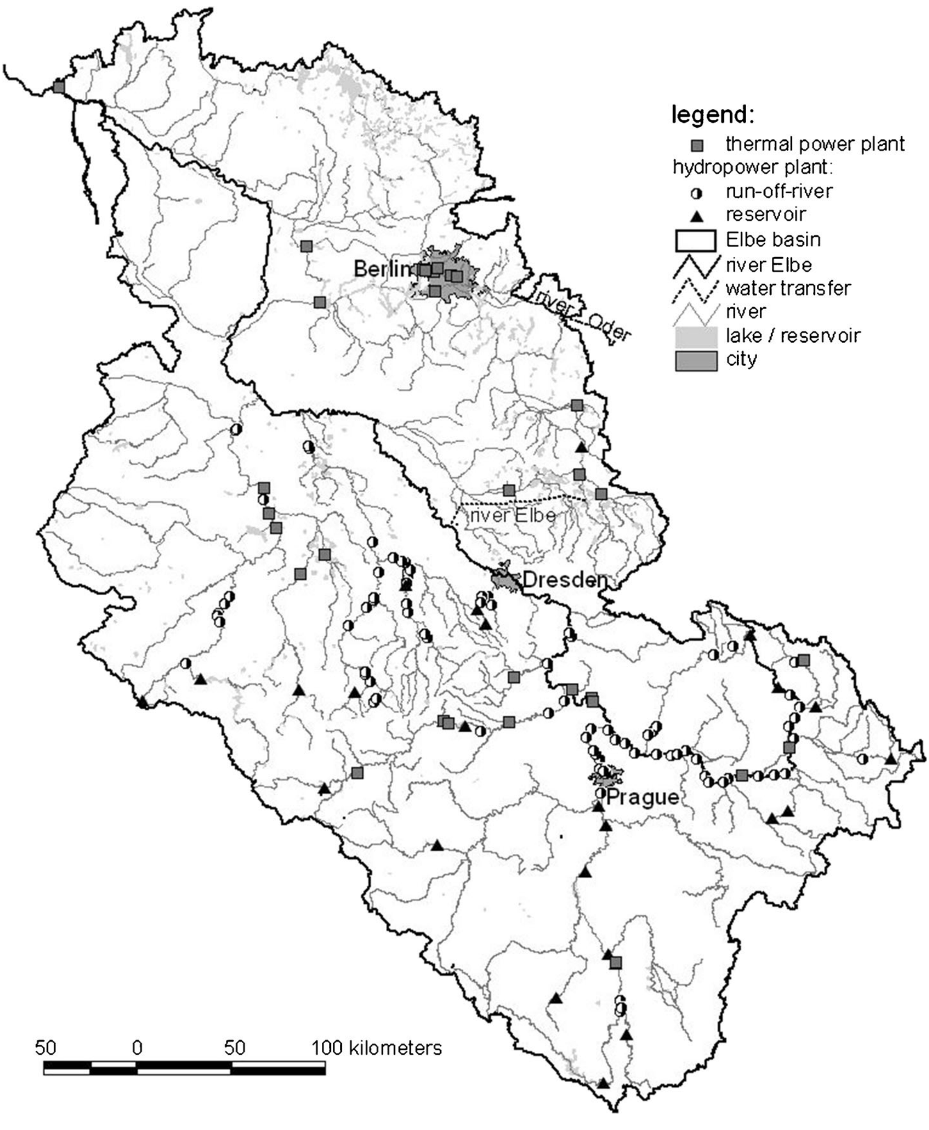

Fig. 1 Elbe river basin showing the location of thermal and hydropower plants, and potential water transfer lines from the river Oder to Berlin and the river Elbe to the sub-basin of the river Spree

Water management, e.g. reservoir releases or water transfers, was not included in the simulations of SWIM. However, these natural discharge time series served as input for a water resources management model described below, which was used to simulate water management, e.g. reservoir releases, water withdrawals, or water transfers.

The basic trends "globalisation" and "differentiation" were further differentiated to account for the impact of environmental policies. In the first case, a continuation of the present policy was assumed. In the second, higher standards for environmental protection, especially higher reduction targets for CO_2, were assumed, which had a strong impact on the development of electricity prices.

This resulted in a combined total of four scenarios that can be analysed. This paper analyses those scenarios with the greatest divergence in water demand:

i) "Globalisation without stronger environmental protection" (Gw/oE),
ii) "Differentiation with stronger environmental protection" (DwE).

4 Models Used

4.1 Model for Thermal Power Plants

The simulation model KASIM (see Koch and Vögele 2009) was used to simulate the water demand of thermal power plants. One of the main sources of data for the model is a power plant database containing data on more than 600 power plants in Germany. It includes data on the technical, economic, and ecological characteristics of different power plant types. To assess the use of water as realistically as possible, data provided by the power plant operators was used where available. Whenever no recent data was available, average values were taken from the database.

In the version of KASIM used here, the capacity, efficiency, year of completion, and specific water demand of all generating units of the respective power plants are recorded. It was assumed that each generating unit is used up to the end of its maximum operating life. The model does not consider any decreases in plant efficiency over time. Once a plant reaches the end of its operating life, the generating unit is retired. If there is substantial electricity demand, a new generating unit is built. New generating units are also built if the electricity demand rises considerably. New units are equipped with closed-circuit systems or once-through systems with cooling towers, depending on environmental policy. In the DwE scenario, new generating units are equipped with closed-circuit cooling systems. In the Gw/oE scenario, new generating units are equipped with once-through systems with cooling towers. However, generating units already equipped with closed-circuit systems retain this cooling system. The type of power plant built depends on the assumed cost and framework conditions in the respective scenario. Cost factors considered were investment costs, costs for fuel, maintenance, and CO_2 allowances. New-build generating units were lignite-, hard-coal-, or gas-fired. The construction of new thermonuclear power plants in Germany was ruled out.

4.2 Model for Hydropower Plants

The hydropower plants modelled here had a potential water demand of approximately 1,290 m^3/s. This demand remained constant over the period of analysis from 2010 to 2052, because new sites were excluded from the model. This assumption was based on the strong restrictions on hydropower development resulting for example from the requirements of the EU Water Framework Directive (EU-WFD 2000; see Reinhardt 2007; Godde 2008). Differences in hydropower production therefore reflect changing discharges. The analysis was restricted to reservoir and run-off-river hydropower plants. A constant monthly water demand corresponding to the maximum turbine flow capacity was assumed:

$$DQ = QT_{max} \tag{1}$$

where DQ is the water demand (m^3/s), and QT_{max} is the specific maximal turbine capacity of the plant (m^3/s). The return flows of the turbines are equal to the inflows. For reservoirs included in the model, evaporation losses were simulated. The electricity generated was calculated as follows:

$$P_{el} = Q * h * t * k \quad \text{with } Q = MIN(AQ, DQ) \tag{2}$$

where P_{el} is the electricity generated (kWh), Q is the flow through the turbine (m^3/s), AQ is the actual flow (m^3/s), h is the water head (m), t is time (3,600 s), and k is the efficiency factor (here 7 kN/m^3). For run-off-river hydropower plants, h is the fixed water head; for reservoirs, h was calculated depending on the volume of the respective reservoir.

4.3 Water Resources Management Model

The modelling system used for water management simulation was the 'Interactive Simulation System for Planning and Management in River Basins' WBalMo®[1] (Water Balance Model). The river basin was represented by a network of branches representing running waters and nodes (balancing profiles). Water users, reservoirs, water transfers, etc. were connected to these balancing profiles. The general modelling system was combined with input data characterising the river basin—spatial configuration, hydrology, water resource practices, water use requirements, etc. Minimum streamflows, e.g. for ecological purposes or navigation, were also implemented. The water availability for water users was simulated according to the given water management plan including water transfers or releases from reservoirs. For the present study, a time step of one month was chosen. Further information on the modelling system can be found in Kaden et al. (2008). The model developed for the river Elbe covers the basin up to the Geesthacht weir.

For thermal power plants, the water demand as calculated by KASIM and a water temperature model were integrated into the water resources management model. Information about the water temperature model is given in Koch et al. (2012). Climate effects were considered in different ways in the calculation of water demand. When a cooling system with cooling tower was used, air temperature and humidity were incorporated into the water demand function. The lower the humidity and the higher the air temperature, the higher the water loss via the cooling tower. For power plants without cooling towers, the standard water demand as calculated by KASIM was used and climate parameters were not considered. As long as the permissible water temperature rise was maintained, the water demand as calculated by KASIM was used. If the permissible water temperature rise was exceeded, the water demand rose to discharge the heat load to a larger quantity of water. A comprehensive description of the integration of the water demand functions into the water resources management model is given in Koch and Vögele (2009). The hydropower plants with their respective water demand were integrated into the water resources management model.

5 Results

Results were analysed for five-year periods, i.e. results presented for 2020 represent the time period from 2018 to 2022. Since 100 stochastic realisations were used, 500 values (5 years * 100 realisations) were available for the statistical analysis for each month of the respective five-year time period.

[1] WBalMo is a registered trademark of DHI-WASY GmbH.

As a rough indicator of economic effects, an economic loss approach was used. It was assumed that in case of reduced generation the power plant operators have to buy additional electricity to ensure the supply to their customers. Economic losses, addressed as supplementary costs, were calculated based on the difference between electricity generation on demand and actual water supply levels multiplied by the assumed price of electricity, less the saved fuel and operation costs.

The market price of base load electricity increased from 0.035 €/kWh in 2010 to 0.09 €/kWh in 2050 in the DwE scenario, while in the Gw/oE scenario an increase to 0.07 €/kWh was assumed. For small hydropower plants, i.e. installed capacity lower than 5 MW, a renewable energy price of 0.066 €/kWh was assumed in 2010. This price increased to 0.09 €/kWh (DwE) and 0.07 €/kWh (Gw/oE), respectively.

While the water demand of thermal power plants in the scenarios used changed considerably (see next section), the water demand of other water users, e.g. industrial or drinking water supply, only changed slightly (see Blazejczak et al. 2012).

5.1 Thermal Power Plants

The development of water demand for thermal power plants is shown in Fig. 2a. The strong decline in water demand from 2010 to 2020 is due to the replacement of old plants with a high water demand. Higher environmental standards in the DwE scenario meant that new-build generating units were equipped with closed-circuit cooling systems. In the Gw/oE scenario, power plants may also be equipped with once-through cooling systems, which require 10 to 100 times more water than closed-circuit systems (Macknick et al. 2012). Therefore, in the Gw/oE scenario, the water demand was higher.

In Fig. 2b, the development of power plant water consumption is displayed. In both scenarios, the water demand of thermal power plants could be 100 % satisfied, except for the city of Berlin. Due to declining discharges in the Spree river sub-basin, there was not enough water to cover the demand, especially during the dry and hot summer months. A detailed description of the assumptions and the results for Berlin can be found in Koch et al. (2012). The development of supplementary costs for power plants in the city of Berlin is shown in Fig. 5.

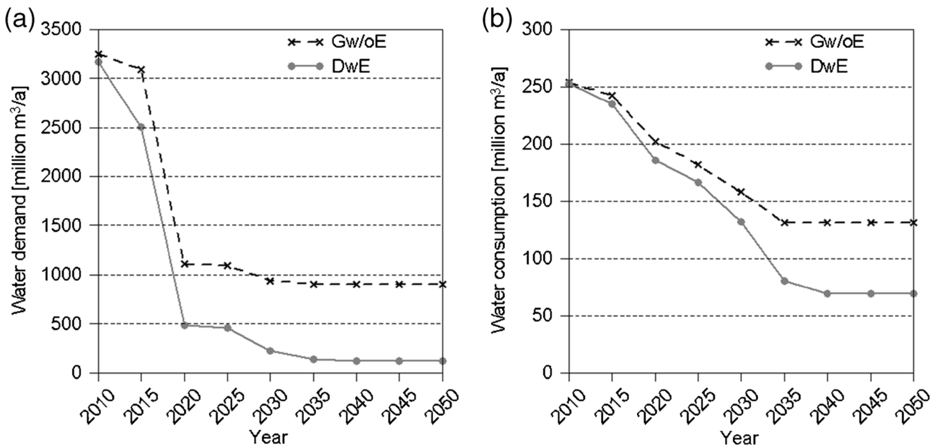

Fig. 2 Development of **a** water demand and **b** water consumption in the scenarios for the Elbe river basin

5.2 Hydropower Plants

Due to lower discharges and lower water levels in the reservoirs, electricity production declines in both scenarios (Fig. 3). The differences regarding electricity production in the two scenarios are negligible. However, the assumptions regarding future electricity prices have a significant effect on the calculated economic costs: the DwE scenario has higher prices leading to higher costs compared to Gw/oE.

5.3 Adaptation Options: A Case Study of the Spree River Basin

An analysis of adaptation options for thermal power plants in the city of Berlin was conducted, focussing on inter- and intra-basin water transfers. Thermal power plants in Berlin are restricted in their operation by high water temperatures and low discharges during the summer months. The inflow to Berlin via the river Spree is strongly affected by lignite mining activities in the upstream Lusatian region where groundwater is pumped and fed as “artificial discharge” into the river Spree and its tributaries. The closure of a number of mines after 1990 led to water quantity problems because of the reduction in this artificial discharge. The water demand that had become established under conditions of stable and sufficient water availability did not alter.

In the mountainous upper part of the Spree river sub-basin, there are three reservoirs with a capacity of 53.4 million m^3. Water is released from these reservoirs during periods of low flows. Due to the problems mentioned earlier, the affected German federal states developed a joint water resources management strategy. It was decided to fill five open mining pits and use them as reservoirs. During periods of low flow, in particular, these reservoirs are used to balance water quantity deficits. For instance, water is released from the reservoirs to maintain a required inflow to Berlin of 8.00 m^3/s via the river Spree. The combined capacity of the new reservoirs is 114.2 million m^3.

Although the new reservoirs were included in this analysis, water shortages must still be expected in Berlin for thermal power plants, industrial water users, municipal water supply, etc. Therefore, the effects of water transfers from the river Elbe to the Upper Spree and from

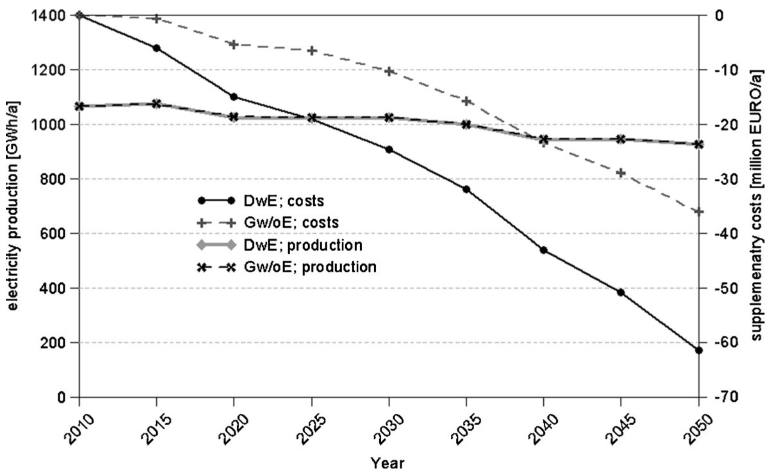

Fig. 3 Results for electricity generation and supplementary costs of hydropower plants, annual expected values from 100 realisations for each scenario

the river Oder directly to Berlin were also analysed (location of potential transfers, see Fig. 1). As there are no hydropower plants downstream of both points of withdrawal, water withdrawal does not affect electricity generation in hydropower plants. For the transfer from the river Elbe, which was assumed to start in 2015 with a capacity of 3 m^3/s, construction costs of approximately 194 million € and running costs of approximately 1.1 million €/a were calculated. For the transfer from the river Oder via the Oder-Spree channel, which was assumed to start in 2015 with a capacity of 3 m^3/s increasing to 6 m^3/s from 2030 on, the construction costs were approximately 3 million €. The running costs were approximately 60,000 €/a and 200,000 €/a from 2015 to 2030 on, respectively. Further information on these water transfers is given in Koch et al. (2009).

One significant difference between these water transfers is the fact that water transferred from the river Elbe to the Upper Spree region can be stored in the reservoirs downstream of the discharge point. Therefore, during dry periods, additional quantities surpassing the transfer capacity are available for water users and hydroelectric power generation.

Table 2 shows the electricity required for water transfers, the electricity generated by the hydropower plant (HPP) at the Spremberg reservoir and by thermal power plants in Berlin for 2020 and 2050. The annual mean values from 100 realisations are given. Only in scenarios with transfer from the Elbe are differences simulated for the HPP, because the transfer from the Oder is only effective downstream of this reservoir.

Overall, the differences are rather small, especially for the power plants in Berlin. However, when the results for drought conditions are compared, the picture changes. The results for the power plants in Berlin with a probability of exceedance of 95 %, i.e. drought conditions with a statistical return period of 20 years, are shown in Fig. 4. For 2020, the results are only shown for the Gw/oE scenario, because the differences between the scenarios at this time period are relatively small.

In Fig. 5, the development of supplementary costs is displayed for the basis scenarios DwE and Gw/oE and for the adaptation options. To show the effects of the scenario assumptions, the costs are also given for a scenario “Status 2010”, where the plant units are operated in the present configuration up to 2050.

Table 2 Annual mean values for electricity required for water transfer, electricity produced at the HPP Spremberg reservoir and thermal power plants in Berlin for 2020 and 2050, management options for scenarios DwE and Gw/oE

	DwE			Gw/oE		
Year 2020	Basis	Transfer Elbe	Transfer Oder	Basis	Transfer Elbe	Transfer Oder
Electricity for water transfer [GWh/a]		18.28	0.83		18.55	0.83
HPP reservoir Spremberg [GWh/a]	3.89	4.85	3.87	3.87	4.85	3.86
Thermal power plants city of Berlin [GWh/a]	23,865	23,906	23,912	22,982	23,026	23,035
Year 2050	Basis	Transfer Elbe	Transfer Oder	Basis	Transfer Elbe	Transfer Oder
Electricity for water transfer [GWh/a]		18.36	2.80		17.09	1.75
HPP reservoir Spremberg [GWh/a]	2.44	3.62	2.40	3.23	4.40	3.30
Thermal power plants city of Berlin [GWh/a]	24,896	24,936	24,966	26,577	26,694	26,718

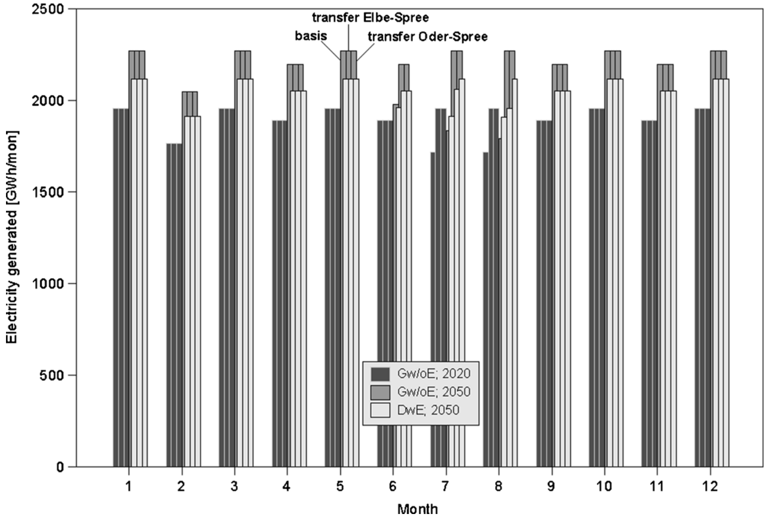

Fig. 4 Electricity generation in thermal power plants in Berlin for 2020 and 2050, management options for scenarios DwE and Gw/oE, probability of exceedance 95 %

When comparing the costs for the construction, running, and maintenance of the potential water transfers, it must be remembered that other water users, e.g. production of biofuels and other agricultural products, and ecosystem services, e.g. the Spreewald wetland (see Grossmann and Dietrich 2012), which are not included in this analysis, also benefit from water transfers.

Figure 6 shows the safety of water supply for industrial water users for the basis scenarios DwE and Gw/oE and the adaptation options for the DwE scenario. For "basis 2020", the results are only shown for DwE, because the differences between the scenarios in 2020 are rather small. Lower mine discharges in the DwE scenario mean that the water availability for

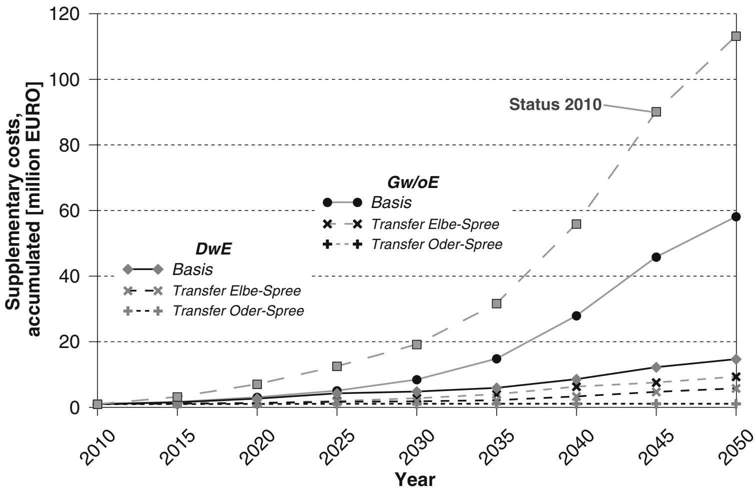

Fig. 5 Supplementary costs (accumulated annual expected values) for thermal power plants in the city of Berlin for basis scenarios and adaptation options

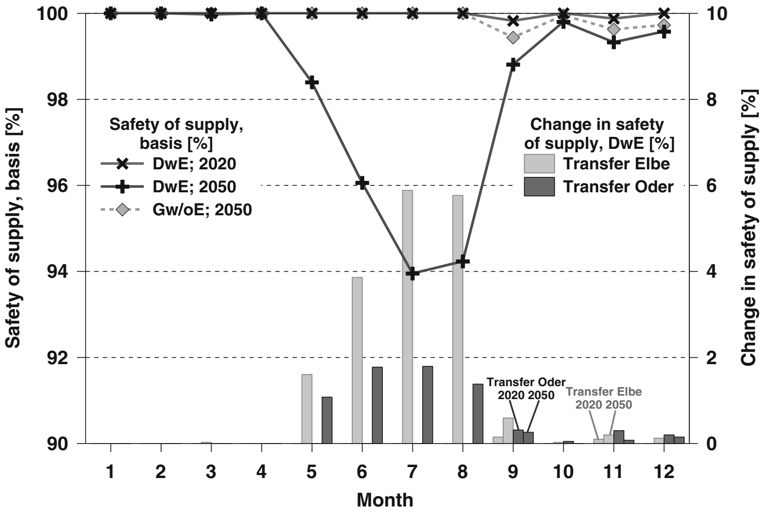

Fig. 6 Safety of water supply for industrial water users in the Spree river basin

water users is considerably lower than in scenario Gw/oE. However, the water transfers increase the safety of water supply to almost 100 %.

6 Conclusion

With increasing shares of renewable sources in electricity generation, the power sector is becoming more dependent on climate/weather parameters. One way of securing the electricity supply is to increase the reliability of water supply for production and cooling processes in power plants. Although it is not further discussed in this paper, the production of biofuels also depends on reliable water resources in many regions.

This paper presented scenarios of future electricity production in hydropower and thermal power plants for the Elbe river basin. For hydropower generation, the electricity produced does not differ markedly between the scenarios. This analysis found production in hydropower plants to decline by approximately 13 % between 2010 and 2050, i.e. a rate of 0.3 % per year. The decline caused by climate change could be compensated for by optimising and modernising existing hydropower plants. Even when technical, ecological, and economic aspects were considered, a number of new hydropower sites could be developed. However, the restrictions on hydropower development resulting for example from the requirements of the EU WFD (EU-WFD 2000) may hamper this development.

A potential of 15 % for optimisation, modernisation, and new sites is estimated for hydropower plants in Germany (BMU 2010). This increase corresponds roughly to the decline in electricity generation due to climate change in the Elbe river basin.

Higher efficiencies and the conversion of cooling systems mean that no water shortages are expected for most thermal power plants. For the plants in the city of Berlin, however, water shortages are expected. Inter- and intra-basin water transfers constitute a possible adaptation option. Keeping in mind that Germany plans to abandon nuclear energy, the safety of supplying electricity from other sources should be given a high priority. These water transfers also increase the water availability for other, e.g. industrial, water users.

While the transfer of water from the river Oder would be the most cost-efficient solution from Berlin's perspective, the transfer from the river Elbe would have additional positive effects in the upstream Spree river sub-basin, including the Spreewald wetland (see Koch et al. 2009).

Acknowledgments This work was carried out as part of the German Research Programme on Global Change in the Hydrological Cycle (GLOWA), namely GLOWA-Elbe, funded by the German Federal Ministry of Education and Research (BMBF).

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