Meteorologische Zeitschrift, Vol. 24, No. 2, 173–188 (published online April 13, 2015)

Article

The impact of climate change and variability on the generation of electrical power

Hagen Koch[1]*, Stefan Vögele[2], Fred F. Hattermann[1] and Shaochun Huang[1]

[1]Potsdam Institute for Climate Impact Research, Potsdam, Germany
[2]Forschungszentrum Jülich, Institute of Energy and Climate Research – Systems Analysis and Technology Evaluation (IEK-STE), Jülich, Germany

(Manuscript received August 30, 2013; in revised form April 30, 2015; accepted July 2, 2014)

Abstract

Climate variability and change affect electricity generation in several ways. Electricity generation is directly dependent on climate/weather parameters like wind (wind power generation) or air temperature and resulting water temperature (thermal power plants). River discharge as a result of precipitation and temperature, the latter being one main factor influencing evapotranspiration, is important for hydro power generation and cooling of thermal power plants. In this study possible effects of climate variability and change on electricity generation in Germany are analyzed. Considered is electricity generation by thermal power plants, wind power plants and hydro power plants. While hydro power plants and thermal power plants are affected negatively due to declining river discharge or higher water temperatures, for wind power generation no clear tendency was found. The reduction for hydro power generation could be leveled out by a slight increase in installed capacity and modernization of turbines and generators. By a replacement of old once-through cooling systems by closed-circuit cooling systems for new thermal power plants the negative impacts on electricity generation can be reduced significantly. The planned increase of installed capacity for wind power generation clearly surpasses the changes arising from climate change.

Keywords: climate change, electricity generation, Germany

1 Introduction

There is a close connection between electricity generation and climate variability and change. Electricity generated by combusting fossil fuels is a mayor driver of anthropogenic climate change, while the effects of hydro power generation on climate are still debated. Some authors argue that methane emissions from reservoirs strongly contribute to climate change. Electricity generation is dependent on climate/weather parameters. For instance the electricity generation by hydro power plants is strongly connected to river discharge and hence on rainfall and evapotranspiration. Most thermal power plants are using water in production and cooling processes. About 65 percent of the water withdrawn in Germany is used in thermal power plants (UBA, 2010), making it the largest water user, whereby the major part is discharged back into the surface waters. These power plants are conventionally fired (e.g. use coal or gas) or use renewable sources (e.g. biomass). In the latter case also the production of the fuel itself depends on climate/weather parameters (cf. Gutsch et al. 2015). Other types of electricity generation, e.g. wind or solar power, make direct use of climate/weather phenomena and therefore are directly depending on these.

During the last years the possible effects of climate change on thermal power plants have been analyzed in several studies for different regions and countries. Hurd and Harrod (2001) found a large span of economic losses for thermal power plants in the US depending on the region studied. For the city of Boston, US, Kirshen et al. (2008) show an increasing water demand of thermal power plants and increasing heat loads in the river systems. Cooling water shortages are assumed to lead to economic losses for electricity producers. Feeley et al. (2008) analyzed scenarios for thermal power plants with different cooling systems and a set of future energy demand trends for the US. Depending on the scenario water demand is decreasing by up to 30 percent by 2030. Scenarios with different development trends for the economy and corresponding assumptions for future power plant capacities, cooling systems and water demand for the city of Berlin, Germany, have been analyzed by Koch et al. (2012). They show that due to technological progress and by adaptation of cooling systems negative effects of climate change can be reduced significantly. Förster and Lilliestam (2010) and Linnerud et al. (2011) analyzed the effects of climate change on nuclear power plants and estimate occurring costs. Using a statistical model Linnerud et al. (2011) find that a 1 °C increase of air temperature leads to a reduced electricity generation of approximately 2 percent, mostly due to environmental restrictions for cooling water temperature and withdrawal quantities.

*Corresponding author: Hagen Koch, Potsdam Institute for Climate Impact Research, P.O. Box 60 12 03, 14412 Potsdam, Germany, e-mail: hagen.koch@pik-potsdam.de

DOI 10.1127/metz/2015/0530
Gebrüder Borntraeger Science Publishers, Stuttgart, www.borntraeger-cramer.com

Van Vliet et al. (2012) analyzed the impacts of climate change on thermoelectric power plants in the US and nuclear power plants in Europe. They use a large scale coupled hydrological water temperature model with bias-corrected global climate model outputs. Germany had been excluded because of the German phasing-out decision on nuclear power plants. Hoffmann et al. (2013) present an approach to estimate climate effects on performance losses of thermal power plants. They apply this approach to selected power plants in Germany, but point out that in their analysis no detailed hydrological modelling was included.

The electricity generation by hydro power plants has a significant share on renewable electricity generation in Germany. Although the installed capacity has slightly increased in the last years, its overall share on renewable electricity generation has declined from 91 percent to 20 percent from 1990 to 2010, respectively (BUNR, 2011). This decline is due to the sharp increase in installed capacity and generation of wind and solar power plants. However, because hydro power generation can deliver base-load and peak-load electricity this type of production will play an important role also in future (renewable) electricity generation.

According to Aguiar et al. (2002) hydro power generation is the sector strongest affected by climate change in Portugal. For Austria an increase in electricity generation between 4 to 10 percent until 2040 is expected, depending on the climate scenario used (KlimAdapt, 2010). By the end of the century mostly negative effects are assumed. Compared to the reference period a decline of up to 10 percent is assumed. For the Upper Danube, i.e. the German part of the Danube river, a reduction of electricity generation between 8 to 16 percent until 2060 was calculated by Koch et al. (2011). Schaefli et al. (2007) simulate a decline of electricity generation of 36 percent for small catchments in the Swiss Alps for 2070 to 2099, compared to the control run. For parts of Norway Seljom et al. (2011) calculate an increase of more than 20 percent by 2050, while for other parts of Norway a reduction of 10 percent is calculated. Lehner et al. (2005) give a rough estimation for Europe. For northern parts of Europe they simulate an increase of 25 percent, for parts of southern Europe a decrease of 25 percent is given. For the Elbe river basin in Central Europe a decrease of 13 percent by 2050 compared to 2010 is simulated by Grossmann and Koch (2011).

The production by wind power plants delivers an important contribution to the increasing share of renewable electricity generation in Germany. The installed capacity has increased strongly over the last 20 years in Germany. According to BUNR (2011) the installed capacity in the years 1990, 2000, and 2010 was 55 MW, 6,097 MW, and 27,209 MW, respectively. The share on renewable electricity generation in Germany has increased from 0.4 percent (1990) to 20 percent in 2000 and 36 percent in 2010.

In terms of climate change effects on wind power production for different regions the findings are divers. According to Pryor et al. (2005a/b) for northern Europe positive effects can be expected, especially for winter. Seljom et al. (2011) find only small changes for Norway. Brayshaw et al. (2011) simulate changes of up to 10 percent for Great Britain. Regarding off-shore wind power generation Barstad et al. (2012) find small negative effects, while they point to the wide spread of their results. Koch and Büchner (accepted) use two runs from the regional climate model CCLM to assess the effects of climate change on wind power production in Germany. The overall effects are rather small, however they find positive trends for winter and negative trends for summer, while the northern parts of Germany profit strongest and for some southern parts negative signals are found.

For Germany there are only a few studies analyzing possible effects of climate change on electricity generation. However, these studies have either a regional focus, e.g. one Federal State, or only one type of electricity generation is considered, e.g. hydro power plants, thermal power plants, or wind power plants.

In this paper possible effects of climate change on electricity generation in Germany are analyzed. Changes in environmental legislation or technologies are not considered. Negative aspects of the different generation types, e.g. greenhouse gas emissions from thermal or hydro power plants, effects of wind power plants on local climate or (migratory) birds etc., are not discussed. The results presented should be seen as a general overview in which regions and to what magnitude the analyzed sectors can be affected by climate change. It is not intended to provide in-depth local information. For the latter more data, e.g. on water use (thermal power plants), management of reservoirs (hydro power) and local land use (wind power), are required.

2 Data, models and methods

2.1 Thermal power plants

Water shortages and environmental regulations, e.g. regarding water temperature, are affecting the production of thermal power plants. The main use of water in thermal power plants in Germany is for cooling; the water demand for other processes is rather small. The amount of water required for cooling depends mainly on waste heat to be discharged and the cooling system applied. If the waste heat is not used for local or district heating (combined heat and power generation) it is discharged. In Germany most thermal power plants are using water dependent cooling systems. These systems can be divided into three main types:

i) once-through cooling, where water is withdrawn from a body of water and used for cooling in the condenser, subsequently it is returned into the body of water; the amount of water required for this type of cooling is considerable;

ii) once-through cooling with cooling tower, where water is cooled down in a cooling tower before it is returned, the potential heat load on the body of water is reduced; and

iii) closed-circuit cooling, the heated water is cooled down in a cooling tower and led back to the condenser; the amount of water required for this type of cooling is small.

Beside these technical aspects environmental conditions and regulations differ for individual power plants. For instance temperature thresholds for cold water rivers (salmonid waters) are different from those for temperate rivers (cyprinid waters). These temperature thresholds are usually set for maximum discharge water temperature and mixed water temperature downstream of the plants discharge. Also a threshold for maximum water withdrawal exists usually. Depending on site specific conditions other restrictions to the operation of thermal power plants can apply. In general the production is reduced gradually if one of the thresholds is approached and fully stopped if one of the thresholds is crossed.

Due to the listed specifications regarding cooling systems, environmental conditions and regulations an individual analysis for thermal power plants is needed if precise results for climate change impacts on electricity generation are desired. If the site specific data needed are not available only a rough estimation is possible. Koch and Vögele (2013) use site specific data for nuclear power plants to develop an approach to simulate water temperature, water demand and production losses. In Koch et al. (2014) this approach is applied to 17 nuclear power plants in Germany to assess possible effects of climate change on electricity generation. From these results an approach is developed that can be used for a more general assessment.

In this approach water temperature is the main parameter affecting electricity generation. Depending on the cooling system, i.e. with or without cooling tower, different water temperature thresholds are derived (see Fig. 1). Also shown are observed data as given in Deutsches Atomforum (2004, 2007) for the years 2003 and 2006.

For most rivers, in Germany cyprinid waters, temperature thresholds of 23 °C (without cooling tower) and 26 °C (with cooling tower) are estimated. Reaching these thresholds the production must be reduced gradually. Production must be stopped fully when the maximum discharge or mixing temperature are reached. For salmonid waters (not displayed), e.g. river Isar in Bavaria, thresholds of 20 °C (without cooling tower) and 24 °C (with cooling tower) are derived. The temperature threshold of 23 °C used for cyprinid waters and power plants without cooling tower corresponds to the threshold used by van Vliet et al. (2012). However, in their simulations no differentiation between cooling systems, e.g. without and with cooling tower, and river type, e.g. cyprinid and salmonid waters, is made.

A comparison of results obtained for nuclear power plants using the approach of Koch and Vögele (2013) and using the described general approach shows that the later can be used to derive long term average effects of climate change. In this sense it can be applied to identify regions where power plant operators should expect restrictions on power plants operation. However, the approach can not be used for extreme conditions. Thermal power plants using other sources than surface water, e.g. pumped mine discharges, or power plants used to produce heat for production processes are not included.

For 65 gauges in Germany river discharge is simulated using the ecohydrological model SWIM (see Hattermann et al., 2015). SWIM has been validated for the hydrological processes in Germany by Huang et al. (2010) and widely been used for climate impact assessments in different studies (see e.g. Hattermann et al., 2011, Hattermann et al., 2008). Thermal conditions in the surface waters next to the power plants were simulated using a water temperature model developed for the river Elbe by Koch and Grünewald (2010). Based on this model for the 65 gauges related water temperature models were developed. To be applicable to different gauges and river basins with diverse characteristics the model was extended. For some gauges beside air temperature the river discharge was included in the water temperature simulation. For river basins with huge lakes or reservoirs upstream of the gauges a hysteresis model was used, because of thermal storage effect of these water bodies. Results of the adapted water temperature models for the locations of nuclear power plants in Germany are given in Koch et al. (2014).

2.2 Hydro power generation

Hydro power plants can be used to generate peak-load, mid-load or base-load electricity. While the first are often pumped storage plants the other two are usually placed at reservoirs or are run-off-river plants. The electricity generated by hydro power plants depends mainly on the fall height and the quantity of water passing the turbines. The maximum fall height and the maximum capacity of the turbine are setting the plant-specific limits.

Plant-specific data like maximum fall height and maximum turbine capacity are not available for several thousand hydro power plants in Germany. Furthermore reservoirs upstream of a hydro power plant can change the annual cycle of river flow. Lehner et al. (2005) apply separate functions for hydro power plants at reservoirs and for run-off-river plants. They argue that hydro power generation at reservoirs is less susceptible to changes in the annual cycle of river flow because of their storage effect. However, an analysis of the location of hydro power plants in Germany shows that most hydro power plants at reservoirs are located in the head waters while run-off-river plants are located downstream

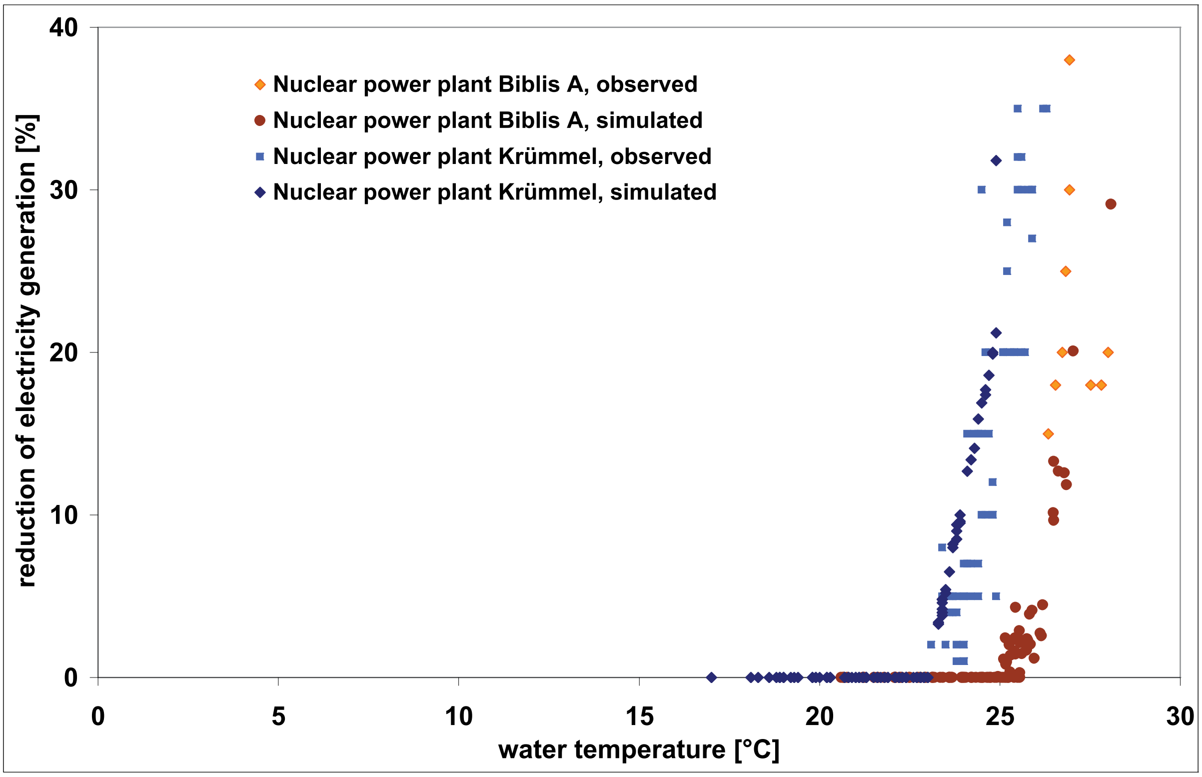

Figure 1: Water temperature thresholds for cooling system with (Biblis A) and without (Krümmel) cooling tower

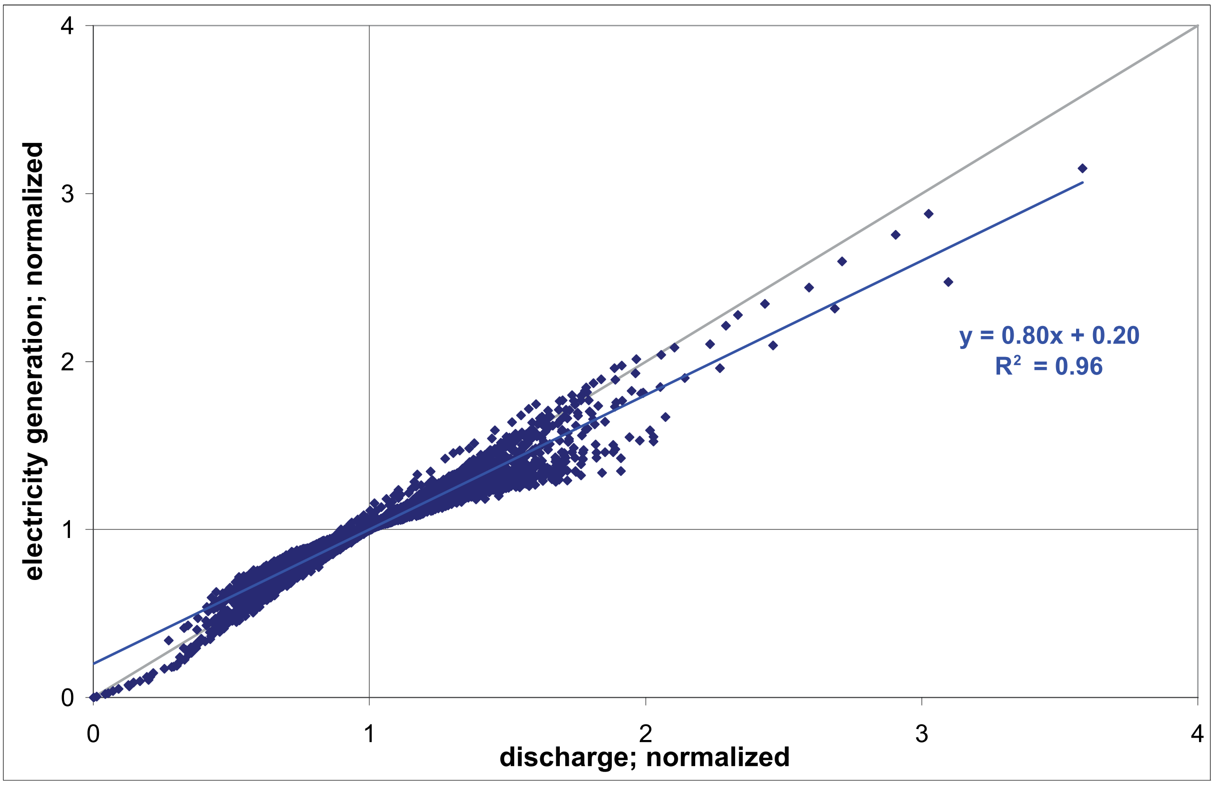

Figure 2: Mean annual river discharge and mean annual electricity generation (simulation for 118 hydro power plants in the river Elbe basin), normalized

of these reservoirs. Therefore the storage effect of the reservoirs applies also to run-off-river plants.

From a project analyzing climate change effects on water availability in the Czech-German Elbe river basin data about changes in hydro power generation were available (Grossmann and Koch, 2011). Data for 118 hydro power plants, 27 reservoir plants and 91 run-off-river plants, were reported in this project. Simulation results for mean annual river discharge and mean annual electricity generation at these 118 hydro power plants were normalized (see Fig. 2). Thus changes in discharge and electricity generation can be treated independent of their magnitude. By using mean annual values inner-annual variations due to reservoir management must not be considered, because very few reservoirs are intended for over-year-storage. The relationship found is:

$$\Delta y = 0.8 * \Delta MQ + 0.2 \quad (2.1)$$

where ΔMQ is the difference to the normalized mean discharge and Δy is the change in mean annual electricity generation. According to function (2.1) the effects of changes in the mean annual river discharge are buffered, i.e. a change of mean annual river discharge by 50 percent leads to a change of 40 percent with regard to mean annual electricity generation.

For 38 gauges in Germany river discharge is simulated using the ecohydrological model SWIM (see Hattermann et al., 2015). These gauges are located along the most important rivers and their tributaries.

2.3 Wind power generation

In the simulations of climate change effects on wind power generation a power curve as described in Akdag and Güler (2011) or Koch and Büchner (accepted) is applied. An horizontal-axis wind turbine with a hub height of 100 m and blades of 50 m length is simulated. The wind turbine does not produce as long as the wind speed is below 4 m/s. Above this threshold the utilization increases up to a wind speed of 15 m/s and is utilized by 100 percent for wind speeds below 30 m/s. The wind turbine is shut down if the wind speed threshold of 30 m/s is surpassed.

The applied power curve is only one type of a number of possible power curves. In future times much higher hub heights and lower or higher thresholds can be valid. The future scenario runs do not include any new technologies or changed power curves for wind power generation. Therefore, only climate change effects are considered.

Usually wind speed is fluctuating in the course of a day (see Fig. 3). Therefore it is important to include these fluctuations in the modelling of wind power generation accordingly. However, since the STARS model (see next section) delivers daily values only a reliable way to include these fluctuations in the assessment of climate change on wind power generation is needed.

Hourly wind speed measurements from different stations of the German Weather Service (Deutscher Wetterdienst DWD, Augsburg, Cuxhaven, Kassel, Potsdam) were available. On the example of the DWD-station Potsdam (Telegrafenberg) the differences between the application of daily and hourly time intervals for the simulation of wind power generation is shown.

From the hourly station data daily averages were calculated. The data for the hourly and daily time intervals were extrapolated to a height of 100 meter above ground using the logarithmic wind profile (Hoogwijk et al., 2004):

$$V_H = V_M(\ln(H/z_0)/\ln(M/z_0)) \quad (2.2)$$

where H is the hub height (m), V_H is the wind speed at H (m/s), M is the anemometer height, and z_0 is the roughness length of the surface (m). In this function no thermal effects on wind speed are included.

Using the hourly and daily data, and applying the power curve described above, the utilisation for the Potsdam station was calculated. As shown in Fig. 5 the generation calculated for daily and hourly time intervals deviate strongly, especially for low and high wind speed. For low daily wind speed, i.e. lower than or at approximately 4 m/s, the calculated generation is lower than for the hourly generation. This is because the lower threshold of 4 m/s is effective and no generation is calculated. However, during days with an average daily wind speed of 4 m/s there are times where hourly wind speed is higher than this threshold (see Fig. 3). The opposite can be found for wind speed of approximately 15 m/s. For wind speed of 15 m/s and beyond an utilisation of the wind power plant of 100 percent is calculated (the upper threshold of 30 m/s is not crossed in the measured data). During days with an average daily wind speed of 15 m/s there are times where hourly wind speed is lower than this threshold and a generation less than 100 percent is calculated. Therefore the generation for the hourly data is lower than for the daily data.

Due to the deviation between the calculated generation using hourly and daily time steps a way to minimize the differences is required. The main problem is the fluctuation of the hourly data around the daily mean value, especially at the thresholds. To incorporate this fluctuation in the daily time step calculation, for all days the average daily wind speed was calculated from the hourly data. These daily data then were grouped, e.g. all days with an average wind speed between 3.95 m/s and 4.05 m/s into the group 4.00 m/s etc. For each group the standard deviation was calculated from the hourly data (see Fig. 3 for the group 4.00 m/s). These calculations were repeated for separate months. No difference of the standard deviation compared to the calculation of all data, i.e. without considering season or month, was found. The average daily wind speed and the corresponding standard deviation calculated from hourly data were plotted. Parameters for a function to calculate the standard deviation depending on average daily wind

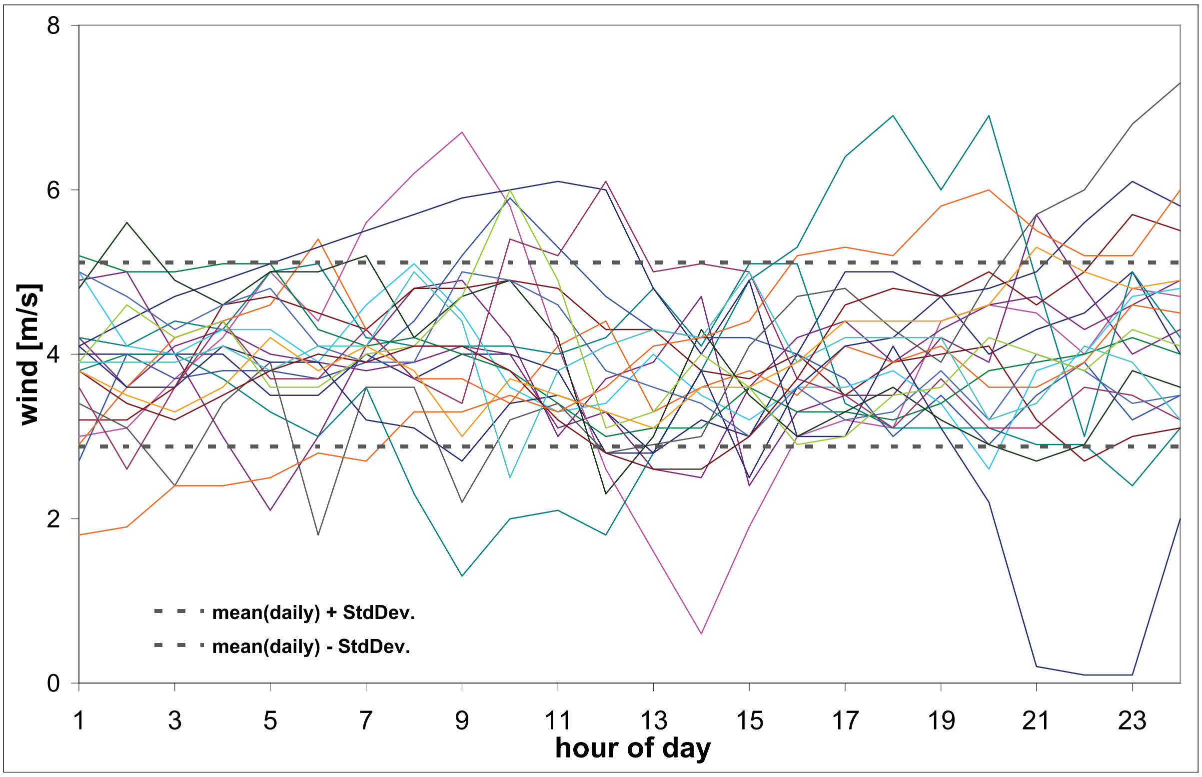

Figure 3: Hourly wind speed (daily average 4 m/s) and daily average ± standard deviation, DWD-station Potsdam (Telegrafenberg)

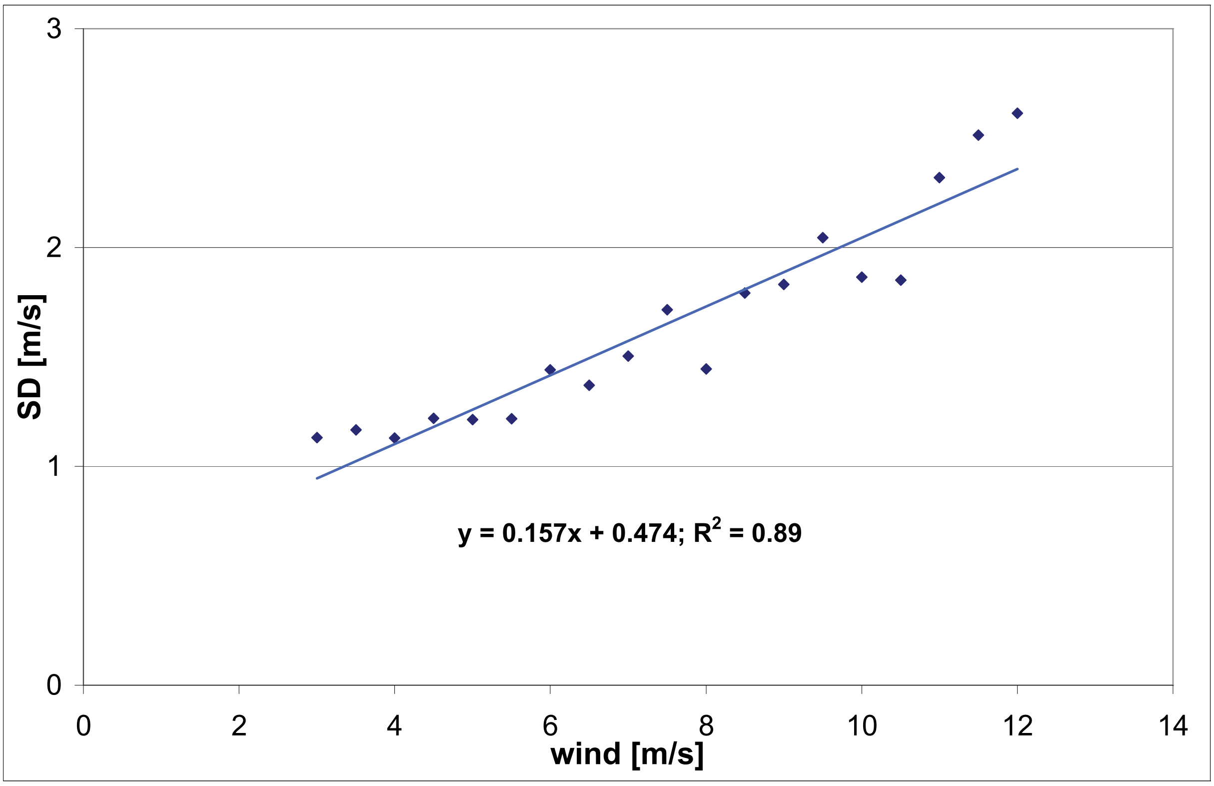

Figure 4: Average daily wind speed and corresponding standard deviation

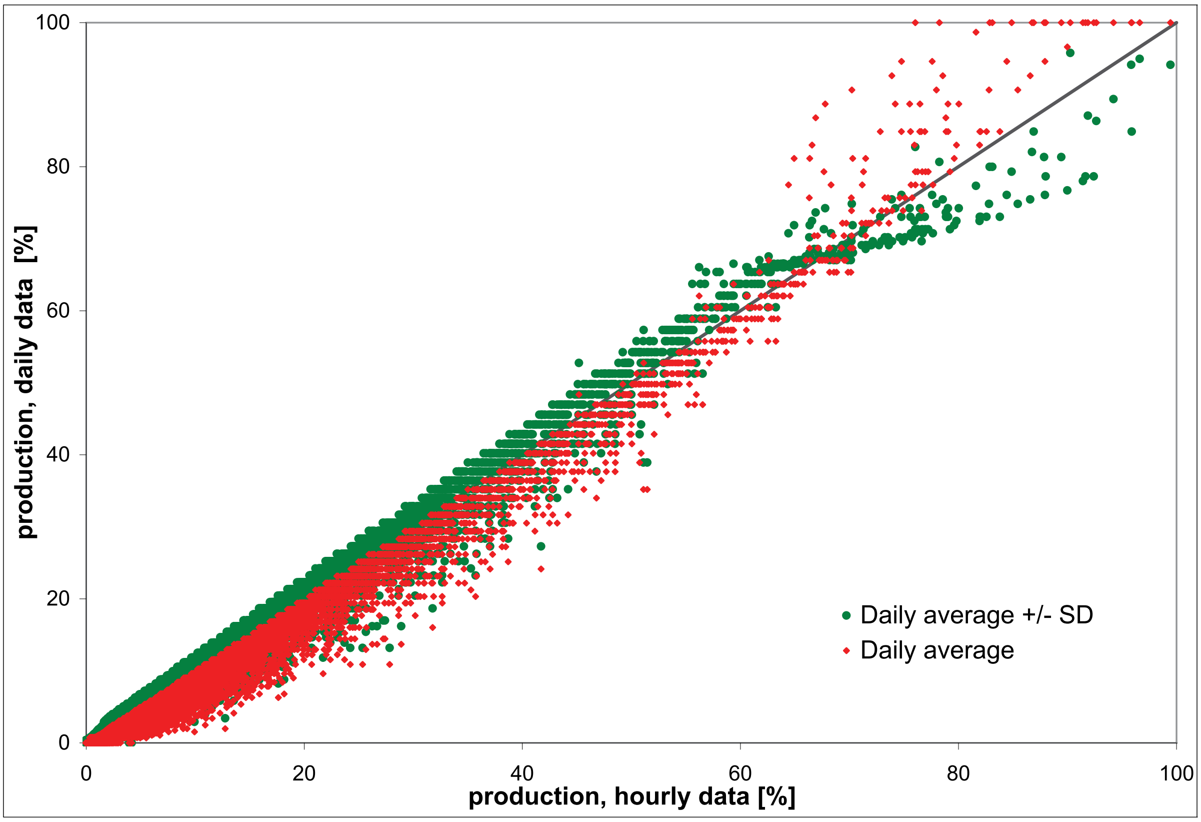

Figure 5: Calculated production of a wind power plant (data: DWD-station Potsdam Telegrafenberg) using hourly data, daily data and daily data including standard deviation of hourly data

speed were determined (see Fig. 4). Due to the low number of days with wind speed above 12 m/s there were not enough data to calculate a reliable value for the standard deviation.

$$SD = 0.157V_M + 0.474 \quad (2.3)$$

For each day the standard deviation was added and subtracted from the daily average. Both of these calculated values were extrapolated to a height of 100 meter above ground using the logarithmic wind profile and used for the power curve. Therefore for each day two values for the generation were calculated and the mean of these was used as daily generation. As shown in Fig. 5 most of the daily results including the standard deviation are much closer to the 1:1-line than those when applying the daily mean only. The correlation increases from 0.988 to 0.992, and the BIAS is reduced from −17.1 percent to +1.4 percent.

Wind speed data for the DWD-station Potsdam (Telegrafenberg) are available from 1893 onward. It has declined markedly during this time, e.g. because of the growing of tall trees. However, it can not be ruled out that other effects like changed measurement devices may also have affected the data. While the mean wind speed for the time period 1901–1930 was 5.22 m/s for the time period 1981–2010 it was 4.16 m/s. These changes give the opportunity to test the presented approach. In Fig. 6 the changes in the generation between 1901–1930 and 1981–2010 using hourly, daily and daily including standard deviation data are presented. While the calculations for daily data show a strong deviation from the calculations using hourly data, the differences using daily data including the standard deviation are rather small.

Wind speed data from the other named DWD-stations, which are located in northern (Cuxhaven), central (Kassel) and southern (Augsburg) Germany presenting different local conditions, are used to test the approach. By using the daily data including the standard deviation the quality of the results increases comparable to the results presented for DWD-station Potsdam (Telegrafenberg).

For the extrapolation of measured wind speed applying the logarithmic wind profile anemometer heights (m over ground) for 146 stations were delivered by DWD while the roughness length of the surface (z_0) for these stations was estimated using the CORINE land cover dataset (Corine Land Cover, 2006). In Fig. 7 the average generation simulated for these 146 DWD-stations is displayed (reference period 1981–2010). Also shown is the long-term wind speed at 80 m over ground as calculated by the DWD (2008). Except for mountain ranges the wind speed decreases from the northern to the southern parts of Germany. As can be seen in the inset of Fig. 7 for the Harz Mountains, for higher ranges (here Brocken Mountain) high wind speed and generation is

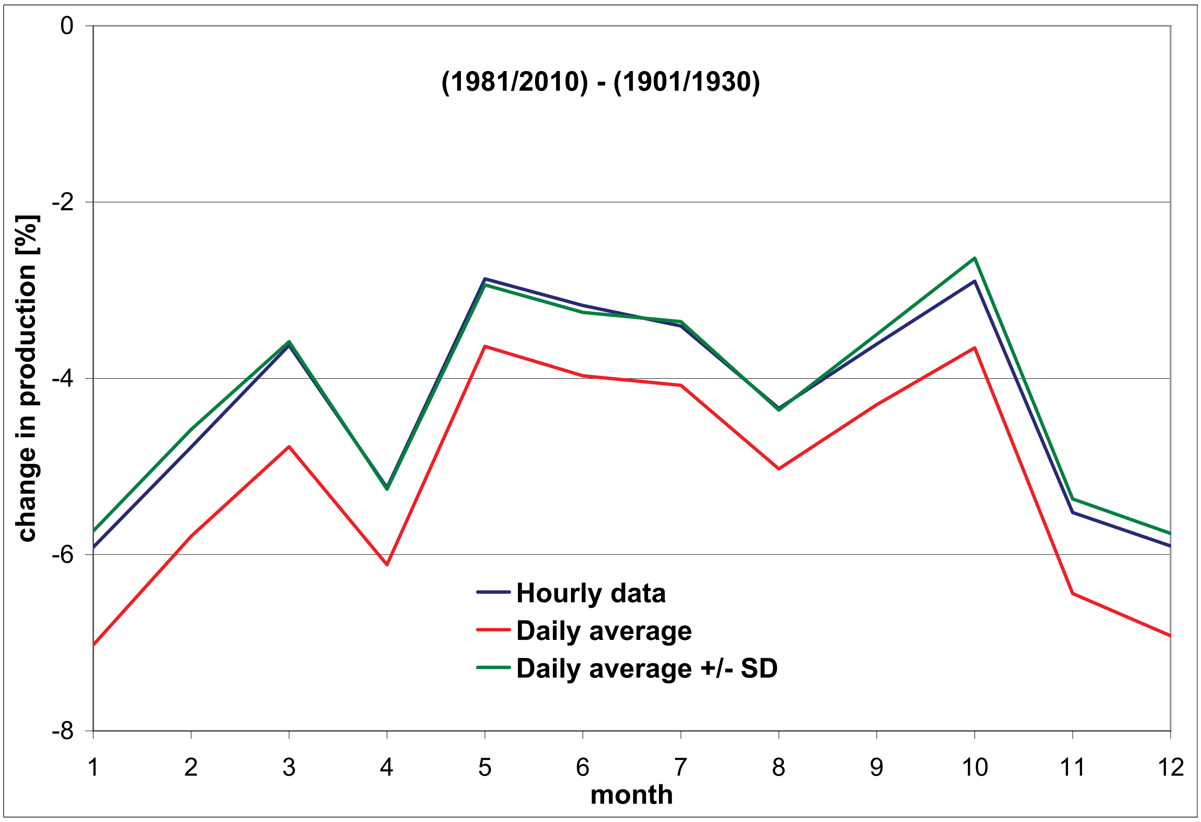

Figure 6: Calculated changes in wind power production using hourly data, daily data and daily data including standard deviation of hourly data

calculated, while for valleys low wind speed and generation is calculated. However, due to the low number of stations available and the strong local effects of surrounding terrain an interpolation between these stations is not reasonable.

2.4 Climate scenarios

To assess the possible effects of climate change on electricity generation by thermal power plants, hydro power plants and wind power plants, scenarios as described in Gerstengarbe et al. (2015) are applied. In this study scenarios of two Representative Concentration Pathways (RCP) are used, RCP 2.6 and RCP 8.5. The first scenario is a low concentration scenario. Future climate warming by the end of the century is kept to a maximum of 1.3 K for Germany. In the second scenario greenhouse gas emissions are much higher and reflect actual emission very well. Warming is much more pronounced and is between 2 and 5.5 K by the end of the century. For each RCP the minimum (TMin), median (TMed) and maximum (TMax) temperature trend from 23 model runs calculated in the CMIP5 program (http://cmip-pcmdi.llnl.gov/cmip5/availability.html) is used. Applying the statistical regional climate model STARS (STatistical Analog Resampling Scheme) Gerstengarbe et al. (2015) produce 100 realizations (ensemble runs) for each scenario. Overall six scenarios, RCP 2.6 and 8.5 each with TMin, TMed and TMax, are used in this study.

3 Results

Results shown are mean values derived from 100 STARS-realizations of each RCP scenario. Selected parameters - the value below which 5 percent of the results are located (Q5), the median (Q50), and the value exceeded by only 5 percent of the results (Q95) - illustrate the range of results given by the large set of realizations.

3.1 Thermal power plants

Results for scenario RCP 8.5 for thermal power plants without and with cooling tower are displayed in Figs. 8 and 9. Regions with the most severe effects are found in the central north western part, the river Weser basin, and the central south western part, the river Rhine basin with its tributary rivers Neckar and Main. In these regions for thermal power plants without cooling tower a mean annual utilization of 94 percent is simulated for the scenario period 2031–2060, i.e. a total stand still of 22 days per year. For thermal power plants with cooling tower a mean annual utilization of 99.4 percent is simulated, i.e. a total stand still of 2.2 days per year. Compared to the reference period (not displayed) this is a doubling (without cooling tower: 97 percent or 11 days total stand still)

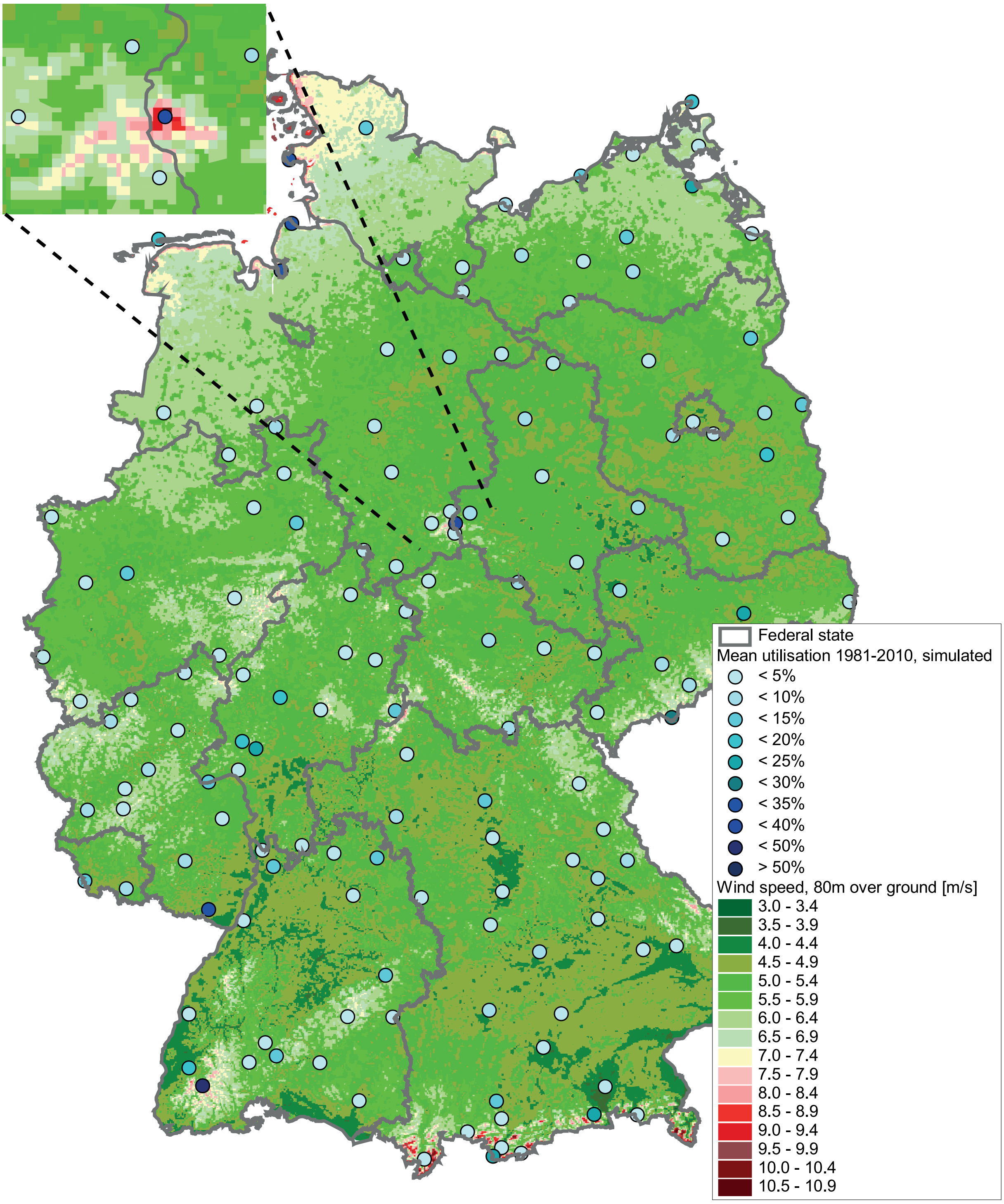

Figure 7: Calculated mean annual utilisation of wind power plants (circles: DWD-stations) for reference period (1981–2010) and long term mean wind speed 80 m over ground (source: DWD, 2008); inset: Harz Mountains with Brocken Mountain in the centre

and an increase by a factor of three (with cooling tower: 99.8 percent or 0.7 days total stand still) for these regions.

3.2 Hydro power generation

River discharge for 38 gauges in Germany was simulated using the ecohydrological model SWIM (see Hattermann et al., 2015). These gauges are located along the most important rivers and their tributaries (see Fig. 10). Using the simulated river discharge and the relation between changes in discharge and electricity generation described above, for these gauges changes in generation potential compared to the reference period (1981–2010) are calculated. In Fig. 10 results for RCP 2.6 (left) and RCP 8.6 (right) are shown. In Figs. 11 and 12 the changes between 2015 and 2050 for RCP 2.6 and 8.5 are displayed. To show the ranges for each RCP

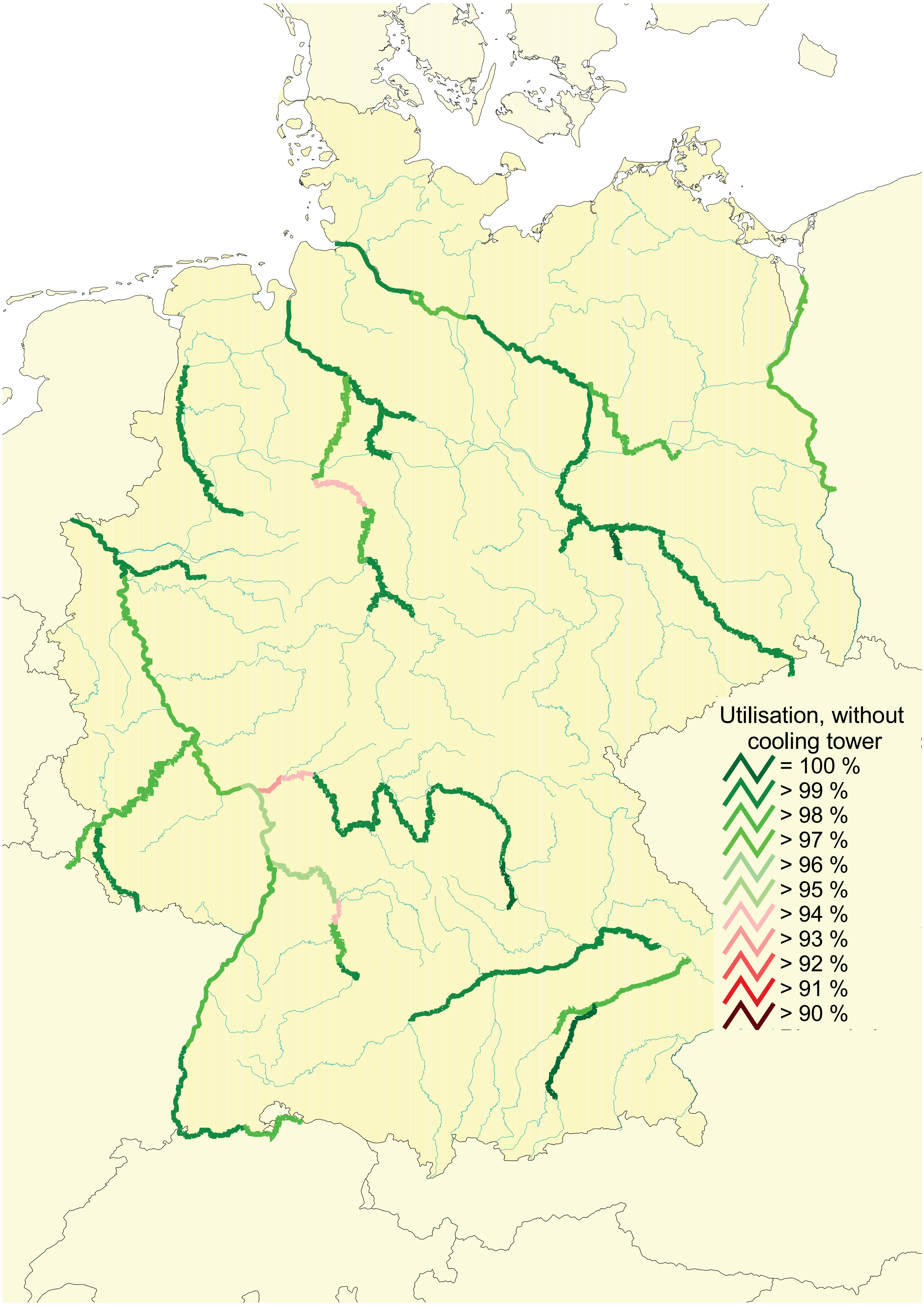

Figure 8: Mean annual utilisation of thermal power plants without cooling tower, scenario period 2031–2060 (RCP 8.5, TMed)

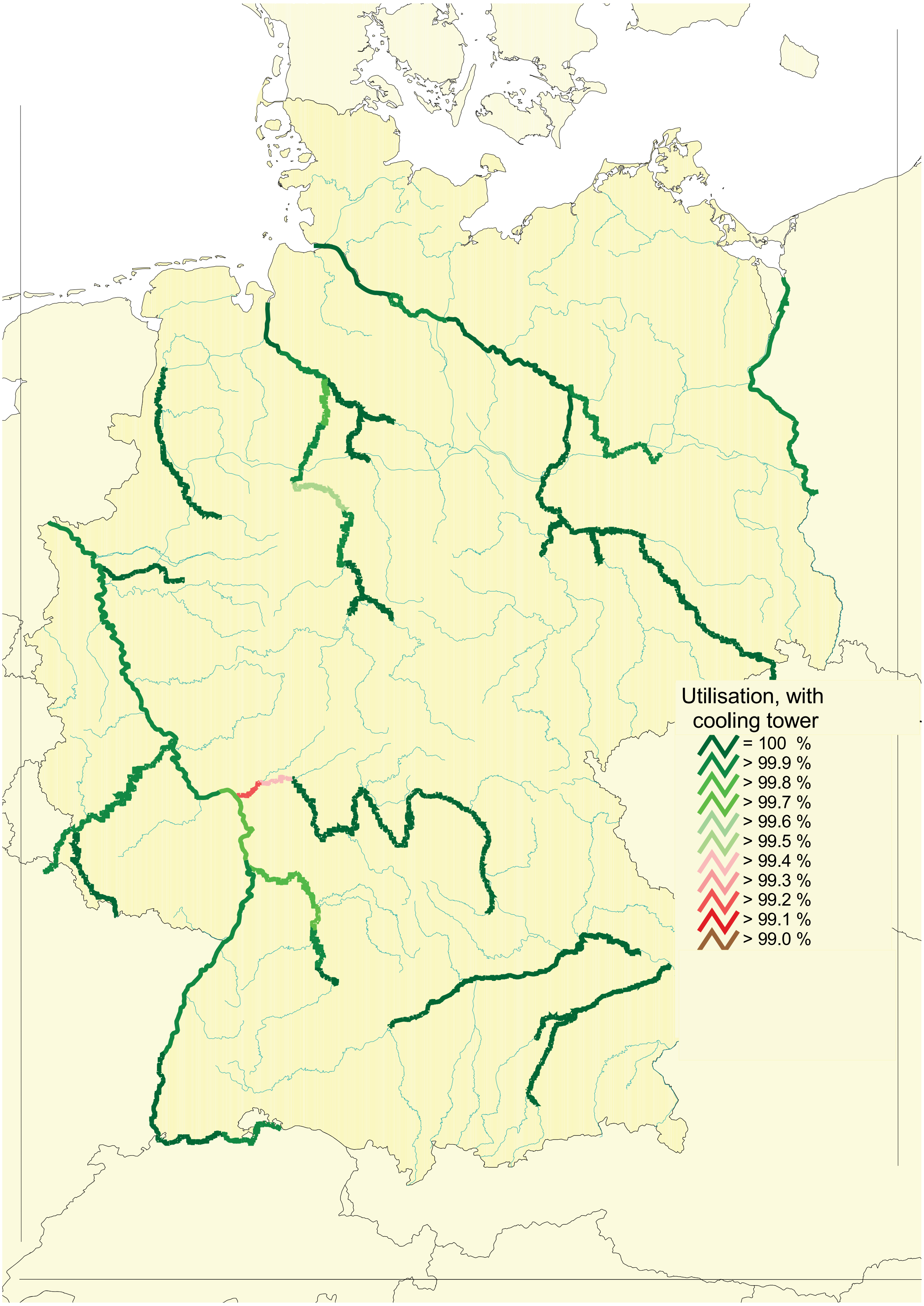

Figure 9: Mean annual utilisation of thermal power plants with cooling tower, scenario period 2031–2060 (RCP 8.5, TMed)

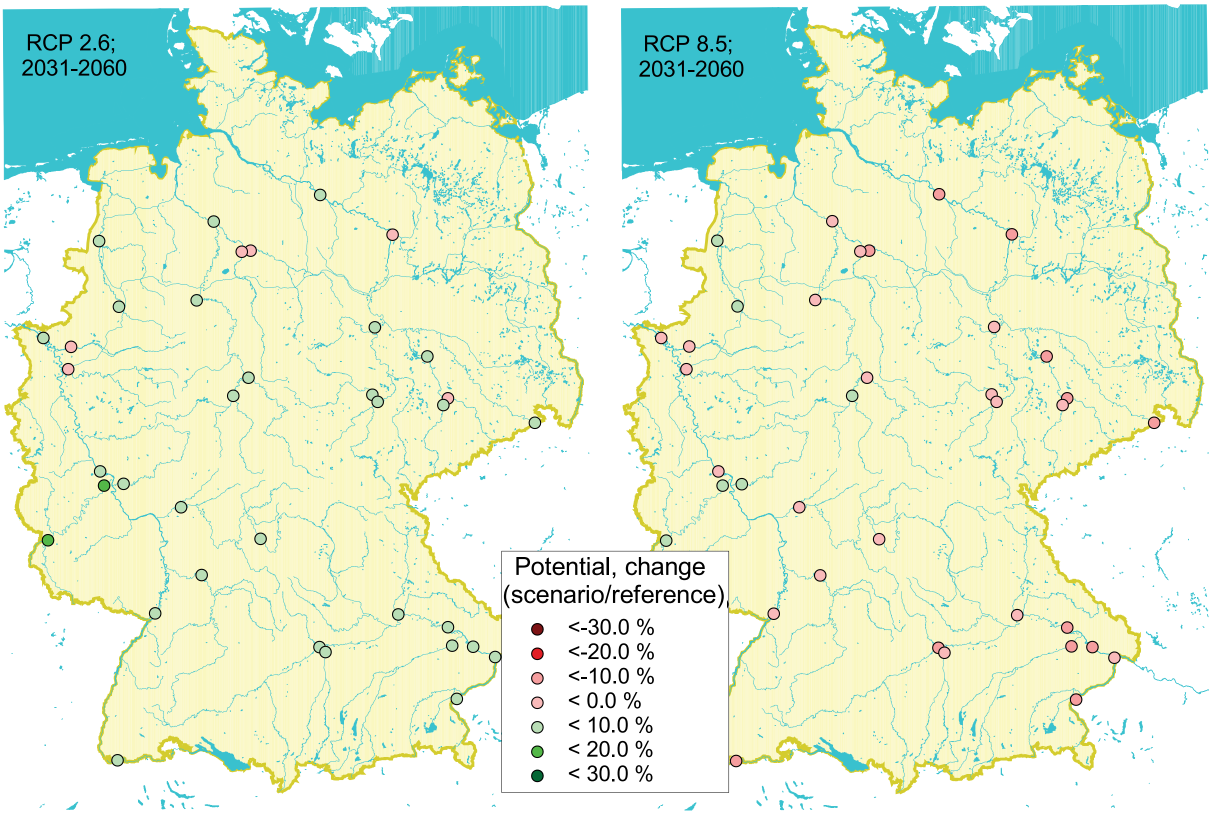

Figure 10: Changes in hydro power generation potential compared to reference period (1981–2010) for RCP 2.6 (left) and RCP 8.6 (right), median temperature trends (TMed), 50th percentiles (Q50)

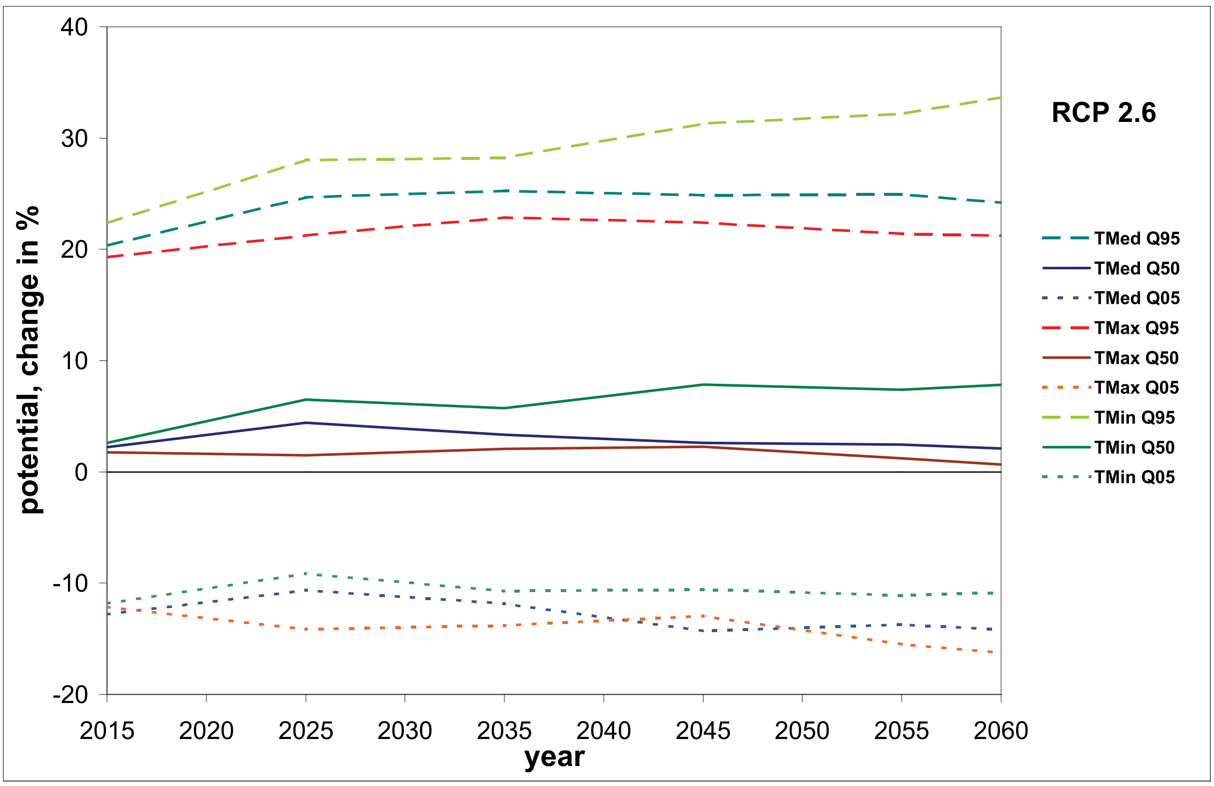

Figure 11: Changes in hydro power generation potential compared to reference period (1981–2010) for RCP 2.6, minimum, median and maximum temperature trend (TMin, TMed, TMax) and 5th, 50th and 95th percentile (Q05, Q50, Q95)

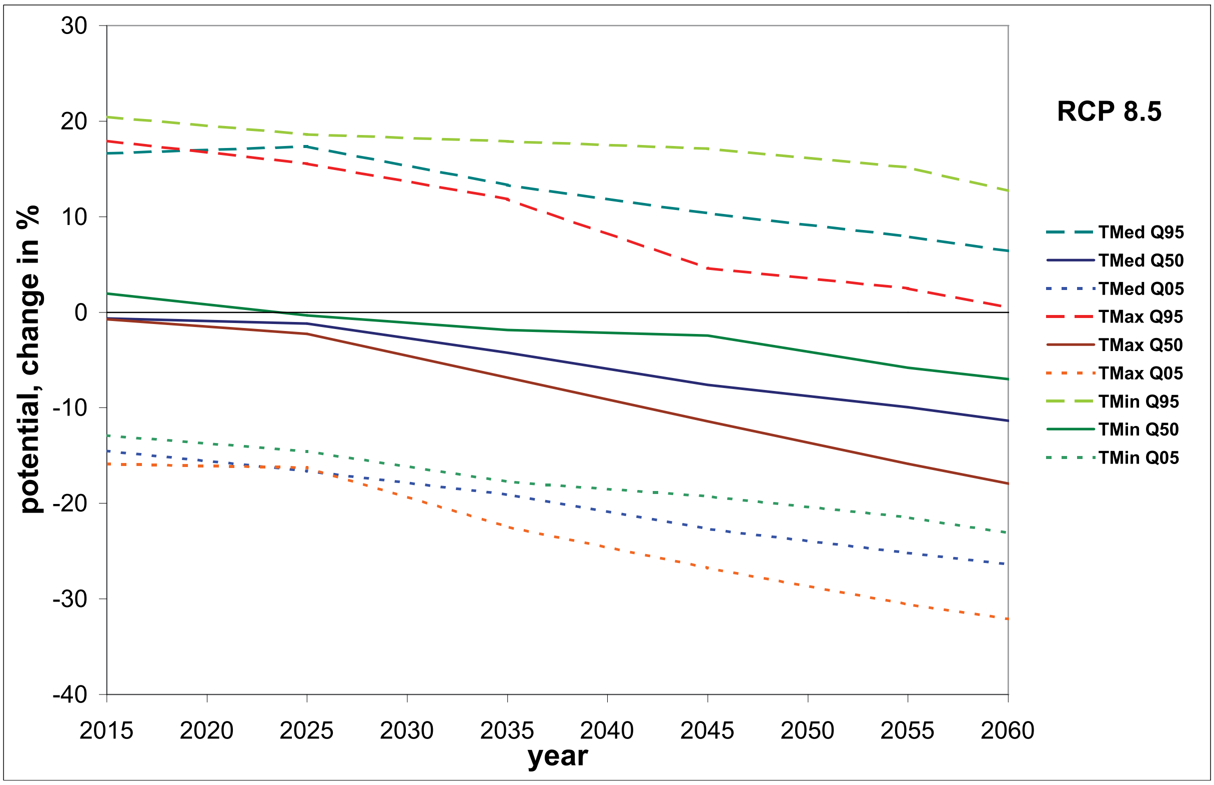

Figure 12: Changes in hydro power generation potential compared to reference period (1981–2010) for RCP 8.6, minimum, median and maximum temperature trend (TMin, TMed, TMax) and 5th, 50th and 95th percentile (Q05, Q50, Q95)

results for the minimum, median and maximum temperature trend, with the 5th, 50th and 95th percentiles from 100 STARS-realizations are given.

For RCP 2.6 (Fig. 11) changes of 8 percent (TMin), 3 percent (TMed), 2 percent (TMax) for the 50th percentiles (Q50) from 100 STARS-realizations are simulated. For dry realizations (TMax Q05) a decrease of up to 15 percent, for wet realizations (TMin Q95) an increase of up to 35 percent is found.

For RCP 8.5 (Fig. 12) changes of −7 percent (TMin), −11 percent (TMed), and −18 percent (TMax) for the 50th percentiles (Q50) from 100 STARS-realizations are calculated. For dry realizations (TMax Q05) a decrease of up to 30 percent, for wet realizations (TMin Q95) an increase of up to 15 percent is calculated.

3.3 Wind power generation

Using the wind speed calculated by STARS for the selected weather stations and the described power curve, changes in generation compared to the reference period (1981–2010) are simulated. In Fig. 13 changes for RCP 2.6 (left) and RCP 8.6 (right) are shown. Overall the changes for RCP 2.6 are rather small and no clear trend is visible (light bluish and light reddish colors dominate). For RCP 8.5 the change signals are somewhat more pronounced. Especially for parts in southern Germany a decrease of 2 percent is found. For the northern parts and some stations in central and southern Germany located on mountains an increase of up to 3 percent is simulated.

In Fig. 14 monthly changes, the 50th percentiles (Q50) for the minimum, median and maximum temperature trend averaged over Germany, for RCP 2.6 and RCP 8.6 are displayed. For RCP 2.6 no clear signal is visible, while RCP 8.5 shows an increase from November to February, and a decrease for the rest of the year.

4 Discussion and conclusion

In this study possible effects of climate variability and change on electricity generation in Germany are analyzed. Hydro power generation and thermal power plants are affected negatively due to declining river discharge or higher water temperatures. For wind power generation no clear trend was found. The reduction calculated for hydro power generation could be leveled out by a slight increase in installed capacity and modernization of turbines and generators (cf. Koch and Grünewald, 2011). The negative effects for thermal power plants can be reduced significantly by replacing old once-through cooling systems by closed-circuit cooling systems (cf. Koch et al., 2012, 2014). The planned increase of installed capacity for wind power generation clearly surpasses the changes arising from climate change.

The results presented are produced using more or less simple approaches. However, data, e.g. technical parameters for the respective type of electricity generation, are rarely available for individual generation units encompassing the whole of Germany. Therefore, the results

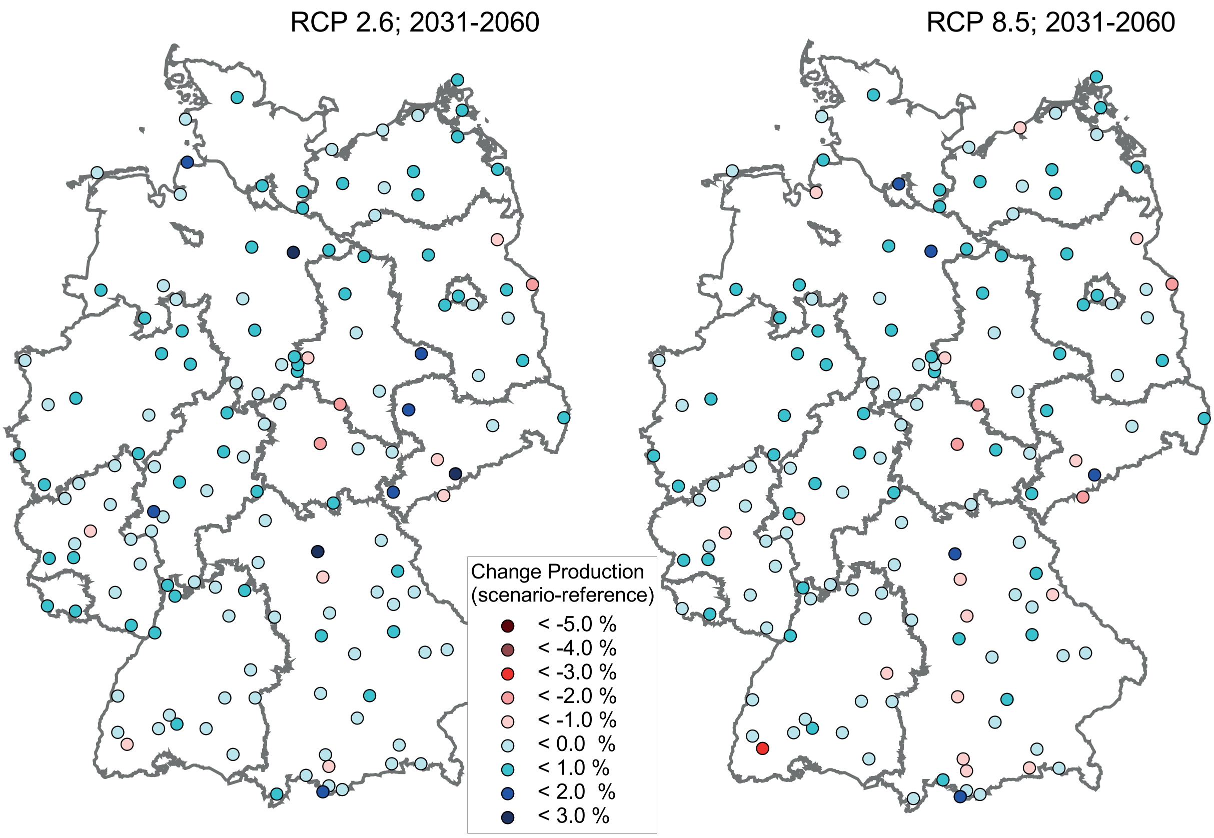

Figure 13: Changes in wind power electricity production compared to reference period (1981–2010) for RCP 2.6 (left) and RCP 8.6 (right), median temperature trends (TMed), 50th percentiles (Q50)

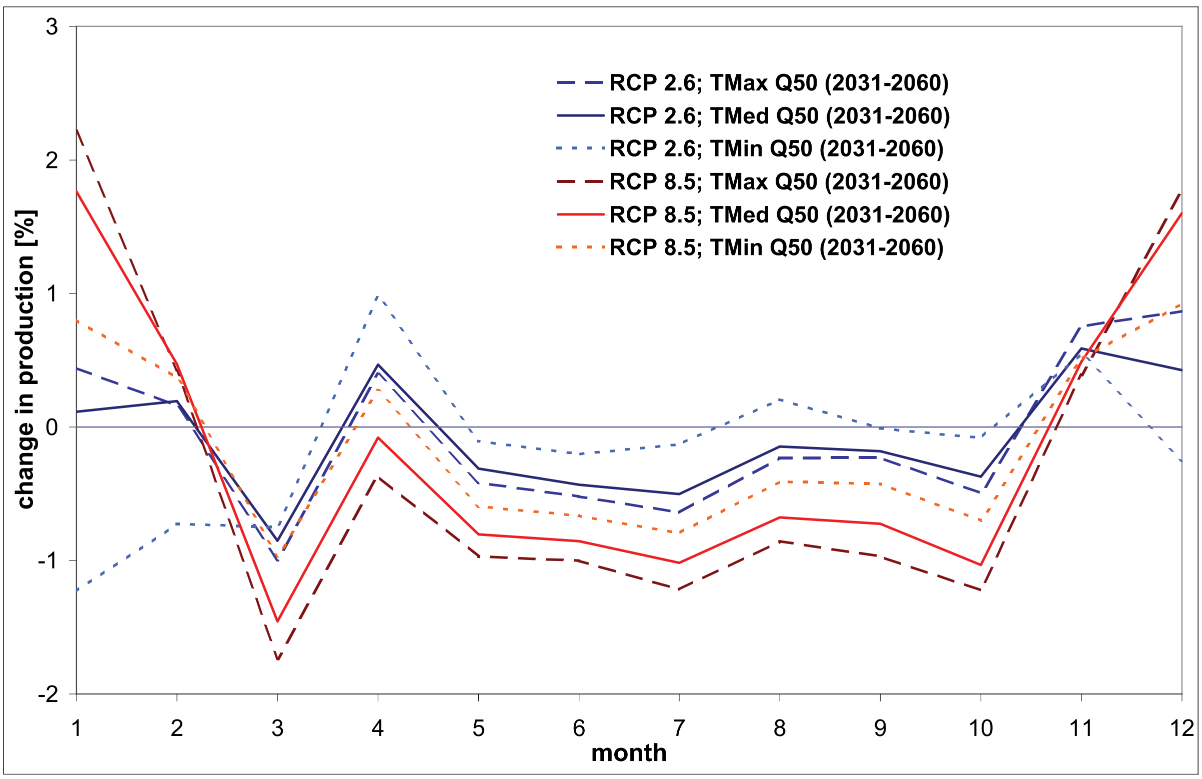

Figure 14: Changes in wind power electricity production for scenario RCP 2.6 and RCP 8.5 compared to reference period (1981–2010), minimum, median and maximum temperature trend (TMin, TMed, TMax), 50th percentiles (Q50)

give only a general overview in which regions and to what magnitude the analyzed types of electricity generation can be affected by climate change.

Despite these shortcomings, the application of different Representative Concentration Pathways (RCP) and 100 statistical realizations of a regional climate model can give useful information. For instance positive effects of reduced greenhouse gas emissions (RCP 2.6 compared to RCP 8.5) can be found for all presented types of electricity generation. The calculation of percentiles from 100 realizations shows the range of possible effects arising from the used climate regionalization. The wide spread of results on the one hand complicates adaptation, on the other hand it can foster flexibility in planning processes.

Although different climate scenarios are used in this study some restrictions of the results need to be mentioned. As shown by Hattermann et al. (2015) and Gädeke et al. (2013) the selection of the regional climate model affects the results for river discharge. While some give a rather dry future, like the one used in this study, others show little changes in discharge or even an increase. Since the change in river discharge is the only parameter used in the calculation of changes in hydro power potential, the application of other regional climate models can lead to different results. For thermal power plants the main factor affecting production is the water temperature (cf. Koch et al., 2014). Therefore, the application of other regional climate models, all giving a temperature increase, will not lead to different trends compared to those presented.

The results presented for wind power generation overall confirm the results of Koch and Büchner (accepted) using data from the regional climate model CCLM for Germany.

Acknowledgements

For the calibration and validation of the hydrological model runoff measurements provided by the Global Data Runoff Center (GDRC) in Koblenz were used. Institutions from the following river basins delivered data for the calibration and validation of the water temperature model:

i) Elbe (river Elbe),

ii) Bayerisches Landesamt für Umwelt (rivers Donau, Isar and Main),

iii) Bundesanstalt für Gewässerkunde Koblenz (river Rhein),

iv) Flussgebietsgemeinschaft Rhein (river Rhein),

v) Flussgebietsgemeinschaft Weser (river Weser),

vi) Hessisches Landesamt für Umwelt und Geologie (river Main),

vii) Landesamt für Umwelt, Messungen und Naturschutz Baden-Württemberg (rivers Rhein and Neckar),

viii) Niedersächsischer Landesbetrieb für Wasserwirtschaft, Küsten- und Naturschutz (rivers Ems and Weser).

References

Aguiar, R., H. Gonçalves, M. Oliveira, M.J. Reis, 2002: Energy. – In: Santos, F.D., K. Forbes, R. Moita (Eds.): Climate Change in Portugal. Scenarios, Impacts and Adaptation Measures – SIAM Project. – Lisbon, http://www.siam.fc.ul.pt/SIAM_Book/9_Energy.pdf

Akdag, S.A., Ö. Güler, 2011: A Comparison of Wind Turbine Power Curve Models. – Energy Sources, Part A: Recovery, Utilization, and Environmental Effects **33**, 2257–2263.

Barstad, I., A. Sorteberg, M. dos-Santos Mesquita, 2012: Present and future offshore wind power potential in northern Europe based on downscaled global climate runs with adjusted SST and sea ice cover. – Renewable Energy **44**, 398–405.

Brayshaw, D.J., A. Troccoli, R. Fordham, J. Methven, 2011: The impact of large scale atmospheric circulation patterns on wind power generation and its potential predictability: A case study over the UK. – Renewable Energy **36**, 2087–2096.

BUNR, 2011: Entwicklung der erneuerbaren Energien in Deutschland im Jahr 2010 – unter Verwendung aktueller Daten der Arbeitsgruppe Erneuerbare Energien-Statistik AGEE-Stat. – Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit.

Corine Land Cover, 2006: Raster data on land cover for the CLC2006 inventory. – http://www.eea.europa.eu/data-and-maps/data/corine-land-cover-2006-raster.

Deutsches Atomforum, 2004: Kernenergie in Deutschland – Jahresbericht 2003. – Deutsches Atomforum e. V., Berlin.

Deutsches Atomforum, 2007: Kernenergie in Deutschland – Jahresbericht 2006. – Deutsches Atomforum e. V., Berlin.

DWD, 2008: Windkarten und Winddaten für Deutschland, Bezugszeitraum 1981–2000. – Deutscher Wetterdienst. Abteilung Klima- und Umweltberatung, Offenbach, http://www.dwd.de/bvbw/generator/DWDWWW/Content/Oeffentlichkeit/KU/KU1/KU12/Klimagutachten/Windenergie/Windkarten__entgeltfrei/Windkarten__80m/BRD__1kmRasterA3__80m,templateId=raw,property=publicationFile.pdf/BRD_1kmRasterA3_80m.pdf)

Feeley, T.J., T.J. Skone, G.J. Stiegel, A. McNemar, M. Nemeth, B. Schimmoller, J.T. Murphy, L. Manfredo, 2008: Water: A critical resource in the thermoelectric power industry. – Energy **33**, 1–11.

Förster, H., J. Lilliestam, 2010: Modeling thermoelectric power generation in view of climate change. – Reg. Environ. Change **10**, 327–338.

Gädeke, A., H. Hölzel, H. Koch, I. Pohle, U. Grünewald, 2013: Analysis of Uncertainties in the Hydrological Response of a Model-Based Climate Change Impact Assessment in a Subcatchment of the Spree River, Germany. – Hydrol. Proc., article first published online 11 July 2013, doi:10.1002/hyp.9933.

Gerstengarbe, F.W., P. Hoffmann, H. Österle, P.C. Werner, 2015: Ensemble simulations for the RCP8.5-Scenario. – Meteorol. Z., **24**, 147–156 doi: 10.1127/metz/2014/0523

Grossmann, M., H. Koch, 2011: Wasserkraftanlagen. – In: Wechsung, F., H. Koch, P. Gräfe (Eds.): Elbe-Atlas des globalen Wandels. – Weißensee Verlag Berlin, 70–71.

Gutsch, M., P. Lasch-Born, A.B. Lüttger, F. Suckow, A. Murawski, T. Pilz, 2015: Uncertainty of biomass contributions from agriculture and forestry to renewable energy resources under climate change. – Meteorol. Z., **24**, 213–223 doi: 10.1127/metz/2015/0523

Hattermann, F.F., J. Post, V. Krysanova, T. Conradt, F. Wechsung, 2008: Assessment of water availability in a Central – European River Basin (Elbe) under climate change. – Adv. Climate Change Res **4**, 42–50.

Hattermann, F., M. Weiland, S. Huang, V. Krysanova, Z. Kundzewicz, 2011: Model – supported impact assessment for the water sector in Central Germany under climate change – a case study. – Water Res. Manag. **25**, 3113–3134.

Hattermann, F.F., S. Huang, H. Koch, 2015: Climate change impacts on hydrology and water resources. – Meteorol. Z., **24**, 201–211 doi: 10.1127/metz/2014/0575

Hoffmann, B., S. Häfele, U. Karl, 2013: Analysis of performance losses of thermal power plants in Germany – A System Dynamics model approach using data from regional climate modelling. – Energy **49**, 193–203.

Hoogwijk, M., B. de Vries, W. Turkenburg, 2004: Assessment of the global and regional geographical, technical and economic potential of onshore wind energy. – Energy Econ. **26**, 889–919.

Huang, S., V. Krysanova, H. Österle, F. Hattermann, 2010: Simulation of spatiotemporal dynamics of water fluxes in Germany under climate change. – Hydrol. Proc. **24**, 3289–3306.

Hurd, B., M. Harrod, 2001: Water Resources: Economic analysis. – In: Mendelsohn, R. (Eds.): Global Warming and the American Economy. – Cheltenham, Edward Elgar Publishing Ltd., 106–131.

Kirshen, P., M. Ruth, W. Anderson, 2008: Interdependencies of urban climate change impacts and adaptation strategies: a case study of Metropolitan Boston USA. – Climatic Change **86**, 105–122.

KlimAdapt, 2010: Ableitung von prioritären Maßnahmen zur Adaption des Energiesystems an den Klimawandel. Endbericht. – Studie im Auftrag der Österreichischen Forschungsförderungsgesellschaft mbH FFG, Wien.

Koch, H., M. Büchner, accepted: Is climate change a threat to the growing importance of wind power resources in the energy sector in Germany? – Energy Sources, Part B: Economics, Planning, and Policy.

Koch, H., U. Grünewald, 2010: Regression models for daily stream temperature simulation: case studies for the river Elbe, Germany. – Hydrol. Proc. **24**, 3826–3836.

Koch, H., U. Grünewald, 2011: Anpassungsoptionen der Wasserbewirtschaftung an den globalen Wandel in Deutschland. – acatech Materialien Nr. **5**, München, 35 pp.

Koch, H., S. Vögele, 2013: Hydro-climatic conditions and thermoelectric electricity generation–Part I: Development of models. – Energy **63**, 42–51.

Koch, F., M. Prasch, H. Bach, W. Mauser, F. Appel, M. Weber, 2011: How will hydroelectric power generation develop under climate change scenarios? A case study in the Upper Danube basin. – Energies **4**, 1508–1541.

Koch, H., S. Vögele, M. Kaltofen, U. Grünewald, 2012: Trends in water demand and water availability for power plants–scenario analyses for the German capital Berlin. – Climatic Change **110**, 879–899.

Koch, H., S. Vögele, F.F. Hattermann, S. Huang, 2014: Hydro-climatic conditions and thermoelectric electricity generation–part II: model application to 17 nuclear power plants in Germany. – Energy **69**, 700–707.

Lehner, B., G. Czisch, S. Vassolo, 2005: The impact of global change on the hydro power potential of Europe: a model-based analysis. – Energy Policy **33**, 839–855.

Linnerud, K., T. Mideksa, G. Eskeland, 2011: The Impact of Climate Change on Nuclear Power Supply. – Energy J. **32**, 149–168.

Pryor, S.C., R.J. Barthelmie, E. Kjellström, 2005a: Potential climate change impact on wind energy resources in northern Europe: analyses using a regional climate model. – Climate Dyn. **25**, 815–835.

Pryor, S.C., J.T. Schoof, R.J. Barthelmie, 2005b: Climate change impacts on wind speeds and wind energy density in northern Europe: empirical downscaling of multiple AOGCMs. – Climate Res. **29**, 183–198.

Schaefli, B., B. Hingray, A. Musy, 2007: Climate change and hydro power production in the Swiss Alps: quantification of potential impacts and related modelling uncertainties. – Hydrol. Earth Syst. Sci. **11**, 1191–1205.

Seljom, P., E. Rosenberg, A. Fidje, J.E. Haugen, M. Meir, J. Rekstad, T. Jarlset, 2011: Modelling the effects of climate change on the energy system – A case study of Norway. – Energy Policy **39**, 7310–7321.

UBA, 2010: Umweltpolitik – Wasserwirtschaft in Deutschland. Teil 1 – Grundlagen. – Umweltbundesamt, Dessau-Roßlau.

van Vliet, M.T.H., J.R. Yearsley, F. Ludwig, S. Vögele, D.P. Lettenmaier, P. Kabat, 2012: Change Vulnerability of US and European electricity supply to climate change. – Nature Climate Change **2**, 676–681, doi:10.1038/nclimate1546.