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# Analysis of performance losses of thermal power plants in Germany – A System Dynamics model approach using data from regional climate modelling

Bastian Hoffmann*, Sebastian Häfele, Ute Karl

*European Institute for Energy Research, Emmy-Noether-Straße 11, 76131 Karlsruhe, Germany*

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ABSTRACT

The majority of thermal power plants of more than 300 MW use river water for cooling purposes. Increasing water and air temperatures due to climate change can significantly impact the efficiency and the power production of these power plants. In this paper we analyse these impacts by modelling selected German thermal power plant units and their respective cooling systems through dynamic simulation taking into account legal thresholds for heat discharges to river water together with climate data projections (SRES scenarios A1B, A2, and B1). Possible output and efficiency reductions in the future (2011–2040 and 2041–2070) are quantified for thermal power plants with once-through (OTC) and closed-circuit (CCC) cooling systems under current legislative framework. The model validation showed that the chosen System Dynamics approach is appropriate to analyse impacts of climate change on thermal power units. The model results indicate lowest impacts for units with CCC systems: The mean trend for CCC for the A1B scenario (2011–2070) is expected to be −0.10 MW/a and −0.33 MW/a for an OTC system. On a daily basis, the power output of all considered OTC units is reduced down to 66.4% of the nominal capacity, for a single unit even down to 32%.



## 1. Introduction

Hot summers in Europe in 2003 and 2006 have shown the vulnerability of electricity supply with regard to these events. Also in the scientific literature an increasing interest in the vulnerability of the energy sector to climate change can be stated [1]. Heat waves and the entailed scarcity of cooling water for thermal power plants (nuclear and fossil) are among these impacts. In Germany, the highest share of power plant capacity is represented by thermal power plants using predominantly river water for cooling purposes. Varying river temperatures have a significant impact on power production: cooling water discharges have to comply with regulatory threshold values for the protection of the aquatic environment. Reduced cooling capacities of river water therefore restrict production capacities [2]. In addition, river water temperature influences the temperature before condenser which in turn has an impact on the efficiency of the power plant [3].

A detailed knowledge of the interaction of power plant operation, cooling water availability and climate change impacts is crucial for power plant operators and public authorities. Power plant operators need decision support with regard to the planning of plant revisions or potential investments. Consequences of the current or future regulatory framework need to be analysed in a quantitative way in order to ensure its efficiency [4,5].

Therefore, impacts of climate change on power plant cooling systems were already analysed in the past with varying foci and methods.

The analyses of Koch et al. [6,7] are focussing on the future management of water resources in the light of climate change. This work combines hydrological and climate modelling to assess the future availability of cooling water. The impacts on power plant operation are simulated using the model KASIM. This model shows a monthly time resolution and is based on the results of empirical analyses and comprehensive power plant data [6]. The approach was applied to various river basins in Germany. Recently, a similar methodology was used by van Vliet et al. [8] to assess potential climate change impacts on electricity production in Europe and the United States for a total of 96 power plants.

On the other hand there are a number of studies focussing on the problem of power plant cooling for specific sites or technologies [9–16]. Most of these studies assess the impact of varying cooling water temperature through sensitivity analyses. The paper of Greis et al. [13] quantified these effects for an individual thermal power plant with a CCC (closed-circuit) system based on plant specific empirical relationships. Similar to the study presented here,

* Corresponding author. Tel.: +49 721 61051434; fax: +49 721 61051332.
*E-mail addresses:* bastian.hoffmann@eifer.org (B. Hoffmann), sebastian.haefele@eifer.org (S. Häfele), ute.karl@eifer.org (U. Karl).

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a System Dynamics approach was chosen to calculate long-term scenarios including potential impacts of climate change.

In this paper a similar approach was chosen for a prospective study on the potential impacts of climate change on thermal power plants in Germany. In contrast to the work of Koch et al. [6,7] the focus was put on the simulation of the dynamic interaction between power plant cooling, plant efficiency and water temperature. The cooling system model presented here is covering the two most common cooling technologies in Germany: the OTC and the CCC system. Furthermore, for every modelled power plant we used plant specific technical parameters from different sources. In this context the System Dynamics approach allows for the representation of these interactions with a daily temporal resolution through empirical as well as thermodynamic relationships. The performance of the cooling process is calculated with thermodynamic algorithms. This allows for an adaptation of the model to the various power plant sites. Climate scenarios are derived from regional climate model results for all investigated power plant sites. The data were taken from the REMO model (UBA run) for the IPCC SRES scenarios A1B, A2 and B1 [17]. These scenarios reflect different political, economical and socio-demographical developments and represent the possible range of climate prognostics in terms of greenhouse gas emissions and global warming. In addition, site-specific legal thresholds values for cooling and river water temperatures are integrated in the model. This study does not include a detailed hydrological modelling of the river basins concerned. Nevertheless, water temperatures have been derived from site-specific measured time series and regression analyses.

In our analysis, the dispatching of the power units, their economic lifetime and political large scope energy decisions, such as nuclear phase-out, are not considered in order to isolate the impact of climate change and to assess the vulnerability of the existing thermal power plants in Germany (reference year: 2010). The underlying regulatory framework (threshold values) also refers to the year 2010. The analysis of the vulnerability of a future German infrastructure for electricity supply with regard to climate change impacts is not in the scope of this paper. It also has to be noted, that the emission from the power plant park that underlies the IPCC scenarios is different from the emissions of the park that we assume in this study.

This study quantifies possible output reductions of thermal power plants in Germany in the mid-term and long-term future (2011–2040 and 2041–2070). It analyses differences between cooling systems and compares them to the control period (1961–1990). To further assess important factors of vulnerability two alternative scenarios are included in the analysis: the impacts of retrofitting the cooling system from OTC to CCC and the sensitivity analysis on runoff reduction where average runoff was reduced by 10%, 20% and 50%.

## 2. Methodology

In this study output reductions due to river water related thresholds as well as effects on the efficiency of power units are analysed by modelling cooling systems of thermal power plants based on the System Dynamics (SD) approach. In this section the focus is put on the CCC model. The methodological background of the OTC system model is described in [18]. In Section 2.1, reasons are given which justify the use of SD and first qualitative analyses are carried out. Efficiency reductions are implemented via linear regression into the SD model. A heat balance engineering software was used to estimate the regression model and coefficient (see Section 2.2). Insights in the applied cooling-down mechanism of the natural draught cooling tower (NDT) are given in Section 2.3. The used input data concerning river water related thresholds, technical parameters and hydro-meteorological data series is described in Section 2.4.

### 2.1. System Dynamics approach

SD was developed to analyse the dynamic behaviour of complex and nonlinear systems [19]. Dynamic models can improve the understanding of such systems and support decisions [20]. Dynamic systems consist of feedbacks and delays which are typical characteristics for the operation of cooling systems: complex interdependencies can be found between technical, hydro-meteorological parameters and legal threshold values (see Fig. 1). The dynamic behaviour in time and the adaptation to a changing environment is described via differential equations. In addition, with the respective modelling software VENSIM® DSS [21] climate scenarios can be incorporated simultaneously and the graphic representation helps to identify the most sensitive parameters of the system.

With SD two different options to visualise dynamic systems can be applied: causal-loop and stock-and-flow diagrams. Causal-loop diagrams are rather qualitative and describe the relationship between variables (Fig. 1). Such a diagram consists of nodes and arrows labelled either positive or negative. A positive link means that increasing variable A would increase variable B, whereas a negative link means that an increase of variable A would decrease variable B. The causal effect between several variables forming a loop can be either balancing or reinforcing. In Fig. 1, a causal-loop diagram is applied to a CCC system.

Here only the most important causalities are considered. Three feed-back loops can be identified: i) (1,2,3), ii) (2,3,4,5) and iii) (1,6,5,2,3). The first feed-back loop is reinforcing (even number of negative links), the second and third are balancing (uneven number of negative links) the system. Regarding the second loop, the balancing occurs temporarily (when the thresholds are exceeded) and causes an output reduction of the power plant unit. The third loop consists of the thermodynamical efficiency limits but has only a small effect on the whole system. The causal-loop diagram shows that SD can help to understand the mechanism of cooling systems. However, the causal-loop diagram needs to be complemented by a quantitative implementation whose basis is the stock-and-flow diagram. These diagrams can be considered as an interface between reality, model and computer simulation. The most important entities of these diagrams are shown in Fig. 2.

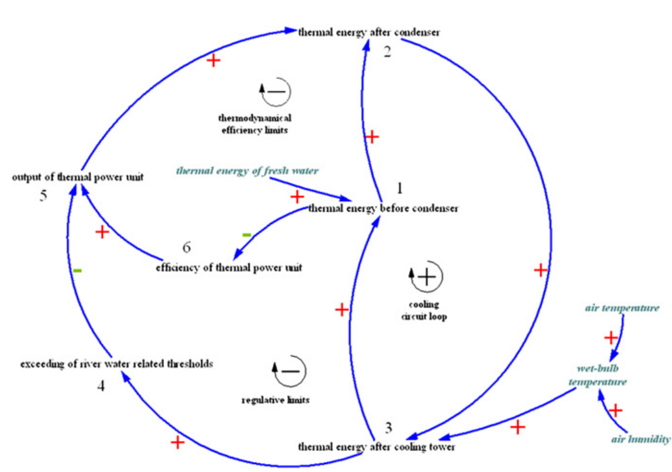


**Fig. 1.** Causal-loop diagram of a CCC system. The numbers mark feed-back loops and are explained in the text.

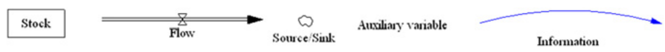


**Fig. 2.** Elements of a stock-and-flow diagram [22].

Stocks represent the status of a system and have at each time step a measurable value. Flows pointing at a stock increase this value (inflow), flows pointing away from a stock decrease its value. Clouds stand for sources and sinks outside of the model, auxiliary variables are used for calculation purposes. A simplified extract of the stock-and-flow cooling system diagrams can be seen in Fig. 3.

For the sake of simplicity, thermal energy is separated into cooling water temperature balance and cooling water mass balance. The extract shows in detail the cooling system before and after the condenser (see number 1 and 2 in Fig. 1). In the model, the stock and auxiliary variables are calculated for each time step. Eq. (1) indicates the calculation of waste heat that needs to be discharged [23].

$$P_W = P_{\text{th}} - P_l - P_{\text{el}} - P_a = \frac{P_{\text{el}}}{\eta_{\text{act}}} - P_l - P_{\text{el}} - P_a \tag{1}$$

where: $P_W$ = waste heat (W) $P_{\text{th}}$ = thermal power (W) $P_{\text{el}}$ = net electrical output (W) $P_a$ = auxiliary power (W) $P_l$ = losses into environment via chimney (W) $\eta_{\text{act}}$ = actual efficiency (−)

Some of the cooling water is lost through evaporation and drift when using a cooling tower. These losses cause an increase in salt concentration in the cooling water which must then be reduced by withdrawing a certain amount of fresh river water. The losses and necessary water replacements are calculated using an estimation from Moyers and Baldwin [24]:

$$Q_e = Q_c \times 0.0000965 \times (T_h - T_c + 32) \tag{2}$$

where: $Q_e$ = evaporation loss (kg s$^{-1}$) $T_h$ = hot water temperature (tower inlet) (°C) $Q_c$ = cooling water quantity (kg s$^{-1}$) $T_c$ = cold water temperature (tower outlet) (°C)

The spray and drift losses $Q_d$ are estimated with a factor from [24]:

$$Q_d = Q_c \times 0.0015 \tag{3}$$

The amount of water that is to be discarded and replaced to prevent scale formation is determined via the following formula [23]:

$$Q_b = \frac{Q_e}{\frac{c_c}{c_m} - 1} \tag{4}$$

where: $Q_b$ = blowdown (kg s$^{-1}$) $c_c$ = salt concentration in circulating water (mg l$^{-1}$) $c_m$ = salt concentration in makeup water (mg l$^{-1}$)

The amount of makeup water to replace the losses $Q_m$ is thus:

$$Q_m = Q_e + Q_d + Q_b \tag{5}$$

### 2.2. Cooling water temperature effect on power unit efficiency

The relation between cooling water temperature and efficiency is estimated by modelling ideal and actual thermodynamic cycles. The modelling was carried out with the heat balance engineering software THERMOFLEX from Thermoflow, Inc. Four different processes were simulated: an ideal rankine cycle with overheating, an actual rankine cycle with overheating, an actual rankine cycle with overheating and preheating, and the cycle of the German hard coal power plant unit Staudinger 5 [25]. For each cycle, the difference between cooling water temperature after condenser and the temperature of the condensing steam is assumed to be constant at 3 K according to expert judgement. The cycles are simulated with a cooling water inlet temperature of 274 K which is stepwise increased by 5 K whereas the other parameters are held constant. In consequence, by variation of the cooling water inlet temperature a linear relation can be derived. Comparing the four different cycles - including the application of the hard coal power plant unit Staudinger 5 - the same order of magnitude can be observed in all cases: by increasing the cooling water temperature by 1 K, the efficiency is reduced by 0.12%. Moreover, this main outcome is in the same range as the one found in the study of Durmayaz and Sogut [3] for a nuclear power plant site. Therefore, this approach is chosen and implemented via the following Eq. (6):

$$\eta_{\text{act}} = \frac{-(0.12 \times T_{\text{bc}}) + (\eta_{\text{des}} \times 100) + (0.12 \times T_{\text{c,des}})}{100} \tag{6}$$

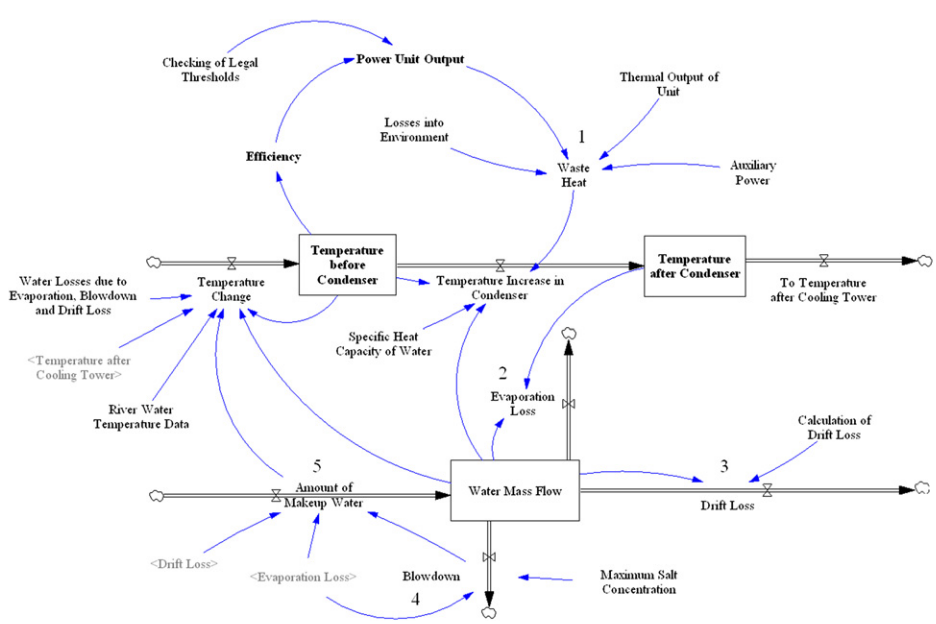


**Fig. 3.** Stock-and-flow diagram of a CCC system (simplified extract).

where: $\eta_{act}$ = actual efficiency (−) $\eta_{des}$ = design efficiency at design cold water temperature (−) $T_{bc}$ = temperature before condenser (°C) $T_{c,des}$ = design cold water temperature (°C)

#### 2.2.1. Cooling tower simulation

To calculate the cooling water temperature after the cooling tower (cold water temperature $T_c$) a one-dimensional approach according to Benton [26] was used. Every cooling tower is characterised by its design values that determine the performance of the cooling tower under certain conditions. These design values are used to calculate a performance factor, the Duty coefficient ($D_t$). This constant defines the overall performance of the cooling tower under all operating conditions [27]. The equation for $D_t$ set up by Chilton and modified by Benton is:

$$D_t = \frac{Q_c\left(z\Delta h^{-1}\right)^{1.174}}{\sqrt{\Delta t + 0.3124\Delta h}\,(0.0002491T_d - 0.002659T_w - 0.001974z + 1)} \tag{7}$$

where: $z$ = cooling range (°F) $\Delta h$ = enthalpy difference of air (Btu lb$^{-1}$) $T_d$ = dry bulb temperature (°F) $T_w$ = wet bulb temperature (°F) $\Delta t$ = difference between $T_d$ and air temperature leaving the packing (°F)

The coefficients for $T_d$, $T_w$ and $z$ as well as the exponent of the $z/\Delta h$ term were derived by Benton [28]. Since $D_t$ is not dimensionally consistent all input parameters are converted to the respective units used in Eq. (7) and later converted back to SI-units. The conversion values are given below [29]:

$$^\circ\text{C}\,^\circ\text{F: } \left(x - 32\right)\frac{5}{9} \quad 1\text{ US gallon} = 3.785\text{ l or kg} \quad 1\text{ Btu} = 1.055\text{ kJ}$$

$$1\text{ lb} = 0.4535\text{ kg}$$

The temperature of the water at the cooling tower outlet (cold water temperature $T_c$) is determined via an iterative approach, where its value is approximated using $D_t$ given by the design tower characteristics and $D_t$ given by the characteristics at each simulation point. The iteration breaks if the condition $(T_{c[i]} - T_{c[i-1]}) < 10^{-4}$ is met.

### 2.3. Input data

The exogenous model input data consists of administrative regulations (Section 2.4.1), hydro-meteorological parameters (Section 2.4.2) and unit specific technical parameters of power plant units (Section 2.4.3).

#### 2.3.1. Water related threshold values

River water related thresholds are set in the European directive 2006/44/EC [30]. On a national level, these thresholds are complemented by the German Working Group on water issues [31]. In addition, each power plant can have its own thresholds defined in the operation permits of the respective units. In directive 2006/44/EC river water sections are classified either as salmonid or as cyprinid water, whereas most power plant sites are located at cyprinid rivers. The following thresholds are defined for this category and are applied to most of the power plant units according to their cooling system:

- Max. water temperature at discharge:
  - OTC: 30 °C (33 °C in exceptional cases)
  - OTC with cooling tower: 33 °C
  - CCC: 35 °C
- Max. temperature increase of river: 3 K
- Max. river temperature after discharge: 28 °C

Considering the model database, the use of power plant unit specific values had the highest priority. If there was no data available, the more general data from [30] and from [31] was used.

#### 2.3.2. Hydro-meteorological parameters

For control runs and model validation, observed time series of hydro-meteorological input parameters were used. Measured air temperature data were taken from climate stations in the vicinity of the power plant sites and water temperature stations. Air temperature data were provided by the German Weather Service DWD as well as measured air pressure and relative humidity. These meteorological parameters were also used to derive wet bulb temperature data. This calculation was accomplished by Paeth and Aich [32]. Water temperature data were derived from various sources: amongst them were public authorities like hydrology institutes, shipping and environmental agencies, and also power plant operators. Runoff data was taken from gauging stations near the power plant sites and mostly provided by German Water and Shipping Authorities (WSA) and also from federal environmental agencies.

For the analysis of possible future impacts simulated water temperature data for the future period (2011–2070) were estimated by using daily means of air temperature of the regional climate model REMO (UBA run) [33]. To account for different climate scenarios we analysed the scenarios A1B (based on economic growth and a balanced fossil and renewable energy mix resulting in a medium $CO_2$ increase), A2 (slow and fragmented technological change, large $CO_2$ increase), and B1 (increasing share of clean and efficient technologies, small $CO_2$ increase) [17]. The different climate scenarios are based on several assumptions of economical, political, cultural and population development and therefore reflect different possible futures. We chose these three in order to have a representative set of scenarios covering the spectrum of possible developments. A correlation analysis of homogenised observed water temperature series and daily air temperature series showed significant correlation between the two parameters [2]. Since there is also a strong relationship between measured water temperatures and simulated air temperatures we chose this approach to estimate future water temperatures of the analysed sites. Water temperatures were simulated by Strauch [2] based on a logistic regression provided by Mohseni et al. [34] by using observed air temperatures as the explanatory variable:

$$\text{TW}_{\text{est}} = \mu + \frac{\alpha - \mu}{1 + e^{\gamma(\beta - T_{\text{Aac}})}} \tag{8}$$

where: $\text{TW}_{\text{est}}$ = estimated water temperature (°C) $\mu$ = estimated minimum stream temperature (°C) $\alpha$ = estimated maximum stream temperature (°C) $\gamma$ = maximum slope of function (−) $\beta$ = air temperature at inflection point (°C) $T_{\text{Aac}}$ = air temperature, altitude corrected (°C)

Parameter $\alpha$, $\beta$, $\gamma$ and $\mu$ were derived by fitting Eq. (8) to water temperature time series from every site with starting values estimated by [2]. The validation of simulated compared to observed water temperatures turned out satisfactory with a Nash–Sutcliffe coefficient of between 0.78 and 0.98 and a root mean square error of between 0.81 °C and 2.14 °C for the different sites [2]. Future wet bulb temperature data series were also calculated by Paeth and Aich [32] using simulated data from REMO (UBA). Runoff was not modelled for the future since runoff projections were not available for most rivers and the application of a hydrological model was beyond the scope of this work. In this case, average daily means of $a \geq 30$-years period were used, usually for the climate reference period 1961–1990. We chose this period, as it is the standard period of the World Meteorological Organization (WMO) and serves as a benchmark for comparisons of the current climate and a possible future climate [35]. Sensitivity analyses were performed to analyse effects of varying runoff on the system as various studies indicate a possible shift in precipitation patterns due to a changing climate [36–39]. The main tendency is less precipitation in the summer months and more during winter. Although the correlation between precipitation and runoff may not be linear we can assume less runoff during the summer months. Therefore, we simulated the model sensitivity towards runoff reductions of 10%, 20% and 50%.

### *2.3.3. Technical parameters of power plant units*

Unit specific technical parameters were collected from various sources [40–42], along with information from power plant operators. Technical parameters like efficiency and gross electric output were complemented by detailed data on cooling systems and cooling tower characteristics. An extract of the collected data is shown in Table 1.

Power units with combined cooling systems (CMB) are able to switch between different operation modes (e.g. between OTC and CCC). In our model CMB with CCC option are included and modelled as CCC power units. Consequently, the results can be considered as an upper estimation for these power units as CCCs have the lowest exceedance of thresholds (see Section 3.2.1). A few of the simulated power units apply cogeneration, thus parts of their waste heat is transmitted to the final consumer. However, data on the yearly distribution of district heat consumption was not available for these units. Therefore, it is assumed that there is only little district heat consumption during summer months and the waste heat is discharged into the environment.

### *2.3.4. Overview of simulated power units in Germany*

In summary, 26 power plant units with an overall capacity of 19 364 $MW_{gr}$ were simulated with the described cooling system models. Hence, only units that were operating at the end of 2010 are considered. Fig. 4 gives an overview of the modelled units, together with information on the respective energy carrier, cooling system, and river water basin.

Lignite power plants in Germany predominantly use open pit water for cooling purposes, thus our approach is not applicable in their case. Consequently, only hard coal and nuclear power units are modelled. Considering the cooling system, 17 simulated power units are using an OTC system. Nine power units have either a regular CCC system or a CMB system that can be operated as a CCC system. Most of the simulated power units are situated at the river Rhine (8 units). For some power units there are additional dischargers from other sources between the measuring point of water temperature and the unit. Therefore, this has to be taken into consideration when discussing the uncertainties in the approach. The sum of the modelled capacity is equal to about 20% of the total installed thermal power plant capacity in Germany in 2010 [43]

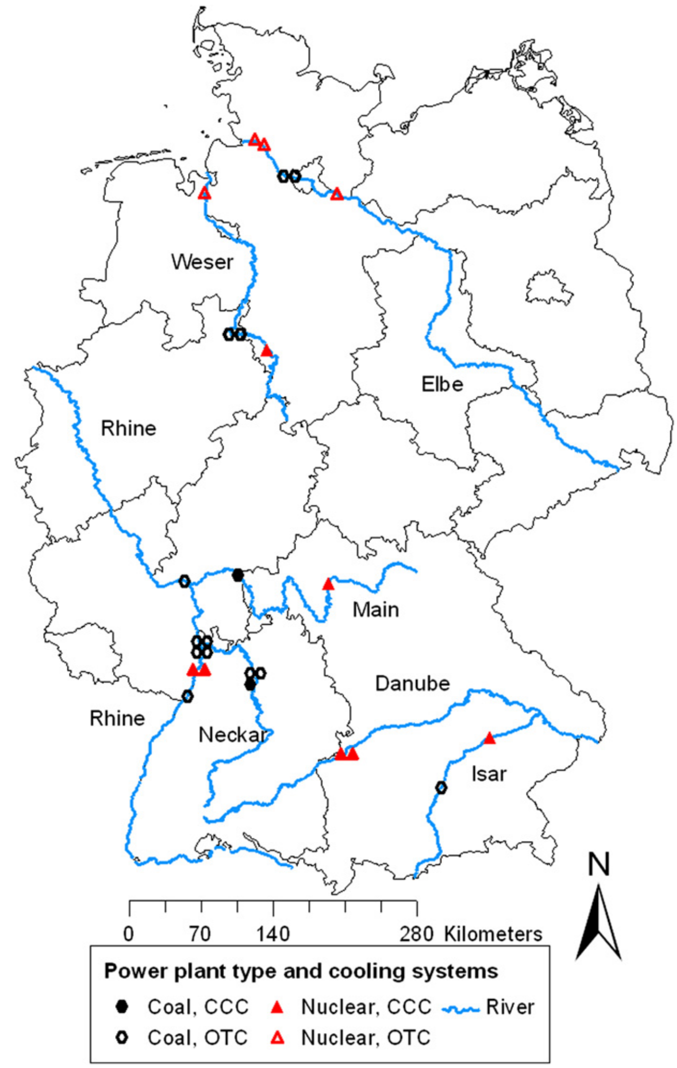


**Fig. 4.** Map of Germany with the respective power plant units, cooling systems, and rivers. The symbols represent power plant type, and cooling system. The number of units per site is indicated by the number (1–4) of symbols at a site (e.g. at the river Neckar, there are two coal OTC units and one coal CCC unit situated at the same site) [based on 2].

## 3. Model results

### *3.1. Model validation*

### *3.1.1. Cooling tower performance*

The simulation of the cooling tower is validated via the cold water temperature, which is the parameter to be determined by the approach presented in Section 2.3. The cooling tower model was validated comparing the results to values of a performance map of an existing cooling tower from the thermal power plant Neurath.

**Table 1**
Extract of collected technical parameters of power plant units, Source: EIFER power plant database.

| Unit | Type | Output ($MW_{gr}$) | Efficiency (%) | Cooling system | Cooling tower | Cooling water quantity (kg $s^{-1}$) | River |
|---|---|---|---|---|---|---|---|
| Brokdorf | Nuclear | 1480 | 36.0 | OTC | – | 60,000 | Elbe |
| Brunsbüttel | Nuclear | 806 | 35.2 | OTC | – | 33,333 | Elbe |
| Grafenrheinfeld | Nuclear | 1345 | 35.7 | CCC | NDT | 44,444 | Main |
| Grohnde | Nuclear | 1430 | 36.4 | CMB | NDT | 48,000 | Weser |
| Gundremmingen B | Nuclear | 1344 | 35.0 | CCC | NDT | 43,900 | Danube |

The performance maps are produced by the cooling tower manufacturer. The cold water temperature was determined via the model run on one hand and graphically from the maps on the other hand. The comparison shows, that for a constant air humidity of 75% the simulation results closely follow the values derived from the map (Fig. 5). The mean absolute percentage error (MAPE) between model and map values is 2%. The air humidity of 75% was chosen, because at the power plant site Neurath the annual average relative humidity is about 76%. The model performs equally well at different relative humidities.

### 3.1.2. Model validation

In this section the model is validated through the comparison to observed data on power plant output. This validation was carried out using publicly available data [44,45] on power production for the units Krümmel (KKK) and Grafenrheinfeld (KKG).

*3.1.2.1. Validation of the OTC model.* The OTC model [18] was validated for the nuclear power plant unit Krümmel in northern Germany. Therefore, reductions that occurred during summer 2006 [45] were compared to the results of the model simulation. In this case, the simulation did not take account of seasonal variations of the efficiency as in the observed data only exceptional performance reductions are described.

Only the threshold exceedances for the temperature of discharge were responsible for the simulated output reduction. As can be seen in Fig. 6, the simulated curve is close to the measured one. The MAPE for the whole year is 0.6% and 2.3% for the summer months of the validation period. Reasons for the deviation can be found in the different temporal resolution (daily time steps in the model vs. hourly values in [45]), model uncertainties, or special authorisation by the local authority allowing the operators to exceed threshold temperatures.

*3.1.2.2. Validation of the CCC model.* In the last years, only the nuclear power plant unit Philippsburg 1 had to reduce the power output when using a CCC system. During summer 2003, the output needed to be reduced by up to 20% according to the German Atomic Forum [46]. Nevertheless, it was not possible to simulate these output reductions by using observed data of 2003 with the CCC model. A possible reason might be the summer maximum of the observed daily mean temperature of the Rhine in 2003 of 27.4 °C. As the thermal energy discharged back into the river is very low, the exceeded threshold is probably the maximum mixing river temperature of 28 °C. It is possible that with the given temporal resolution of the model, daily maximum values of river temperature that exceed 28 °C were not considered and consequently did not cause a reduction of power output. Validation runs of the units Gundremmingen and Grafenrheinfeld in summer 2006 are consistent with observed data. The simulation and the observed values of the German Atomic Forum [45] showed no reductions.

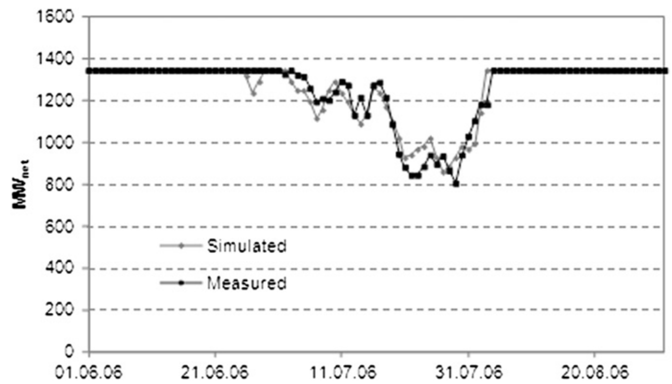


**Fig. 6.** Simulated vs. measured performance of nuclear power plant Krümmel (KKK) during the summer months 2006.

*3.1.2.3. Validation of seasonal efficiency variations.* As there were nearly no output reductions of CCC power units in the past, the validation of the efficiency reductions due to varying cooling water temperatures before condenser is more important. Therefore, unit-specific data of the generated electricity was used [44]. The nuclear power plant unit Grafenrheinfeld is considered for validation purposes. Fig. 7 shows simulated compared to observed values.

As can be seen in Fig. 7, the simulated production is slightly higher than the measured. There is a significant deviation of both data sets despite a good correlation within the summer months. After removing the two revisions (April 08/09) from the data set, MAPE is 1.8% and 1.4% for the whole period and the summer months, respectively. The Mann–Whitney Test (*U*-test) confirms the deviation for the whole period, whereas the alternative hypothesis is rejected if only the summer months are considered ($p = 0.40$). In general, the model simulates the observed values in a satisfying way even if there are significant differences during the winter months.

### 3.2. Scenario analysis

This section describes the results of the prospective simulations of the selected power plant units. The scenarios have in common

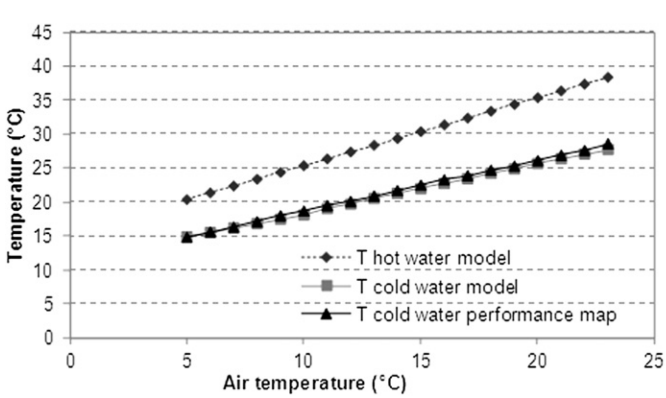


**Fig. 5.** Simulated vs. measured performance of Neurath cooling tower. Cold water temperatures were determined depending on hot water temperature.

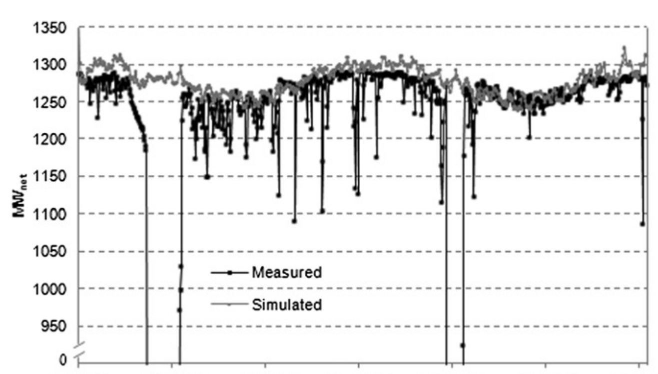


**Fig. 7.** Simulated vs. measured performance of nuclear power plant Grafenrheinfeld during the years 2008–2009. During April 08/09 performance reached zero due to revision.

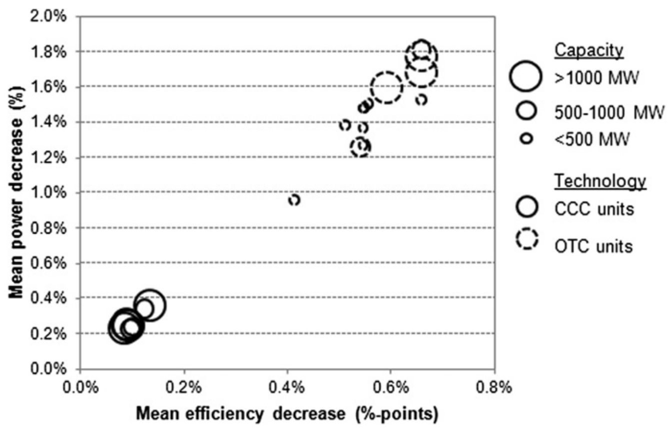


**Fig. 8.** Mean power decrease vs. mean efficiency decrease in 2011–2070 of OTC and CCC units in the A1B scenario compared to the control run.

that neither revision planning nor operational shut-downs are reflected. Therefore, the results need to be considered as an upper estimate. At first (Section 3.2.1), the simulated output and efficiency reductions are presented site-specifically for the simulation period 2011–2070. Afterwards the overall results of the 26 simulated power plant units are cumulated and statistically analysed according to their cooling technologies. In Section 3.2.2 the results of the adaptation scenarios are presented and discussed accordingly. All scenarios assume the hypothetical case of constant technologies, annual operation hours and regulatory constraints over the whole simulation period. In reality, all existing plants will arrive at the end of their lifetime before the end of the simulation period. There is also a high probability for a changing regulatory framework with regard to environmental protection. Therefore, the scenarios isolate the potential impact of a changing climate on today's infrastructure according to the IPCC story lines A1B, A2 and B1 [17].

#### 3.2.1. Climate scenarios A1B, A2, B1 and CR

In this section we will first compare the simulation results of the climate scenarios with the control run in order to show the total and site-specific effect of climatic change. We show this effect on total power production, its mid-term and long-term trend and the effects on efficiency. Following this will be a comparison of simulated power production to the nominal production on a decadal basis and also for the summer months.

Fig. 8 illustrates the average reduction in power output vs. the efficiency decrease for the 26 simulated power plant units in the A1B climate scenario compared to the control run. Whilst the power decrease contains both the influence of river water thresholds and reduced efficiency, the efficiency reductions are solely based on the physical effect of cooling water temperature. The figure shows that there are significant differences between the OTC and the CCC cooling technologies. Comparing the A1B scenario to A2 and B1 (see Fig. A1 and Fig. A2) showed no relevant differences over the whole model period. For the further analysis, we discuss OTC and CCC separately and put a focus on varying temporal periods like 30 year periods, decades, years, summer months and daily level. Efficiency losses are furthermore not analysed separately.

In Table 2 we present the results for the 30 year periods 2011–2040 and 2041–2070 for all scenarios compared to the control run (CR) 1961–1990. As none of the simulated time series was normally distributed, we used the Mann–Whitney Test to analyse whether the annual mean power output of the respective climate scenario is significantly different from the output of the CR. In a next step, the mean and the deviation of the mean to the CR were calculated as well as the standard error of the respective distribution. The Sen's Slope Estimator was used to derive trends of the maximum power output in MW per year. The significance of the trends in time series of power reductions were analysed with the Seasonal Mann-Kendall trend test.

The mean trend over all units of a cooling system shows that CCC systems are expected to have less output reductions than OTC systems (e.g. mean trend in A1B scenario, CCC: −0.10 MW/a, OTC: −0.33 MW/a). Regarding CCC units, there is a positive significant trend for each power unit in the B1 scenario 2011–2040 with up to 0.05 MW/a (nuclear power plant Grohnde). The highest negative trend of a CCC system is expected for Isar 1 in the A1B scenario 2041–2070 (−0.17 MW/a). A positive trend is also expected for 11 out of 15 OTC power units for the B1 scenario 2011 − 2040. For the A1B, the A2 scenario and the B1 2041–2070 period, there are only negative performance trends simulated for both cooling technologies in all scenarios. The highest cumulative negative trend is calculated for the OTC systems with −6.44 MW/a for the A1B scenario 2041–2070.

Further analyses for the three climate scenarios showed that about 50% of the output reductions occur in July and August for the three climate scenarios. The decrease in average annual power output in these months varies from 7% to 26% when compared to the nominal power of all OTC units depending on climate scenario. For the CCC units this reduction ranges between 1% and 2% of the total nominal power.

Fig. 9 shows the decadal results of the OTC power plant units both determined on an annual basis and for the months July and August. On an annual basis the power output is reduced up to

**Table 2**
Cumulated results of the simulated climate scenarios: OTC and CCC power units.

| Technology | Units | Total capacity ($MW_{gr}$) | Scenario | Period | Cumulative trend (MW/a) | Mean trend (MW/a) | Min. neg. trend (MW/a) | Max. neg. trend (MW/a) |
|---|---|---|---|---|---|---|---|---|
| OTC | 17 | 8738 | A1B | 2011–2040 | −4.77 | −0.28 | −0.02 | −0.73 |
| | | | | 2041–2070 | −6.44 | −0.38 | −0.04 | −0.89 |
| | | | A2 | 2011–2040 | −2.64 | −0.16 | −0.02 | −0.53 |
| | | | | 2041–2070 | −4.27 | −0.25 | −0.03 | −0.53 |
| | | | B1 | 2011–2040 | −0.06 | −0.00 | 0.09 | −0.44 |
| | | | | 2041–2070 | −4.24 | −0.25 | −0.01 | −0.56 |
| CCC | 9 | 10625 | A1B | 2011–2040 | −0.81 | −0.09 | −0.04 | −0.13 |
| | | | | 2041–2070 | −1.07 | −0.12 | −0.05 | −0.17 |
| | | | A2 | 2011–2040 | −0.64 | −0.07 | −0.03 | −0.10 |
| | | | | 2041–2070 | −1.03 | −0.11 | −0.05 | −0.15 |
| | | | B1 | 2011–2040 | 0.33 | 0.04 | 0.05 | 0.01 |
| | | | | 2041–2070 | −0.45 | −0.05 | −0.02 | −0.07 |

224 MW (A1B scenario) comparing the current decade 2011–2020 with the long-term future 2061–2070. In contrast to that, the reduction during July and August can be as high as 458 MW in the same scenario and decades. Moreover, the differences between the climate scenarios increase if only the summer months are considered. Compared to a nominal capacity of OTC units of 8738 MW, the simulation of the three climate scenarios results in an average decadal power output between 8422 and 8449 MW (96.4–96.7%) on annual basis and between 7717 and 7769 MW (88.3–88.9%) for the summer months for the current decade 2011–2020. Whilst the differences in the climate scenarios remain relatively low, the overall simulated performance losses in the summer months are significant both for operators and for regulators to ensure the security of supply.

Considering CCC units, it turns out that there are no output reductions due to the exceeding of river water related thresholds over all scenarios and periods. Therefore, Fig. 10 reflects exclusively performance reductions with regard to efficiency variations. Therefore, the amplitude of the output reductions is considerably lower compared to the OTC power units.

Analysing the summer months showed significantly larger reductions than on the annual average level. However the mean value of the summer months can still average out single periods of extreme heat. By simulating on a daily basis the power output of all considered OTC units can be reduced to 66.4% of the nominal capacity (5803 MW compared to 8738 MW in the A2 scenario) as can be seen in Fig. 11. For single OTC power plant units, the minimal daily power output can be as low as 32% (A2 scenario, 2041–2070). The CCC units do not show relevant differences and have minimal power outputs of roughly 97%.

### 3.2.2. Adaptation scenario

For the creation of an adaptation scenario the simulated OTC units are analysed assuming the cooling system is retrofitted to a CCC system. This section shows the results of this adaptation scenario for all OTC units.

All simulated power plant units show a positive trend in electricity production following upgrade from OTC to CCC (Fig. 12). The overall MAPE for the power units in the summer months July and August is 26.4%. Nonetheless the impacts strongly vary from site to site in a range from 0.3% to 93.7%. In general, retrofitting these power units has a significant positive impact on electricity production. The magnitude of power plant performance increase of such an adaptation measure is valuable information for power

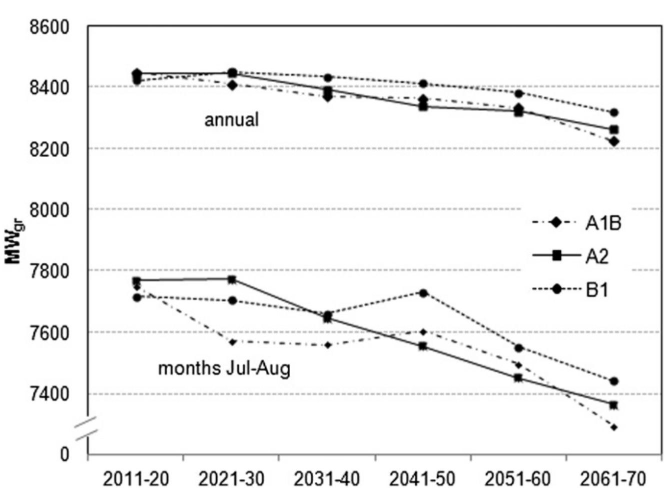


**Fig. 9.** Simulated mean decadal power output of the OTC power units over the whole year (annual) and for the months July and August.

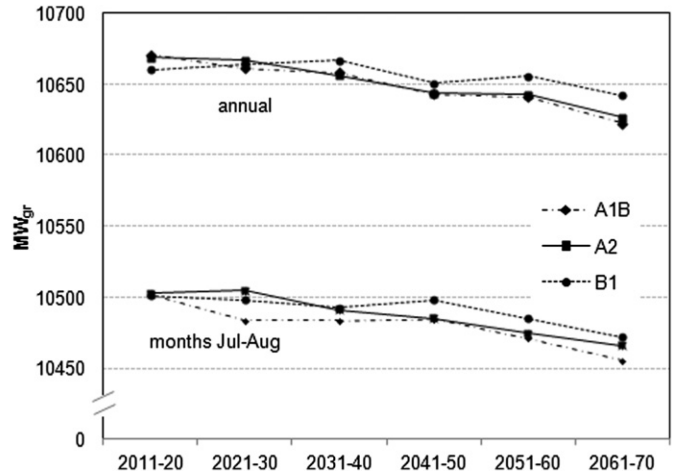


**Fig. 10.** Simulated mean decadal power output of the CCC power units over the whole year (annual) and for the months July and August.

plant operators. However, the potential benefits need to be opposed to the necessary investment.

### 3.3. Sensitivity analysis: reduced river runoff

The sensitivity analyses demonstrate the impact of the runoff regime on the studied power plant units. Therein, the power plants München Nord 2 (Fig. 13) and Unterweser (Fig. 14) showed significant reductions in performance and exhibit different seasonal patterns. München Nord 2 is situated on the river Isar, which has a different runoff regime compared to the river section of the Weser with the site of the unit Unterweser. River Isar shows higher runoff during summer, since it receives large amounts of melting water from the nearby Alps. For this unit, reductions in power output due to runoff occur during the winter months when most precipitation is stored as snow in the mountains. Significant performance reductions can be seen at $\geq$ 20% runoff reduction.

The power plant Unterweser clearly exhibits reductions in performance during the summer months. These reductions are

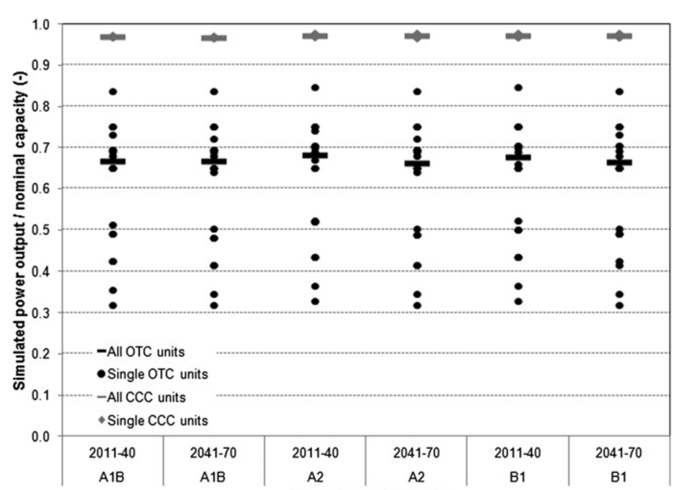


**Fig. 11.** Minimum cumulated daily power output of all power units (bars) and minimum daily power output of single units (circles) for all scenarios and cooling technologies.

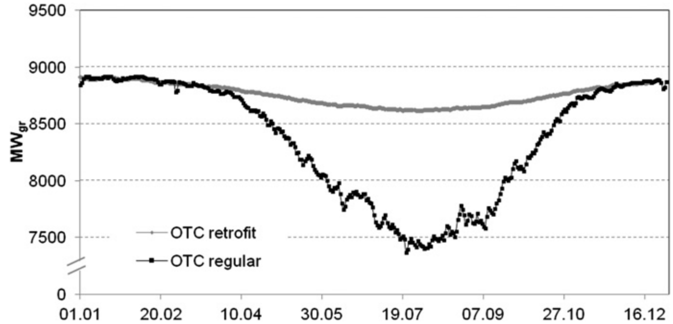


**Fig. 12.** Mean (maximum) daily performance values from 2011 to 2070 (scenario A1B) of all OTC power units with their regular cooling system and a CCC (retrofit) cooling system.

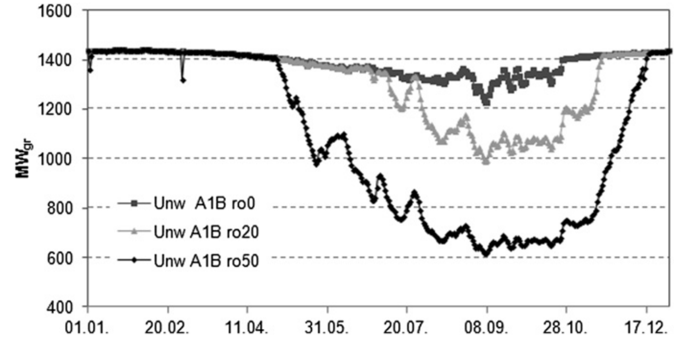


**Fig. 14.** Reduced runoff scenario for 0%, 20%, and 50% (ro0, ro20, ro50, resp.) reduction of the power plant Unterweser. Shown are mean daily values for the period 2011–2070 and the climate scenario A1B.

aggravated by reduced runoff, showing significant effects at ≥20% reduction. For the 20% and 50% scenario the MAPE of performance can be up to 7% and 38%, respectively, during the summer months.

## 4. Discussion

The methodology developed in this paper allows for the appropriate simulation of the impacts of changing cooling water temperatures on power plant availability. Thereby, the temporal resolution of one day and the detailed parameterisation of the cooling technology are essential to simulate the power plant performance over a long time horizon. The results have also demonstrated that the use of CCC systems is an appropriate adaptation measure.

The results show the vulnerability of the different power plant units with regard to the climate scenarios and the respective cooling systems. Significant negative trends were found for several units both for the periods 2011–2040 and 2041–2070. Cumulated, there is a trend of −5.58 MW/a for the A1B scenario for 2011–2040 and −7.51 MW/a for the 2041–2070 period respectively whereas the lowest negative or even positive trends occur for the B1 climate scenario. Although the annual trends are apparent and statistically significant, the absolute annual output reduction remains comparatively low. Nevertheless, significant reductions can be stated for the summer months. For July and August, we determined average power outputs at 88.3–88.9% of the nominal capacity of the simulated OTC power units in the three climate scenarios for the current 2011–2020 decade. On an annual basis this effect varies between 7% and 26% for the OTC units. This is close to the results presented by van Vliet et al. [8]. They calculated a reduction between 6.3% and 19% for European power plants. Förster and Lilliestam [12] determined a range of 0.8% and 11.8% for one German power unit depending on climate scenarios. In their study the reduction raised up to 16.8% if additionally runoff was reduced by 50%. Greis et al. [13] found a decrease in power production of 0.36% for a CCC unit during the summer months, whilst results of this study vary between 1% and 2%.

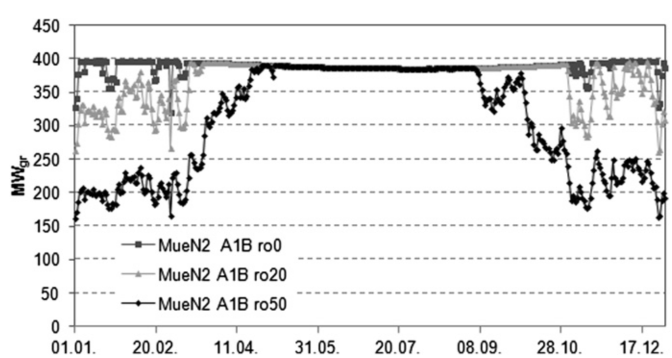


**Fig. 13.** Reduced runoff scenario for 0%, 20%, and 50% (ro0, ro20, ro50, resp.) reduction of the power plant München Nord 2. Shown are mean daily values for the period 2011–2070 and the climate scenario A1B.

On a daily basis, the observed effect is aggravated further: the power output of OTC units can be reduced down to 66.4% of the nominal capacity in the A2 scenario (equals to a performance loss of 2935 MW). For a single OTC power plant unit, the restricted daily power output can be as low as 32% (A2 scenario, 2041–2070). Moreover, the results showed that the CCC system is significantly less vulnerable to impacts of climate change as no reductions due to river water related thresholds are expected for this technology. Even on a daily level, the CCC units do not show relevant differences and have minimal power outputs of about 97%. This issue is also reflected in the results of the adaptation scenario. Compared to the results of the currently installed OTC cooling system, the overall MAPE for these retrofitted power units in July and August is 26.4%.

The approach of this paper can be further improved through more detailed modelling of the hydro-meteorological data. Here, only the regional climate model REMO is used. Consequently, an ensemble approach by using other climate models or runs could improve the robustness of the results. Furthermore, results of a detailed hydrological model of the river basins could be integrated. Nevertheless, the sensitivity analyses show that the effect of reduced runoff is not influencing the results at most sites.

## 5. Conclusions

It is shown that System Dynamics is an appropriate approach to analyse impacts of climate change on cooling systems and power plant efficiency. The limitations of this approach arise from the assumptions. For example the revision and operation of power units are excluded thus only the maximum theoretical output is simulated. Furthermore, the use of heat in cogeneration plants is not taken into account. Unlimited technical lifetime and constant regulatory thresholds are assumed in order to isolate the impact of climate change. These limitations need to be taken into account in the interpretation of the results. Nevertheless, this approach may be used by power plant operators and authorities for decision support.

For power plant operators the plant availability plays a major role in the planning of production and optimisation of plant revisions. Moreover, the site-specific results of the adaptation scenario can be used as basis for an economic evaluation of a possible retrofit of the cooling system. Furthermore, both regulators and plant operators need to evaluate impacts of a changing legal framework such as threshold values for heat discharges. Due to its high temporal resolution and the detailed representation of site specific plant properties the presented modelling approach can support these tasks.

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## Appendix A. List of abbreviations

| | |
|---|---|
| $\alpha$ | estimated maximum stream temperature (°C) |
| $\beta$ | air temperature at inflection point (°C) |
| $c_c$ | salt concentration in circulating water (mg $l^{-1}$) |
| $c_m$ | salt concentration in makeup water (mg $l^{-1}$) |
| CCC | closed-circuit cooling |
| CMB | combined cooling (more than one cooling technique possible) |
| CR | control run |
| $D_t$ | duty coefficient |
| $\gamma$ | maximum slope of water temperature function |
| $\eta_{act}$ | actual efficiency |
| $\eta_{des}$ | design efficiency |
| $h$ | enthalpy (kJ $kg^{-1}$) |
| $\mu$ | estimated minimum stream temperature (°C) |
| NDT | natural draught cooling tower |
| OTC | once-through cooling |
| $P_a$ | auxiliary power (W) |
| $P_{el}$ | net electricity output (W) |
| $P_l$ | losses to environment (W) |
| $P_{th}$ | thermal power (W) |
| $P_w$ | waste heat transfer (W) |
| $Q_b$ | dilution water (kg $s^{-1}$) |
| $Q_c$ | cooling water quantity (kg $s^{-1}$) |
| $Q_d$ | spray and drift losses (kg $s^{-1}$) |
| $Q_e$ | evaporation loss (kg $s^{-1}$) |
| $Q_m$ | makeup water (kg $s^{-1}$) |
| $T_{Aac}$ | air temperature, altitude corrected Natural draught cooling tower (°C) |
| $T_{bc}$ | temperature before condenser (°C) |
| $T_c$ | cold water temperature (°C) |
| $T_{c,des}$ | design cold water temperature (°C) |

*DBT*

| | |
|---|---|
| $T_d$ | dry bulb temperature(°C) |
| $T_h$ | hot water temperature (°C) |

*WBT*

| | |
|---|---|
| $T_w$ | wet bulb temperature (°C) |
| $TW_{est}$ | estimated water temperature (°C) |
| $z$ | cooling range (K) |

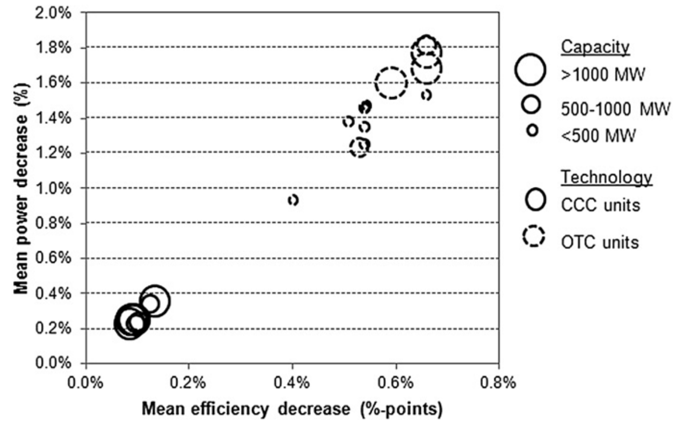


**Fig. A.1.** Mean power decrease vs. mean efficiency decrease in 2011–2070 of OTC and CCC units in the A2 scenario compared to the control run

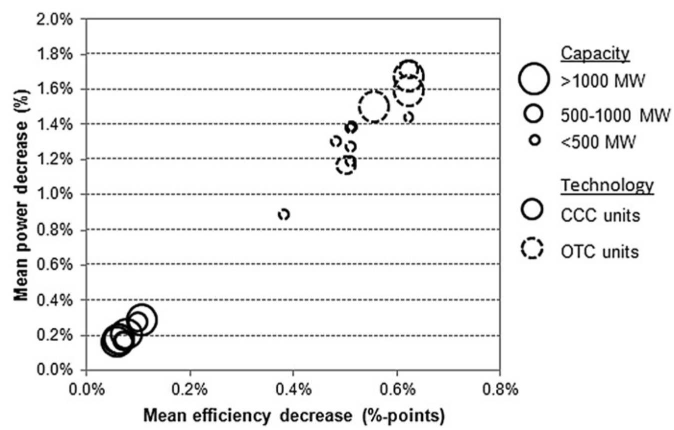


**Fig. A.2.** Mean power decrease vs. mean efficiency decrease in 2011–2070 of OTC and CCC units in the B1 scenario compared to the control run

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