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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

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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,

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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.

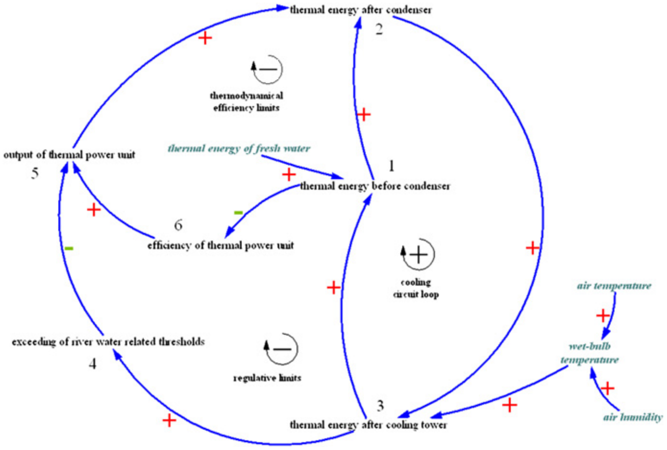

Fig. 1. Causal-loop diagram of a CCC system. The numbers mark feed-back loops and are explained in the text.