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Hydro-climatic conditions and thermoelectric electricity generation – Part I: Development of models

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ABSTRACT

In recent years there have been several heat waves affecting the use of thermoelectric power plants, e.g. in Europe and the U.S. In this paper the linkage between hydro-climatic conditions and possible electricity generation restrictions is described. The coupling of hydrological models and a power plant model is presented. In this approach each power plant is considered separately with its technical specifications. Also environmental regulations, e.g. permissible rise in the cooling water temperature, are considered for the respective power plant. The hydrological models developed to simulate river runoff and water temperature are also site specific.

The approach presented is applied to Krümmel nuclear power plant in Germany. Analysed are the uncertainties with regard to electricity generation restrictions on account of climatic developments and corresponding higher water temperatures and low flows. Overall, increased water temperatures and declining river runoff lead to more frequent and more severe generation restrictions. It is concluded that the site-specific approach is necessary to reliably simulate power plants water demand, river runoff and water temperature. Using a simulation time step of one day, electricity generation restrictions are significantly higher than for simulations at monthly time step.

1. Introduction

Due to sustained population growth and increasing industrial activity, the need for water is continuously rising throughout the world. The ever greater (as well as over-) exploitation of water resources is thus causing a growing problem for making water available in sufficient quantities and quality. While greenhouse-gas emissions due to the combustion of fuels are a global problem, the so called water energy nexus is a regional problem because of regional variations in water demand and water availability (e.g. Martin [1]).

It is generally expected, moreover, that this problem will become increasingly serious in future on account of climate change. It can be assumed, for example, that in numerous regions of the world climate change will decrease water availability and/or have a negative effect on water quality, e.g. water temperature. Among the regions that might be affected are those in which there is still a sufficient supply of water at present so that large quantities can be used as cooling medium. For these reasons growing attention has been given in recent years in particular to the link between climate, hydrology and thermoelectric electricity generation.

Förster and Lilliestam [2] have made a comparative static analysis of the effects of climate change on Krümmel nuclear power plant in Germany. They have simulated costs arising from climate change of up to €2.6bn over a period of 32 years. On the basis of statistical data pertaining to air temperature and electricity generation restrictions at nuclear power plants, Linnerud et al. [3] have developed a regression function. They have found that, with a 1 °C increase in air temperature, the thermal efficiency of nuclear power plants decreases by approximately 0.5%. This decrease in efficiency, however, can be largely compensated for by an increased use of combustible fuels. Above the existing threshold values with regard to the temperatures of the water withdrawn from and discharged to the water system, as well as the mixed water temperature, an increase in temperature by 1 °C of the water used as cooling medium leads to a electricity generation decrease of approximately 2%. The authors point out, however, that this value can vary greatly, depending on the location of the power plant, the cooling system, etc. Koch et al. [4] have analysed the effects of global change on thermoelectric power plants in Berlin (Germany). Besides climate change, their analyses take into account future changes in electricity needs, as well as

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developments in the field of power plant technology. They show that, in spite of rising electricity needs and falling water availability, electricity generation restrictions can be kept within reasonable limits by the use of new power plant technologies and/or adaptations to cooling systems. The focus of studies undertaken by Rübbelke and Vögele [5,6] is on the effects of climate change on the use of nuclear power plants in Europe from the perspective of ensuring the supply of electricity, also taking into consideration induced changes in European electricity trading mechanisms.

The effects of climate change on power plants and other water users have been studied by different authors. An analysis undertaken by Hurd and Harrod [7] for the whole of the United States point to negligibly small to significant electricity generation losses on account of climate change for power plants in different regions. In the case of Boston Kirshen et al. [8] postulate a growing need for cooling water in fossil-fired power plants and increasing heat stress on bodies of water due to the discharge of cooling water into them; here, water shortage and/or restrictions in the discharge of water would lead to economic losses. Increased water temperature, both at the point of withdrawal from the water system and at the point of discharge must also be taken into consideration for all power stations which use water for cooling purposes. Feeley et al. [9] have studied the effects of scenarios with differing assumptions about the cooling systems used and energy needs in the USA. Depending on the assumptions used, cooling water needs might fall by around 30% or remain constant until the year 2030.

Van Vliet et al. [10] have analysed the impacts of climate change on thermoelectric power plants in the United States and nuclear power plants in Europe using a coupled hydrological water temperature model with bias-corrected global climate model outputs. Germany was excluded because of the German phasing-out decision on nuclear power plants. Van Vliet et al. [10] use a grid-based modelling system with 0.5 by 0.5° resolution. This is especially problematic if more than one power plant is located in one grid cell. A further problem arises when a large tributary river joins a main river since this may cause considerable changes in runoff or water temperature. The advantage of their modelling approach is the fact that large areas can be simulated to give rough estimates.

Most recently Hoffmann et al. [11] have presented a method for estimating climate effects on performance losses of thermal power plants and applied this method to selected power plants in Germany. However, they point out that no detailed hydrological modelling was implemented in their analysis.

Despite the increasing attention given to this topic in recent years Mideksa and Kallbekken ([12], p. 3584) state that the "Sensitivity of thermal power supply to changes in air and water temperature…" is one important issue which is not very well covered in the literature on climate change impacts. According to Schaeffer et al. [13] the interface between energy system modelling and climate change scenarios needs to be improved.

The paper presented here attempts to fill some gaps. As already pointed out, e.g. by Gleick [14] or Carrillo and Frei [15], there is a close relationship between water and electricity generation.

In the following the linkage is described between hydro-climatic conditions and possible electricity generation restrictions at thermoelectric power plants. The coupling of hydrological models (i.e. river runoff as well as water temperature models) and a power plant model presented in the first part of the article serves to illustrate possible influences of climate change on the generation of electric power. In the approach presented each power plant is considered separately with its technical specifications, i.e. installed capacity, electrical efficiency etc. Environmental regulations, e.g. the permissible rise in the cooling water temperature, are also considered separately for each power plant. The hydrological models used to simulate river runoff and water temperature are also site specific. This means that each power plant is considered with all of its technological and environmental specifications.

In the first step the coupled models are applied to Krümmel nuclear power plant in Germany, chosen because of the very detailed data available. Analysed are the uncertainties with regard to electricity generation restrictions on account of climatic developments and corresponding higher water temperatures. In a second paper the analyses are extended to include 17 nuclear power plants in Germany.

Section 2 gives a description of various cooling systems of thermoelectric power plants which use water as cooling medium. The model used for calculating the water demand and electricity generation restrictions is described in Section 3. In Section 4 the hydrological models (water temperature model, precipitation runoff model) and the applied regional climate model are described and in Section 5 the input data and the results of the model coupling are presented. The article ends with a discussion of the results in Section 6.

2. Power plant cooling systems using water as cooling medium

The cooling systems of power plants can be broadly divided into wet and dry systems. While in the former the waste heat is conducted away by water, in the latter it is directly discharged into the atmosphere. The following observations apply to wet cooling systems.

Fresh water is mainly needed by power plants for cooling purposes; the amount of water needed for other purposes can be regarded as very small. The amount of water required for cooling depends to a considerable extent on the amount of waste heat produced and the cooling procedure used. The amount of heat to be conducted away is largely determined by plant-specific factors, e.g. degree of fuel utilisation and electricity generation capacity of the plant. At the power plants currently in operation in Germany only an average of around 41% of energy input is transformed into electricity while the remainder is given off in the form of heat. That part of the heat generated that is not used for local or district heating is removed by cooling systems, in which water is predominantly used as cooling medium. One distinguishes between three main types of wet cooling systems:

i) once-through cooling, in which the water withdrawn from a body of water is used for cooling in the condenser and subsequently returned in its entirety into the body of water; the amount of water required for this type of cooling is considerable;
ii) once-through cooling with cooling tower, in which the water is cooled in a tower before it is returned, so that the potential stress on the body of water is reduced; and
iii) closed-circuit cooling, in which the water heated in the condenser is cooled in a tower and led back to the condenser; the amount of water required for this type of cooling is small.

In all these kinds of cooling procedures the body of water undergoes stress due to either increased water temperatures (once-through cooling) or large evaporation losses (from cooling towers). An analysis of water use in thermoelectric power plants must take into account (besides power plant-specific factors) environmental conditions and the legal regulations with regard to the maximum quantity of water withdrawn from a body of water at a particular location, the temperature to which the cooling water rises and the temperature of the returned or mixed water. Since river runoff, water depth and other factors along the rivers vary, the maximum values for individual power plants differ accordingly. If the

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