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Optimization of regional water - power systems under cooling constraints and climate change

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ABSTRACT

Thermo-electric generation represents 70% of Europe's electricity production and 43% of water withdrawals, and is therefore a key element of the water-energy nexus. In 2003, 2006 and 2009, several thermal power plants had to be switched off in Europe because of heat waves, showing the need to assess the impact of climate change on cooling constraints of thermal power plants. An integrated water-power model of the Iberian Peninsula was developed in this study. It includes a physical hydrologic representation, spatially and temporally resolved water demands, management of water infrastructure and a simple power system model. The system was evaluated under present and future climatic conditions using different climate change scenarios. The cost of cooling constraints is found to increase by 220–640 million €/year, for the period 2046–2065 depending on the climate change scenario. Average available capacity of freshwater-cooled thermal power plants is reduced by 16–30% while production is reduced by 5–12% in summer. The power production is shifted from plants equipped with once-through cooling systems (−5 to −14%) towards plants using closed-circuit cooling systems (+41 to +95%).

1. Introduction

Water and energy systems are strongly interdependent: while water is used for energy production through hydropower, extracting and refining combustibles and cooling of thermal power plants, energy is used to extract, treat and supply water as well as collect and treat wastewater [1]. Thermo-electric generation represents 70% of Europe's electricity production [2] and 43% of water withdrawals [3]. Its dependence on freshwater resources has to be considered when defining energy strategies or building new thermal power plants that have a lifetime of around 30–60 years [4]. In order to protect ecosystems, the amount of heat that can be discharged into rivers and lakes by thermal power plants is regulated by law. During recent droughts in Europe, high water temperature combined with water scarcity, forced thermal power plants to reduce their production [5]. For similar reasons, the US energy sector has started to shift production towards power plants requiring less water withdrawals [6]. As climate change will reduce water availability and increase temperature [7], it is necessary to assess its impact on the cooling constraints of thermal power plants and the performance of the system.

Chandramowli et al. [8] presented a literature review on climate change impacts on the power system. The review covers demand-side variation linked to temperature-sensitive demands, risks of extreme climatic events on the physical infrastructure, impacts of changing climatic conditions on renewable energy sources and impacts of reduced freshwater availability on hydropower production and cooling requirements of thermal power plants. Koch and Vögele [9] proposed a method to model shortages in thermal production linked to water availability and temperature constraints. The method, combined with a hydrological and water-temperature model, was applied to assess the impact of climate change on nuclear power plants in several studies. For Germany, Koch and Vögele [10] and Koch et al. [11] estimated available capacity reduction for nuclear power plants. At the global scale, Vliet et al. [4] found that more than 80% of all thermal power plants would face available capacity reductions in the period 2040–2069. A more optimistic study by Wang et al. [12] found that the expected improvement in the efficiency of generation technologies could lead to some water savings; however, this study did neither consider climate change nor the spatio-temporal distribution of water demand. In these studies impacts are evaluated in terms of

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the available capacity and not in terms of the actual production, as the power system is not simulated jointly with the hydrological system. Nuclear power plants are typically operated at full capacity, and the available capacity is therefore a good indicator for the production. In contrast, coal and gas power plants have a more flexible production schedule and use on average only a fraction of their capacity. While available capacity remains a useful indicator, the whole power system needs to be considered, taking into account interactions between the different power producers and power demand, in order to assess the impact of climate change on the actual thermal production. Khan et al. [13] presents a literature review on integrated water-energy models. In general, these models have a more detailed representation of the power system, considering the various steps of power production and more diverse power producers. However, as pointed out in the review, among the 16 reviewed integrated water-energy models, only two take into account cooling water constraints, and only one (Dubreuil et al. [14]) has hydrological constraints. But these two last models are not spatially and temporally disaggregated and may therefore oversee the spatial or temporal scarcity of cooling water identified by the previously mentioned studies. Khan et al. [15] used an integrated water-energy model for Spain to illustrate the importance of the linkages between the energy and water systems when planning infrastructures. However, the impact of river temperature on thermal power-plants was limited to efficiency reduction, disregarding shortages related to environmental regulations. Alternatively, recent studies focus on the trade-offs between environmental constraints and energy production: Gjorgiev et al. [16] finds that relaxing the environmental constraints in extreme events prevents significant capacity curtailments using a basin scale model for a synthetic case study. Logan et al. [17] presents a methodology combining a hydrodynamic-temperature model and a risk assessment for fish species to refine the environmental constraints for individual power plants.

The objective of the present study is to develop an integrated water-power management model including diverse power producers and cooling constraints of thermal power plants, in which water allocation is a decision variable and is connected to a spatially and temporally disaggregated hydrological model. The case study is the Iberian Peninsula, where the thermal power sector represents 47% of total electricity production (OMIE [18]), 17% of freshwater withdrawals (MMA [19]) and where climate change is expected to have severe impacts on water availability (IPCC [7]). The model is used to assess the impact of climate change on the cooling constraints of the water-power system of the Iberian Peninsula.

2. Material and methods

The study constructed a regional joint water-power management optimization model. Water availability is estimated using a rainfall-runoff model developed by Pereira-Cardenal et al. [20]. River network and hydraulic infrastructure are represented in a physical flow-path network approach (Cheng et al. [21]). Available water can be allocated to the water users (agriculture, domestic, electricity production), used for thermo-electric and hydropower generation and be stored/released from hydropower reservoirs. The links between the water and power system are the hydropower and thermal power plants using freshwater resources. They produce electricity in a simple representation of the power system adapted from Pereira-Cardenal et al. [22]. The power system is represented as one single power pool covering the entire Iberian Peninsula where the electricity generated by different producers has to meet the peninsular power demand per time-step. Other power producers are the “special regime”, representing producers having a special agreement (among others renewable energy producers), and the seawater-cooled thermal power plants. Water allocation and power production are represented as decision variables with associated marginal costs, subject to different physical and economic constraints implemented through linear programming [23]. The system is evaluated for the reference period 1971–1990 and under four climate change scenarios for the period 2046–2065. In both periods, the system is considered with and without cooling constraints to assess their impact on the water and power system.

Joint water and power management is formulated as a hydro-economic optimization problem. Hydro-economic models enable integration of economic principles in decision making, as they couple economic concepts to a hydrological representation. Each decision is characterized by its marginal benefit or cost and the optimal management becomes a single-objective problem, solved by maximizing (/minimizing) the economic benefit (/cost). Hydro-economic modelling is frequently used to assess the economic impact of alternative scenarios or strategies [20,24] and is therefore highly suitable for the present study.

2.1. Water system representation

The modelled area covers the seven major river basins of the Iberian Peninsula: Tajo, Ebro, Duero, Guadiana, Guadalquivir, Mino-Sil and Jucar. They extend over 400800 km^2 in Spain and Portugal, representing around 70% of the Peninsula. Using a digital elevation model (European Environmental Agency [25]) the 7 basins were divided into a total of 123 watersheds corresponding to the 116 major hydropower plants (Fig. 1). The hydropower plants characteristics are obtained from Pereira-Cardenal et al. [20]. Their cumulated storage capacity is $46\,000\,10^6\,m^3$ out of the total $56\,000\,10^6\,m^3$ installed capacity regulating around 40% of the flow [26].

The river network and the hydraulic infrastructure are represented in a physical flow-path network approach [21] where water can be allocated from sources (reservoirs, run-off, and groundwater) to sinks (reservoirs, thermal power plants, agriculture, domestic and industrial demand) (Fig. 1). Precipitation, surface runoff and groundwater recharge for the period 1971–1990 are obtained from the rainfall-runoff model developed in Ref. [20]. Generally the data is processed at the daily and weekly resolution; this issue is discussed later in the results. For each watershed groundwater is represented as a lumped linear reservoir subject to the following equations:

$$GWout_t = GWout_{t-1} \cdot e^{-dt/k_g} + GWin_t \cdot \left(1 - e^{-dt/k_g}\right)$$

$$GW_{t+1} = GW_t + GWin_t - GWout_t - GWall_t$$

where t is the present time step, dt (days) the length of the time step, k_g ($days^{-1}$) is the linear reservoir constant, $GWout$ (m^3) represents the groundwater outflow to the river, $GWin$ (m^3) the groundwater recharge, GW (m^3) the groundwater volume in the aquifer and $GWall$ (m^3) the allocated groundwater to water users. An air-water temperature model from Mohseni et al. [27] is implemented in order to convert the weekly-daily air temperature data from Ref. [20] into weekly-daily river temperatures. The relation is formulated as follows:

$$T_r = c_4 + \frac{c_1 - c_4}{1 + e^{c_3(c_2 - T_a)}}$$

where T_r and T_a represent respectively the river and air temperature in °C, c_1, c_2, c_3 and c_4 are the calibration parameters. The calibration was performed for one basin only and can be found in