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Electrical power generation under policy constrained water-energy nexus

Blaže Gjorgiev, Giovanni Sansavini*

Reliability and Risk Engineering Laboratory, Institute of Energy Technology, Department of Mechanical and Process Engineering, ETH Zurich, Leonhardstrasse 21, 8092 Zurich, Switzerland

HIGHLIGHTS

- Electric power conversion is analyzed in a policy-constrained water-energy nexus.
- Severe drought conditions for a river basin hosting thermal and hydro generators are simulated.
- Once-through cooling system is extremely sensitive to abnormal river water conditions.
- Small flexibility in water policy grants large amount of energy to the power system during droughts.
- Coordination of water releases and policy relaxation secures power output during extreme droughts.

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ABSTRACT

Water-energy nexus refers to the interdependence between water resources and energy conversion, and it encompasses the multiple phases of electric power generation and water processing and distribution. Current policies for the utilization of freshwater resources in electric power generation regulate the thermal discharges and their effect on the aquatic life. Water withdrawals and consumption polices are mainly prescribed at the regional level instead. This paper focuses on the effects of water policy constraints on electric power generation in changing climate conditions. A river basin is simulated, which hosts two hydraulically linked power generating stations, namely an upstream hydropower plant with reservoir and a downstream thermal power plant. Two alternative cooling designs are tested for the thermal power plant, i.e. once-through and wet tower cooling. Severe drought conditions leading to small river flows and high water temperatures are analyzed, and the limitations to the energy conversion at the thermal plant stemming from the water policies are quantified. The results show that some small flexibility in the water policy constraints during extreme droughts can secure a significant amount of energy to the power system, which would have been curtailed otherwise. Remarkably, the relaxation of 1.5 °C in the water policy constraints prevents the curtailment of 42% of the generation capacity of a 1000 MW_e thermal plant during the analyzed 24 h drought scenario. In general, the type and the required amount of constraint relaxation depend on the environmental conditions and are to be judged case-by-case. Furthermore, the smart scheduling of water resources grants a 7% increase of the energy converted during droughts in the hydraulically linked hydro and thermal power plants. Finally, the analysis shows that once-through cooling systems are extremely sensitive to changes in water flow and temperature opening space for less sensitive technologies, i.e. wet cooling towers.

1. Introduction

The water utilization is directly dependent on the industrial development and size of population. Massive quantities of water are been deployed for energy conversion with approximately 90% of global electricity generation depending on water, mainly for cooling of thermal power plants and hydropower conversion [1]. According to United States Geological Survey (USGS), the US thermal power plants accounted for 38% of the freshwater withdrawals in 2010 [2] and freshwater consumption is estimated to be 2.5% of the total withdrawal in 1995 [3,4]. Similarly, about 43% of the water withdrawals in Europe are used for thermal power plant cooling [5]. This makes the thermal power plants in US and Europe the largest water users compared to others sectors. Thermal power plants water withdrawal accounts for around half of the total amount of industrial freshwater use in China [6]. In Saudi Arabia, the energy production sector is the second larger user of water, mainly used for cooling of thermal power plants and in extraction, transportation and processing of fuels [7]. South Africa relies on thermal power plants for above 90% of the

* Corresponding author.
E-mail address: sansavig@ethz.ch (G. Sansavini).

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total electricity generation [8]. It is evident that reliable power generation from thermal power plants is highly dependent on the reliable access to freshwater, making thermal generation vulnerable to water scarcity. On the other side, the widespread demand of water requires electricity for pumping, processing and disposal, making water supply systems depended on reliable electrical energy conversion. This interdependence between water and energy is referred to as the water-energy nexus [9,10].

The issues stemming from the water-energy nexus have recently generated a broad academic interest in the energy conversion area. The research challenges of the water-energy nexus with focus on data, information and knowledge gaps are discussed in [11], which highlights the lack of systemic tools for addressing the trade-offs involved in the water-energy nexus. The impact of water scarcity and temperature change on the electrical energy generation in Europe and US is discussed in [12]. Along those lines, climate change may significantly reduce the generation capability of 46% of the power stations in the western US [13]. A model for the smart utilization of water resources in hydrologically-coupled thermal and hydro power plants is presented in [14]. The needs for strategic and coordinated implementation of hydro power installations are discussed in [15] including a trade-off analyses between the increasing energy demand and the sustainability of water exploitation.

In 2013, thermal power plants generated 17,157 million MWh or 77.4% of the electrical generation worldwide [16]; majority of the using wet-type cooling. The USGS defines two modes of water usage, i.e. withdrawal and consumptive use [17]. The withdrawal is defined as the total amount of water displaced from the water source to be exploited, while consumption quantifies the share of the withdrawn water that is evaporated, transpired, used for irrigation, or supplied to humans or livestock. The amount of water which is returned to any water source does not contribute to consumption. The type of cooling technology and the location largely affect water withdrawal and consumption. Cooling technologies for thermal power plant fall into two groups, i.e. wet and dry cooling. Wet cooling is provided by once-trough cooling systems, wet cooling towers and cooling ponds. Once-trough cooling systems withdraw water from a source (e.g. river, lake, ocean), circulate it through the plant condenser, and return it back to the source. Most of the water for cooling is returned back to the source. Wet cooling towers and ponds are open systems that recirculate water through the condenser and dissipate the heat into the atmosphere through evaporation. Cooling towers require smaller space for the spraying nozzles and are more efficient than cooling ponds. Conversely, dry cooling is a closed recirculation system which uses forced air circulation through a tower to dissipate heat and no water. Dry cooling towers are less effective and much more expensive compared to standard wet cooling towers. However, retrofitting the existing thermoelectric generation to achieve zero freshwater withdrawals could greatly reduce the vulnerability of thermometric power generation to drought [18].

Recent climatic changes increase the likelihood of heat waves and droughts, which significantly impact the temperature and availability of river water [19,20]. Such conditions have already affected the worldwide electric power generation, and caused a significant number of events in which thermal-power-generating units have been curtailed or shutdown. Such events occurred in the US in 2007, 2008 and 2012, triggering power curtailments from large number of thermal power plants [12,21]; in France in 2003, 2006 and 2009, where a large number of nuclear power plants was shut down and the additional costs for electricity import topped 300 M€ [22,23]; in Germany in 2003 and 2006 [23,24]; in Spain in 2006 [22], and in Switzerland in 2015, where three nuclear power plants experienced power curtailments [25].

Thermal power plant curtailments occur mainly due to the water policy constraints on thermal pollution to the surrounding environment, i.e. the thermal discharge in rivers is highly regulated to protect wildlife habitat from large and sudden changes in water temperature. Regulations on thermal pollution are in use in Europe, defined by the European Fish Directive [26] and in the US defined, by the Clean Water Act [27]. The European Fish Directive defines two types of rivers with different constraint parameters. In general, the constraints limit the maximum allowed change of river water temperature (calculated as the difference of the river water temperature measured before and after the point of thermal discharge), and the maximum river water temperature measured downstream the point of thermal discharge. Despite unified water pollution policies, there are no coherent regulations on water withdrawal and consumption [28,29]. Indeed, policies for water withdrawal and consumption have a local scope subjected to the authorities responsible for the management of specific rivers or water basins. These policies mainly limit the daily or monthly amount of water withdrawal and consumption from the rivers and usually prescribe no specific constraint on the consumption of the energy generating capacities [30–32].

The implementation of standards for setting the limits on water withdrawal/consumption, and the quantitative relationships between hydrologic alteration and ecological response is discussed in [29]. Based on publicly available data, a mapping of water consumption for energy production in 11,653 watersheds across the 21-member economies of Asia-Pacific Economic Cooperation (APEC) is performed in [33]. Estimates of the operational water withdrawals and consumption amounts for different electrical generation technologies in US are given in [34,35]. The study in [34] shows that even if once-trough cooling withdraws 10–100 times more water per unit electrical energy generation as compared to wet tower cooling, yet it consumes half the amount of water. In [36], the water consumption from coal-fired power plants in China is analyzed and the results show 3–10 times higher consumptive water intensity of the wet-recirculation cooling (wet-type cooling tower) compared to other technologies. The study in [35] provides a critical review of recent publication that deal with future water requirements, and defines the factors that will moderate these requirements for the electrical energy generation sector. In [37], serious vulnerability issues experienced by electric power generation by thermal plants in several areas in North China are shown. The study concludes that to alleviate the vulnerability, it is necessary to manage water resources comprehensively, among which minimizing the water demand for all water uses in the vulnerable areas. The international water-energy nexus of China is studied in [38]. The results implicate that the water usage per unit of energy is much larger than in other countries. The use of electricity by the water sector for supplying, processing and disposal in various developed and developing Countries is investigated in [39]. The results show that water supply and disposal services are energy intensive worldwide mainly due to old infrastructures and technologies. In [40] an assessment of the impact of extreme water temperature and water availability on power system resilience is performed. The water-energy nexus of Illinois is investigated in [41] with focus on the fuel type and cooling technology replacement with alternative options.

Aiming at assessing the impact of the water-energy nexus and mitigating the effect of water policies in the face of changing climate conditions, the objective of this paper is (1) to estimate the benefits to the energy conversion capability of a large thermal power plant provided by several cooling technologies, and (2) to quantify the effects of water policy constraints on the power output in drought conditions. As a topical application for this analysis, a river basin is simulated which hydraulically links the upstream reservoir for hydro power production and the downstream thermal power plant. This is a common configuration in real world applications. Two different cooling technologies are assessed, i.e. once-through and wet tower cooling, and their impact on the thermal power plant output is quantified. Both cooling systems use river water, i.e. once-through cooling withdraws large quantities of water, and, on the other hand, wet towers consume some amount of water as makeup water to compensate for evaporation. In both cases, the river basin is analyzed simulating severe droughts conditions of low river flow and high river water temperature. Consequently, the power output of the thermal power plant constrained by the water policies is determined. The hydraulic link between the