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Water-energy nexus: Impact on electrical energy conversion and mitigation by smart water resources management

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

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ABSTRACT

The water-energy nexus refers to the water used to generate electricity and to the electric energy used to collect, clean, move, store, and dispose of water. Water is used in all stages of electric energy conversion making power systems vulnerable to water scarcity and warming. In particular, a water flow decrease and temperature increase in rivers can significantly limit the generation of electricity. This paper investigates the issues to energy conversion stemming from the water-energy nexus and mitigates them by developing a model for the smart utilization of water resources. The objective is to minimize power curtailments caused by a river water flow decrease and a temperature increase. The developed water-energy nexus model integrates the operational characteristics of hydro power plants, the environmental conditions, the river water temperature prediction and thermal load release in river bodies. The application to a hydraulic cascade of hydro and a thermal power plants under drought conditions shows that smart water management entails a significant reduction of power curtailments. In general, the full coordination of the power outputs of the units affected by the hydrological link provides the most effective mitigations of the potential issues stemming from the water-energy nexus. Finally, critical temperature and flow regimes are identified which severely impact the energy conversion and may cause systemic risks in case the generators in one region must be simultaneously curtailed.

1. Introduction

Water and electrical energy demands are growing worldwide as a result of the economic and population growth and the changing climate [1]. The water-energy nexus captures the interdependency between the two resources, and focuses on the need for water in the energy supply chain, and on the energy used to collect, clean, move, store, and dispose of water [2]. The design and operation of many engineered systems entail several coupling mechanisms between the water and the energy system [3]. In particular, the dominant generation technologies require water in all stages of electricity conversion [4]. The kinetic energy of water is converted into electrical energy at hydro power plants (HPPs). Water is used for cooling of thermal power plants (TPPs), for extraction, transport and processing of fossil fuels, and for the irrigation of biofuels feedstock crops. Therefore, electrical energy generation is in need of reliable, abundant, and predictable sources of water [5].

Increased river flows in winter and decreased river flows in summer have been recorded since 1960s in large part of Europe [6], and annual average summer flows are expected to continue decreasing [7]. A study on the 200 largest rivers, based on a data record 1948–2004, reveals that the number of rivers with decreased flow exceed those with increased flow by a ratio of 2.5 to 1 [8]. Climate models project large variations in annual river flows [9]. Moreover, river water temperatures are also effected by the climate change. Global hydrological-water temperature models project consistent increases in streamflow temperature [10]. The largest increase is expected for the North-East America, Europe, Asia and parts of Southern Africa with moderate increase in Southern America and Central Africa [11].

Seasonal changes in river flows and temperatures have a large impact on the scheduling of electrical energy generation. Seasonal decrease in river flows and increase in river temperatures are typical between late July and early September for the high-latitude regions. Additionally, small river flows occur in January and February. These variations directly affect the availability and reliability of electric power generation.

The thermal load that power plants release in rivers is highly regulated by the authorities in Europe and US. European Union regulations are defined by the “European Fish Directive” [12]. The US regulations are based on the “Clean Water Act” [13]. According to

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

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the former, ground waters are categorized as salmonid and cyprinid waters. For the salmonid river waters the maximum allowed increase in water temperature is 1.5 °C and the thermal discharge in the river water must not cause a temperature increase above 21.5 °C downstream of the point of thermal discharge. For the cyprinid river waters the maximum allowed increase in water temperature is 3 °C and the thermal discharge in the river water must not cause a temperature increase above 28 °C downstream of the point of thermal discharge. However, a 2% exceed of the temperature limits is allowed, and specific cases may require additional temperature constraints [12].

In the last decade, the water-energy nexus revealed as a constraint in worldwide electric power generation. In 2012, severe droughts that affected more than a third of the United States reduced fresh water availability and limited the operations of power plants and energy sources production activities [14]. A similar event occurred in 2007–2008 and caused significant power curtailments from thermal power plants [15]. In France, a severe heat wave affected the cooling capabilities of nuclear and coal-fired plants in 2003 [14]. The government allowed Électricité de France (EDF), national operator of the nuclear fleet, to temporarily raise the maximum allowed water temperature due to cooling of these reactors [16]. Despite the allowance, 17 nuclear reactors and one coal-fired power plant had to shut down [14], and extremely high prices of electricity costed EDF an extra 300 M€ [17]. Recently, during the 2006 and 2009 heat waves in France, 17 reactors had again to shut down or limit their power output [14]. Germany faced similar problems, followed by decisions to lift the legal temperature limits in some regions in 2003 [16]. In 2015, a heat wave reduced the cooling capacity of rivers in Switzerland and three nuclear power plants curtailed their power output [18].

In the face of such frequent events, recent studies investigate the water-energy nexus at the power generation level. The vulnerability of the electric generation system to change of climate and water resources is investigated in [11], and a long term vulnerability analyses of the US and European electricity supply based on climate change models is carried on in [15]. Both studies show strong long-term interdependence among electrical energy generation, hydrology and climate change at the global scale. Options available for adapting the power plants in Berlin to water shortages are studied [19]. Analyzes of the water-energy nexus effects on the long term electricity planning in the Western US are performed in [2]. The impact of climate changes on the inflow volumes in hydropower reservoirs in California and its effect on electrical power generation is investigated [20]. In [21] the water-nexus is analyzed in China, where the proposed energy saving policy in several industrial sectors, including the electrical energy sector, show significant savings in the water consumption. Most of these studies propose adaptations to mitigate the vulnerability of the electricity sector to water constraints and changing climate. Various options are investigated, i.e. increase of plant efficiency, replacement of the once-trough cooling systems with dry cooling or recirculation systems, and replacement of fuel sources for thermal power plants. These changes involve high capital costs and in some cases reduction of plant efficiency. However, no short-term (i.e. hourly scheduling) solutions are proposed using the existing technology for power plant cooling.

This study investigates the water-energy nexus at the electric-power-generation level and contributes by developing a mitigation strategy to reduce the amount of generation curtailments stemming from river flow decreases and river temperature increases. A coupled model for the water-energy nexus is developed. The main coupling point of the nexus is represented by the water discharged from hydro reservoirs which is additionally used for once-trough cooling of thermal power plants. Once-trough cooling systems withdraw water from a source (e.g. river, lake, and ocean), circulate it through the plant condenser, and return it back to the source. The co-location of hydro and thermal power plants on the same water stream is a frequent arrangement, i.e. they are the most common anthropogenic structures that affect many rivers worldwide [22]. The developed model predicts the water temperature at a point of thermal discharge based on the water released from upstream reservoirs and environmental conditions. By tuning the discharge from upstream reservoirs, power curtailments of thermal plants are reduced. The developed model consists of four parts, namely, hydro generation, thermal generation, river water temperature prediction and mixing of river flows. The hydro power plant generation model considers the reservoir characteristics and operational constraints. The thermal power plant generation model is based on the thermal load discharge to the river considering environmental constraints. The river water temperature prediction model considers the heat transfer to and from the atmosphere. The mixing of rivers is modeled as full mixing of two streams with different temperatures. Power generation issues stemming from the water-energy nexus are tackled by the short-term management of water resources using meta-heuristic optimization. A topical case study consisting of a cascade of hydro power plants followed by a thermal power plant positioned downstream a river is used for test purposes. The system resembles a typical, real-world hydraulic connection of hydro and thermal power plants. The analyses are performed over a 24-h period. Additionally, sensitivity analyses on the interdependence among river flow decrease, temperature increase and power generation are performed.

The paper is organized as follows. Section 2 presents the development of the water-energy nexus model. The formulation of the problem of interest as well as the algorithm procedure used to solve the problem are presented in Section 3. The test case study is presented in Section 4. Section 5 is dedicated on the analyses and the results. Sensitivity analyses are performed in Section 6. Section 7 provides a summary of the research.

2. The water-energy nexus model for power generation

The water-energy nexus model for the smart utilization of river water resources is introduced. The model describes river systems which co-locate upstream reservoirs and downstream thermal power plants that use once-trough cooling systems. This setting captures the negative impact on electric power production due to reduced river flows and high river temperatures, and allows the identification of mitigation strategies by regulating the water discharge from reservoirs. The temperature of water in rivers is dependent on atmospheric conditions [23], changes in streamflow [24] and presence of thermal discharges [25]. In many situations, the streamflow can be regulated by selective releases from reservoirs, thus altering the downstream thermal regimes [22]. Larger releases increase the capacity of the stream to accept larger amounts of thermal load and result in smaller changes in stream temperature.

The amount of water stored in the reservoir or in the cascade of reservoirs and their discharges are the main control parameters. Based on the discharges from upstream reservoirs and the atmospheric conditions, the model predicts the hourly river water temperature and the flow at the location of a downstream thermal power plant. The river water temperature profile and the environmental constraints are used to calculate the maximum allowed electric power output of the plant equipped with once-through cooling.