Applied Energy xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Maintaining electric grid reliability under hydrologic drought and heat wave conditions

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HIGHLIGHTS

- We introduce the concept of optimal rules specifying required thermal variances.
- Rules are conditioned on leading modes of hydrological and meteorological variables.
- Rules are developed with a linear optimization with stochastic costs.
- Method aids cooperative decision making between environmental and power grid actors.

ARTICLE INFO

Article history:
Received 29 November 2016
Received in revised form 21 June 2017
Accepted 28 June 2017
Available online xxxx

Keywords:
Energy-water nexus
Environmental policy
Rule curves
Electricity-water nexus
Thermal pollution

ABSTRACT

During droughts and heat waves, thermal power plants that discharge heated effluent into rivers are often granted thermal variances permitting them to exceed the temperature restrictions imposed on effluent for protection of local aquatic ecosystems. These thermal variances are often justified as necessary for maintaining electricity reliability, particularly as heat waves typically cause an increase in electricity demand. However, current practice lacks tools for the development of grid-scale operational policies that specify the minimal thermal variances required to ensure reliable electricity supply. Creating these policies requires consideration of characteristics of individual power plants, topology and characteristics of the electricity grid, and locations of power plants within the river basin. We develop a methodology for creating such policies that considers these necessary factors. Conceptually, the operational policies developed are similar to the widely used rule curves of reservoir management, as we develop optimal rules for different hydrological and meteorological conditions. The rules are conditioned on leading modes of the ambient hydrological and meteorological conditions at the different power plant locations, leveraging the statistical correlation that exists between these conditions due to geographical proximity and hydrological connectedness. Heat dissipation in rivers and cooling ponds is modeled using the equilibrium temperature concept. Optimal rules are determined through a linear optimization with stochastic costs. We illustrate the methodology with a representative electricity grid model of eight power plants in Illinois that were granted thermal variances in the summer of 2012. Our methodology can facilitate cooperative decision making between environmental agencies, power grid operators, and power plant operators.

1. Introduction

The bulk of electricity generation capacity requires significant volumes of water, withdrawn from rivers and reservoirs, during operation. Thermal power plants require water to condense steam while hydropower plants require water to drive turbines. This water dependence creates a vulnerability of electric power systems to drought and heat waves. During dry and hot periods, the electricity generation sector competes with other water uses, including instream ecosystem purposes, with regards to water quantity and water quality requirements, notably water temperature. This *electricity-water nexus* has been the subject of increasing attention [1–4] due to concerns about climate change-induced distortion of freshwater availability, and increasing electricity demand due to population and economic growth.

There is a rich history of research into the water quantity requirements and water quality impacts of hydropower. In recent years there has also been renewed interest in thermal power plant

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http://dx.doi.org/10.1016/j.apenergy.2017.06.091
0306-2619/

water requirements, as well as the impacts of thermal power plant water use on other water users and the environment. This renewed interest has been stimulated by increased concurrence of droughts and heat waves [5] that has exposed the vulnerability of thermal-dominated power systems to water-related disturbances [1]. In recent research efforts, attempts have been made to quantify the water requirements of different types of thermal power plants categorized by fuel type and cooling technology [6]. Cost-benefit analyses of retrofitting thermal power plants with more water-efficient cooling systems, or to use reclaimed water, have been presented [7–11]. Projected effects of climate change on the effective capacity and vulnerability of thermal power plants have been analyzed [12–15]. Models have been developed to study the fate of heat from thermal power plants discharged into rivers [16,17]. Additionally, models that incorporate water constraints into optimal electricity system capacity expansion have been developed [18–20].

The focus of the bulk of this prior work has been on analyzing and addressing the important long-term planning challenges pertaining to thermal power plant water requirements and vulnerabilities. However, there remains a gap in the literature regarding tools to support decision making in near-term operations planning time scales, under the constraints of existing infrastructure. During normal or wet periods, these tools are not required as power plants are sited at locations where there is usually sufficient water. During droughts and heat waves, however, it becomes necessary to apply operational policies that minimize water-related externalities, while ensuring that reliable electricity supply is maintained.

It is not sufficient for such operational policies to be based only on considerations of the characteristics of individual power plants. Individual power plants are part of large and complex electricity grids that have limited transmission capacity and complex reliability requirements. The location of specific power plants within the electricity grid, relative to major electricity demand nodes and transmission capacity, provides useful information for the determination of optimal policies. Additionally, the location of power plants within the river basin must also be considered; water withdrawal, discharge, and consumption by power plants will have differing impacts depending on the heterogenous water quality and quantity requirements of competing water users, including local and downstream ecosystems.

In this paper, we present a methodology for the development of operational policies that minimize the impact of electricity generation on water quality during droughts and heat waves. Specifically, our focus is on minimizing thermal pollution as measured by the granting of provisional thermal variances to power plants that use once-through cooling systems or cooling ponds. Thermal pollution can affect metabolic rates, growth, and reproductive timing of aquatic organisms, in addition to lowering the oxygen carrying capacity of water [21]. In the United States, in accordance with Section 316(a) of the Clean Water Act, restrictions are placed on the amount of heat that can be discharged into receiving water bodies by power plant cooling systems. These restrictions take the form of temperature limits at specified management points to protect local aquatic ecosystems. However, during droughts and heat waves, power plants might be granted thermal variances allowing them to temporarily exceed these temperature limits. These thermal variances are often deemed necessary for maintaining electricity reliability, particularly as heat waves cause an increase in electricity demand. Current practice, however, lacks tools for the development of grid-scale operational policies specifying generator output levels that ensure reliable electricity supply while minimizing thermal variances. We aim to fill this knowledge gap. Our methodology is relevant to power systems with a large number of once-through cooling power plants and cooling ponds, such as in the eastern United States. The methodology captures the factors necessary for making optimal decisions at a system scale, namely: (i) generator characteristics; (ii) location of power plants in the river basin; (iii) location of power plants in the electricity grid relative to loads and transmission capacity; and (iv) electricity reliability requirements.

Conceptually, the methodology is similar to the widely-used *rule curves* for reservoir management, as we develop optimal rules that ensure reliable electricity supply, while minimizing thermal variances under different hydrological and meteorological conditions.

2. Methodology

The methodology developed is best illustrated with a small scale example. Fig. 1a shows two once-through power plants, P_1 and P_2, along a river reach separated by a distance x_{12}. The ambient streamflow level is q, and the upstream stream temperature is T. The two power plants are part of the power transmission network shown in Fig. 1b. A third power plant P_3 is not affected by water constraints. Each of the power plants P_1 and P_2 has a *once-through* cooling system, in which water is withdrawn from the river, passed through the power plant condenser to absorb heat, and then discharged back into the river at a higher temperature. Each power plant is allowed a *mixing zone* that extends a few tens of meters downstream of the power plant outfall, and limits are placed on the temperature at the edge of that mixing zone; that is, T_{edge} should be less than a defined T_{edge}^{max}. Under drought and heat wave conditions, the power plants might be granted thermal variances, temporarily permitting them to exceed these temperature restrictions. Mathematically, we can define the thermal variance TV as follows:

$$TV = \max(T_{edge} - T_{edge}^{max}, 0) \quad (1)$$

A reasonable objective from a water resource management perspective during a drought and heat wave, would be to minimize the thermal variances (TV) that need to be granted to the power plants to maintain power grid reliability. For the case of Fig. 1, this objective can be expressed as minimization of a function of the thermal variance vector that returns a scalar:

$$\begin{aligned} &\underset{\mathbf{x}}{\text{minimize}}: && f(\mathbf{TV}) \\ &\text{where}: && TV_n = \max(T_{edge_n} - 32, 0) \quad n = 1,2 \end{aligned} \quad (2)$$

where $\mathbf{x}$ is the vector of decision variables for all the power plants (i.e., $P_n,\ T_{eff_n},\ q_{eff_n}\ \forall n$). The function $f()$ could take a variety of forms depending on the policy objective. For example, the function $f()$ could be taken as a weighted sum of elements, with weights selected to ensure protection of particularly vulnerable river segments; ecosystems in certain watersheds in the Southeastern and Midwestern United States have been identified as being particularly vulnerable to thermal pollution from thermal power plants [22]. Alternatively, the L^2 norm could be used as the objective function, an approach that would enforce a degree of equity between power plants. Another approach of interest might be to minimize the average or maximum value of the elements of $\mathbf{TV}$. In this example, we use the L^1 norm of the vector $\mathbf{TV}$ as the objective function $f()$.

The temperature at the edge of the mixing zone T_{edge_n} for each power plant, can be related to the power plant output P by Eq. (3):

$$q_{eff_n}(T_{eff_n} - T_n^-) = \frac{HR_n - 3600 - \beta_n}{3600 \times c_p\ \rho} \times P_n \times 1000 \qquad n = 1,2 \quad (3a)$$

$$T_{edge_n} = \frac{(0.25 \times q \times T_n^-) + q_{eff_n} T_{eff_n}}{(0.25 \times q) + q_{eff_n}} \qquad n = 1,2 \quad (3b)$$

where as shown in Fig. 1a, q_{eff_n} and T_{eff_n} are the flow rate and temperature of the power plant effluent, and T_n^- is the temperature of