An Enterprise Control Methodology for the Techno-Economic Assessment of the Energy Water Nexus

Steffi O. Muhanji[1,1,], Amro M. Farid[1,2]

Thayer School of Engineering, 14 Engineering Dr., Hanover, NH 03755

Abstract

In recent years, the energy-water nexus literature has recognized that the electricity and water infrastructure that enables the production, distribution, and consumption of these two precious commodities is fundamentally intertwined. Electric power is required to produce, treat, distribute, and recycle water while water is required to generate and consume electricity. In the meantime, significant attention has been given to renewable energy integration within the context of global climate change. While these two issues may seem unrelated, their resolution is potentially synergistic in that renewable energy technologies not only present low CO_2 emissions but also low water-intensities as well. Furthermore, because water is readily stored it has the potential to act as a flexible energy resource on both the supply as well as the demand sides of the electricity grid. Despite these synergies, the renewable energy integration and energy-water nexus literature have yet to methodologically converge to systematically address potential synergies. This paper advances an enterprise control methodology as a means of assessing the techno-economic performance of the energy water nexus. The enterprise control methodology has been developed in recent years to advance the methodological state of the art of renewable energy integration studies and used recently to carry out a full-scale study in ISO New England. The methodology quantifies day-ahead and real-time energy market production costs, dispatched energy mixes, required operating reserves, levels of curtailment, and grid imbalances. This energy-water nexus methodological extension now includes flexible water-energy resources within the grid's energy resource portfolio and quantifies the quantities of withdrawn and consumed water. The simulation methodology is demonstrated on a modified version of the RTS-96-GMLC test case.

Keywords: , energy-water nexus, electricity market, smart power grid, smart water grid, water distribution, energy management

Email addresses: steffi.o.muhanji.th@dartmouth.edu (Steffi O. Muhanji), amro.m.farid@dartmouth.edu (Amro M. Farid)

[1]Graduate Student at the Thayer School of Engineering at Dartmouth

[2]Associate Professor at the Thayer School of Engineering at Dartmouth

1. Introduction

Water security is one of the main challenges facing mankind today. Due to the effects of climate change on hydrology patterns, the amount of available freshwater resources is quickly declining[1]. It is approximated that only $200,000km^3$–1% of all freshwater is available for human consumption and utilization[2]. This includes water required for all day to day human needs as well as water needed for the agriculture, manufacturing, and electric power sectors[2]. With the expected population growth and industrialization of developing countries, both the energy and water demand per capita are expected to rise significantly. As a result of these challenges, being able to efficiently utilize available water resources and prevent over-exploitation is imperative[2]. On the one hand, these challenges call for better ways of managing available water resources whether it is in the improvement of water treatment standards, flue gas management, or infrastructure upgrades. On the other hand, better management of water-intensive industries such as the electric power sector would go a long way to minimize their strain on available water resources. Flexible control of the electricity supply system is particularly crucial within the context of renewable energy integration studies given that renewables 1). are highly variable 2). have very low life-cycle water consumption, and 3). require the grid to have flexible operating capability to be able to respond to variability of supply. The study of the energy-water nexus must, therefore, converge with renewable energy integration studies.

In recent years, the energy-water nexus literature has recognized that the water and electricity production, distribution, and consumption systems are fundamentally intertwined. The electricity industry is inherently dependent on the adequate supply of water to support generation whether its in cooling thermal power plants, hydroelectric power generation, or in the extraction of raw fuels such as natural gas. Thermal power plants withdraw large quantities of water for cooling purposes and depending on the type of cooling technology, a significant amount of this water is lost through *evaporation* or *blowdown*[3, 4]. To illustrate, a recent study estimates that water withdrawals by electricity generating facilities in 2010 constituted 45% of the overall freshwater withdrawals in the United States with approximately 2% of that water being consumed as a result[4]. In addition to cooling purposes, large quantities of water are utilized in the extraction of raw fuels for electricity generation. A recent study reported that the water consumption (in liters per gigajoule – L/GJ) for worldwide production of carbon-based and nuclear fuels is as follows: 1) traditional oil (3–7 L/GJ); 2) oil from oil sands (70–1800 L/GJ); 3) conventional natural gas (minimal water use); 4) shale gas (36–54 L/GJ); 5) coal (5–70 L/GJ); and 6) uranium (4–22 L/GJ)[5]. Given that in 2015, 76.9% of the world's total electricity was generated from oil, coal, natural gas and nuclear fuels while 16% came from hydroelectricity[6], reducing the water intensity of these generation processes is critical to ensuring water security. Similarly, significant electric power is required to support water production and distribution needs such as desalination, waste-water treatment and recycling, and pumping. With this level of coupling, significant synergies could be realized by studying the two systems holistically.

In the meantime, significant attention has been given to the integration of renewable energy resources into the electricity grid as a means of decarbonizing the electricity supply system. Due to concerns about climate change, solar and wind installations are steadily increasing while coal, nuclear and oil power plants are slowly being retired. Recent studies have shown that variable energy resources (VERs) such as solar and wind possess dynamics that span multiple time scales and hence, affect different layers of power system's control. These findings illustrate that the traditional power system's hierarchical control structure is no longer sufficient to ensure the reliability of the system especially as the penetration of VERs continues to grow. Additionally, these studies have also confirmed that due to a high penetration of VERs, operators are forced to rely on manual curtailment of such resources to balance the net load. In addition, forecast errors of VERs have been shown to increase infeasible dispatches in the real-time market. Another key conclusion of these integration studies is that the intermittency and uncertainty of VERs is likely to increase the reserve requirements and hence the marginal production cost of electricity. These factors pose many challenges to grid operators both at the distribution and transmission level.

While the challenges of renewable generation and energy-water-nexus may seem unrelated, their resolution is potentially synergistic. Renewable energy technologies not only present low CO_2 emissions, but they also have low water-intensities. Furthermore, since water is easily stored, it has the potential to act as a flexible energy resource on both the supply-side as well as the demand-side of the electricity grid. As a consequence of decarbonization, a lot of new natural gas power plants are being installed to replace the retired coal and oil generation facilities. However, natural gas production withdraws and consumes significant amounts of water ($\approx 1000m^3$–$30000m^3$ per shale well per year [8]) and hence, cannot be ignored within the context of renewable energy integration [8–14]. To meet the required CO_2 emission reductions, natural gas production is projected to grow by 44% between 2011 and 2040 [7]. In order to maintain the reliability of the electricity grid with high penetrations of wind and solar, system operators need to flexibly operate generation resources so as to meet the intermittency and uncertainty of solar and wind. Additionally, they must have the ability to flexibly control available water-dependent electricity resources and electricity-intensive water processes both to minimize costs and improve the reliability of supply. In this case, water system operators can potentially increase their profits by providing demand-response ancillary services.

1.1. Literature Gap

Despite the clear synergistic advantages, the renewable energy integration and EWN literature have not yet converged methodologically to systematically address potential synergies. Renewable energy integration studies have focused solely on the operation of electricity markets with large penetrations of VERs. A variety of these studies have been case specific and only considered a single layer of power system control. Others have taken statistical approaches to determining the forecast errors of wind and solar. A majority of these studies have focused on the acquisition of normal operating reserves such as load-following, regulation, and ramping reserves. However, a recent review of integration studies shows major methodological limitations in these studies. First, the quantity of the required reserves is based on the experiences of grid operators which no longer applies to systems with high penetrations of VERs. Second, although both the net load variability and forecast error contribute towards normal operating reserves, most studies consider only one of the variables. Lastly, most studies fail to consider the effects of timescales on the various types of operating reserve quantities. This same review [] proposed a holistic approach based on enterprise control to study the full impact of VERs on power system balancing operation and reserve requirements. *Enterprise control* is an integrated and holistic approach that allows operators to improve the technical performance of the grid while realizing cost savings. This approach allows for a multi-timescale analysis of system dynamics and thus, ensures the accurate determination of operating reserves. An application of enterprise control in the form of the Electric Power Enterprise Control System (EPECS) simulator has been proposed in literature and tested on various case studies including the ISO New England system.

In the meantime, the energy-water-nexus literature has come up with individual technologies, policy recommendations and system analysis techniques to study both the electricity and water supply systems. Policy focused studies tend to take a qualitative and sometimes statistical approach while focusing on a specific geographical region[2, 5, 9, 23, 25–35]. Similarly, system analysis techniques have been case-study driven, geography-specific, rather than generic methodologies that are generally applicable. Some works have studied the water impact of natural gas production, the water-intensity of thermal power plants[1, 3, 24, 36–38], and the optimization of water pumps[39–44]. An interesting group of these system analysis techniques, however, are those that co-optimize energy and water resources[45–49, 51**?** –54]. However, the problem with these approaches is that they are single layer optimizations[48–50]. For example, [48] studied only optimal network flow, [49] the economic dispatch, and [50] the unit commitment problem for a combined water, power, and co-production facilities. Other approaches studied the demand response capabilities of water distribution systems while exploiting key water distribution features such as variable speed pumps to maximize returns and reduce consumption[51–54]. Due to a lack of generic techniques, most of these studies are neither generally extensible nor applicable to other case-study geographies.

1.2. Original Contribution

This paper extends the enterprise control approach presented and implemented in [55–61] so as to assess the techno-economic performance of the energy-water nexus. In recent years, the enterprise control methodology has been developed to advance the methodological state of the art of renewable energy integration studies and has been used to carry out a full-scale study in ISO New England. The methodology quantifies the dispatched energy mixes, the required operating reserves, levels of curtailment, grid imbalances, and the day-ahead and real-time production costs. The energy-water-nexus methodological extension presented in this paper includes flexible water-energy resources within the grid's energy resource portfolio and quantifies the water consumption and withdrawals. For completeness, the methodology presented in this paper is both case and geography independent. The simulation methodology is demonstrated on a modified version of the RTS-96 test case.

1.3. Research Scope

This work adopts as its research scope the yellow system boundary shown in Fig. 1. The traditional electric power system literature does not take into account non-electrical variables at the system boundary. For example, in power

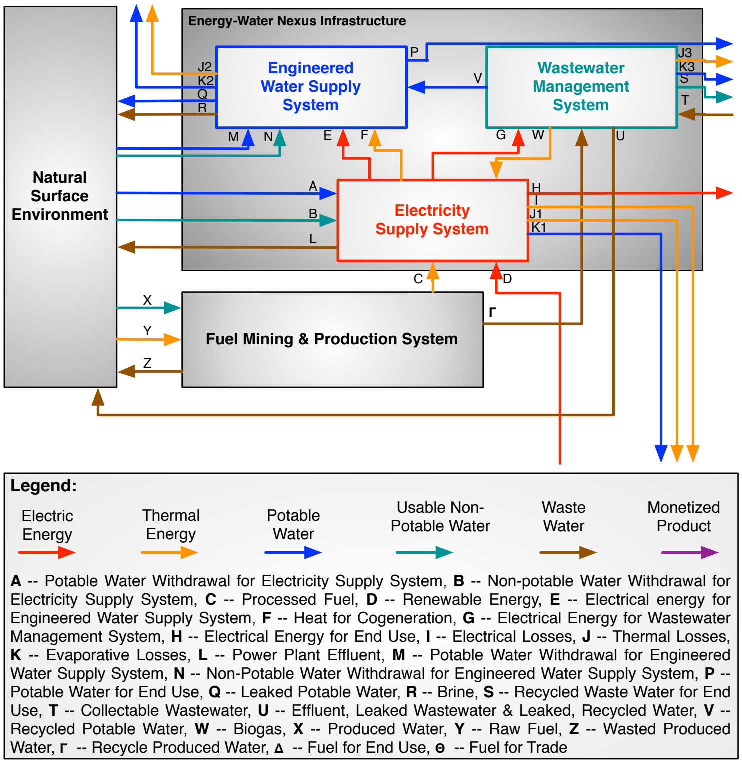

Figure 1: This figure shows all the physical flows between the energy water-nexus and the natural surface environment.

flow analysis, generators are modeled as sources and loads as sinks irrespective of the non-electrical energy flows that they cause upstream or downstream. In contrast, the system boundary indicated in Fig.. 1 explicitly includes all matter and energy flows that enter the electric grid infrastructure. The energy-water nexus literature, in contrast, often suffers from inconsistencies in the choice of system boundary. Many of these inconsistencies are caused by the heterogeneity of energy-water resources (or lack thereof) in a methodology tailored to a specific case study geography. Such studies often fail to recognize that the case study results limit the applicability to other regions and often require that new analytical methodologies be developed as well. Consequently, this study employs a generic methodology that is both case and geography independent to study the flows in and out of the system boundary especially with a high penetration of VERs. This paper considers the effects of flexible water resources on ensuring the reliability of the electricity grid and on the overall cost of supplying electricity to consumers. The study presents the value of flexible water resources based on how they affect the amount of operating reserves, the total imbalances in the systems, and the electricity market production costs.

Probably a good point to say that this message assess the impact between the electric grid and the water system. It does not consider other energy carriers. It does not explicitly model the natural or built water systems and leaves them as exogeneous. We will come back to this in another revision.

1.4. Paper Outline

To that end, the rest of this paper is structured as follows: Section 2 presents the methodological approach for this study. The security-constrained unit commitment (SCUC) and economic dispatch (SCED) formulations are presented in Sections 2.2 and 2.3 respectively. The regulation model and the power flow analysis are discussed in Sections 2.4 and 2.5. A model for studying the water-energy flows is presented in section 2.5. Section 3 describes the RTS-GMLC test case and its application to this study. Section 4 presents the results for the case study focusing on operating reserves, balancing performance, water withdrawal and consumption, and cost implications. Finally, the paper is concluded in Section 5.

2. Methodology

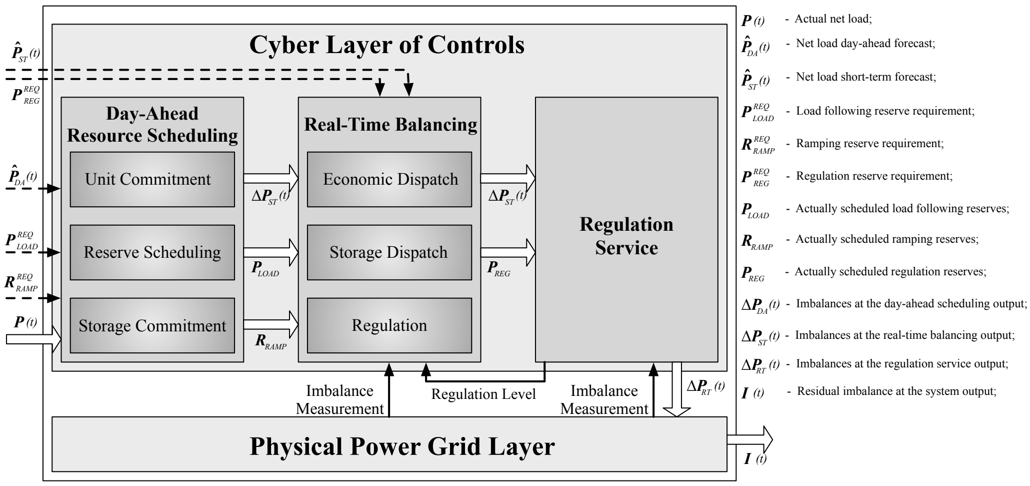

Figure 2: The enterprise control methodology is used to study the real-time flows for the electricity supply system.

2.1. Overview

This paper employs the enterprise control methodology introduced in [58–61] as a holistic approach for the techno-economic assessment of newly integrated variable energy resources. The enterprise control simulator is a modular simulator that comprises of three control and decision-making layers on top of a physical power grid layer as illustrated in Figure 2. The decision-making and control layers include a resource scheduling layer in the form of a security-constrained unit commitment (SCUC), a balancing layer accomplished through the security constrained economic dispatch (SCED), and a regulation layer. These three layers work together to holistically quantify and address imbalances occurring throughout the system. The enterprise control methodology has been assessed and validated through a set of numerical simulations on various well-known test cases such as the IEEE 11-bus test case, and the IEEE RTS-96 test case[59]. Most recently, the enterprise control simulator was used to study the impact of various penetrations of wind and solar on the ISO-New England system[62, 63]. This section presents the enterprise control methodology and extends its application to the techno-economic assessment of the energy-water nexus. The rest of this section is structured as follows: Section 2.2 defines the SCUC formulation, Section 2.3 presents the SCED formulation, Section 2.4 describes the regulation model and finally Section 2.5 presents the mathematics for quantifying the energy-matter flows across the yellow system boundary of Figure 1.

2.2. Security-Constrained Unit Commitment (SCUC)

The SCUC commits a set of generators and demand response resources so as to meet the stochastic net load at a minimum cost. It also dispatches storage units, schedules reserves and is executed a day in advance. The SCUC formulation presented below is adapted from [**?**] in order to accommodate energy-water resources.

$$\min \quad \sum_{t=1}^{24} T_h \Big(\sum_{k=1}^{N_G} (w_{Gkt}C_{Fk} + C_{Lk}P_{kt} + C_{Qk}P_{kt}^2 + u_{Gkt}C_{Uk} + v_{Gkt}C_{Dk}) + \sum_{s=1}^{N_s} C_{es}E_{st} + (C_{sp}P_{st}^{+} + C_{sc}P_{st}^{-}) + \ldots$$
$$\ldots + \sum_{m=1}^{N_D} (w_{Dmt}C_{Fm} + C_{Lm}P_{mt} + C_{Qm}P_{mt}^2 + u_{Dmt}C_{Um} + v_{Dmt}C_{Dm}) + \sum_{\mathcal{L}=1}^{N_{\mathcal{L}}} C_{\mathcal{L}}(1 - w_{\mathcal{L}t}d_{\mathcal{L}})\hat{P}_{\mathcal{L}t} + \sum_{x=1}^{N_x} C_{Qx}P_{xt}^2 + \ldots$$
$$\ldots + \sum_{\mathcal{W}=1}^{N_{\mathcal{W}}} C_{\mathcal{W}}(1 - w_{\mathcal{W}t}d_{\mathcal{W}})\hat{P}_{\mathcal{W}t} + \sum_{\mathcal{V}=1}^{N_{\mathcal{V}}} C_{\mathcal{V}}(1 - w_{\mathcal{V}t}d_{\mathcal{V}})\hat{P}_{\mathcal{V}t} + \sum_{\mathcal{H}=1}^{N_{\mathcal{H}}} C_{\mathcal{H}}(1 - w_{\mathcal{H}t}d_{\mathcal{H}})\hat{P}_{\mathcal{H}t} \Big) \quad (1)$$

The objective function in Equation 1 represents the production costs of N_G dispatchable generators, the utility of the N_D demand response resources, the cost of N_S storage resources, the virtual generation cost of $N_{\mathcal{L}}$ virtual power plants, and the curtailment costs of $N_{\mathcal{W}}$ wind plants, $N_{\mathcal{V}}$ solar PV plants, $N_{\mathcal{H}}$ run-of-river hydro plants. The objective function also includes a quadratic penalty term P_{xt} that implements a soft constraint in the nodal power balance in each node x on the network. The SCUC objective minimizes the total cost, in dollars, of meeting demand over a period of 24 hours.

$$\sum_{k=1}^{N_G} A_{nk}P_{kt} + \sum_{m=1}^{N_D} A_{nm}P_{mt} - (1+\gamma)\sum_{\mathcal{L}=1}^{N_{\mathcal{L}}} A_{n\mathcal{L}}(1 - w_{\mathcal{L}t}d_{\mathcal{L}})\hat{P}_{\mathcal{L}t} + (1+\gamma)\sum_{\mathcal{W}=1}^{N_{\mathcal{W}}} A_{n\mathcal{W}}(1 - w_{\mathcal{W}t}d_{\mathcal{W}})\hat{P}_{\mathcal{W}t} + \ldots$$
$$\ldots + \sum_{s=1}^{N_s} A_{ns}(P_{st}^{+} - P_{st}^{-}) + (1+\gamma)\sum_{\mathcal{V}=1}^{N_{\mathcal{V}}} A_{n\mathcal{V}}(1 - w_{\mathcal{V}t}d_{\mathcal{V}})\hat{P}_{\mathcal{V}t} + (1+\gamma)\sum_{\mathcal{H}=1}^{N_{\mathcal{H}}} A_{n\mathcal{H}}(1 - w_{\mathcal{H}t}d_{\mathcal{H}})\hat{P}_{\mathcal{H}t} + \ldots$$
$$\ldots + \sum_{x=1}^{N_x} A_{nx}(P_{xt}) = \sum_{l=1}^{N_L} B_{nl}F_{lt} \qquad \forall_t \quad (2)$$

Equation 2 maintains the nodal power balance of all generation, storage and demand side resource injections with the line flows out of each node.

$$w_{Gkt}\underline{P_k} \leq P_{kt} \leq w_{Gkt}\overline{P_k} \qquad \forall_{k,t} \tag{3}$$

$$w_{Dmt}\underline{P_m} \leq P_{mt} \leq w_{Dmt}\overline{P_m} \qquad \forall_{m,t} \tag{4}$$

$$w_{Pst}\underline{P_s^+} \leq P_{st}^+ \leq w_{Pst}\overline{P_s^+} \qquad \forall_{s,t} \tag{5}$$

$$w_{S\,st}\underline{P_s^-} \leq P_{st}^- \leq w_{S\,st}\overline{P_s^-} \qquad \forall_{s,t} \tag{6}$$

Equations 3,4, 5, and 6 represent the power capacity constraints for dispatchable generation, active demand response, and storage resources respectively.

$$\underline{E_s} \leq E_{st} \leq \overline{E_s} \qquad \forall_{s,t} \tag{7}$$

Furthermore, Equation 7 represents the energy capacity constraints of the energy storage resources.

$$E_{st} = E_{s,t-1} + (\eta_s P_{st}^- - P_{st}^+) \cdot T_h \qquad \forall_{s,t} \tag{8}$$

Consequently, Equation 8 describes the energy storage state equation of these resources.

$$E_{s0} = \epsilon_s \qquad \forall_{s,t=0} \tag{9}$$

Equation 9 describes the initial conditions for the energy storage resources.

$$w_{Gkt-1} + u_{Gkt} - v_{Gkt} = w_{Gkt} \qquad \forall_{k,t} \tag{10}$$

$$w_{Dmt-1} + u_{Dmt} - v_{Dmt} = w_{Dmt} \qquad \forall_{m,t} \tag{11}$$

Equations 10 and 11 are the logical state equations governing the switching of dispatchable generators and demand side resources on and off.

$$u_{Gkt} + v_{Gkt} \leq 1 \qquad \forall_{k,t} \tag{12}$$

$$u_{Dmt} + v_{Dmt} \leq 1 \qquad \forall_{m,t} \tag{13}$$

Equations 12 and 13 ensure that the dispatchable generators and active demand side resources cannot startup and shutdown simultaneously.

$$w_{Pst} + w_{S\,st} \leq 1 \qquad \forall_{s,t} \tag{14}$$

$$w_{Pst-1} + w_{S\,st} \leq 1 \qquad \forall_{s,t} \tag{15}$$

$$w_{Pst+1} + w_{S\,st} \leq 1 \qquad \forall_{s,t} \tag{16}$$

Equations 14, 15, and 16 are charging/discharging rules that constrain the energy storage resources such that they neither charge and discharge simultaneously and nor do they switch between charging and discharging without switching off first.

$$w_{Ps0} = \omega_{Ps0} \qquad \forall_{s,t=0} \tag{17}$$

$$w_{Ss0} = \omega_{Ss0} \qquad \forall_{s,t=0} \tag{18}$$

Equations 17 and 18 are the initial conditions of the logical states of the energy storage resources.

$$\underline{R_k} - \frac{\overline{P_k}}{T_h} v_{Gkt} \leq \frac{P_{kt} - P_{k,t-1}}{T_h} \leq \overline{R_k} + \frac{\overline{P_k}}{T_h} u_{Gkt} \qquad \forall_{k,t} \tag{19}$$

$$\underline{R_m} - \frac{\overline{P_m}}{T_m} v_{Dmt} \leq \frac{P_{mt} - P_{m,t-1}}{T_m} \leq \overline{R_m} + \frac{\overline{P_m}}{T_m} u_{Dmt} \qquad \forall_{m,t} \tag{20}$$

$$\underline{R_{\mathcal{W}}} \leq \frac{(1 - w_{\mathcal{W}t} d_{\mathcal{W}})\hat{P}_{\mathcal{W}t} - (1 - w_{\mathcal{W},t-1} d_{\mathcal{W}})\hat{P}_{\mathcal{W},t-1}}{T_h} \leq \overline{R_{\mathcal{W}}} \qquad \forall_{\mathcal{W},t} \tag{21}$$

$$\underline{R_{\mathcal{V}}} \leq \frac{(1 - w_{\mathcal{V}t} d_{\mathcal{V}})\hat{P}_{\mathcal{V}t} - (1 - w_{\mathcal{V},t-1} d_{\mathcal{V}})\hat{P}_{\mathcal{V},t-1}}{T_h} \leq \overline{R_{\mathcal{V}}} \qquad \forall_{\mathcal{V},t} \tag{22}$$

$$\underline{R_{\mathcal{H}}} \leq \frac{(1 - w_{\mathcal{H}t} d_{\mathcal{H}})\hat{P}_{\mathcal{H}t} - (1 - w_{\mathcal{H}t-1} d_{\mathcal{H}})\hat{P}_{\mathcal{H}t-1}}{T_h} \leq \overline{R_{\mathcal{H}}} \qquad \forall_{\mathcal{H},t} \tag{23}$$

Equations 19, 20, 21, 22, and 23 represent the ramping constraints for the dispatchable generators, demand response, wind, solar, and run-of-river hydro resources respectively. Although wind, solar, and run-of-river hydro resources are variable in nature, they gain a semi-dispatchable nature by virtue of their curtailment capability. The presence of a curtailment decision implies that such a resource must ramp between two consecutive curtailment values (in time). This work assumes these variable energy resources can ramp between their maximum and minimum capacities within a single SCED time step of five minutes.

$$\sum_{n=1}^{N_B} \Big(\sum_{k=1}^{N_G} A_{nk}(w_{kt}\overline{P_k} - P_{kt}) + \sum_{\mathcal{W}=1}^{N_{\mathcal{W}}} A_{n\mathcal{W}} \hat{P}_{\mathcal{W}} w_{\mathcal{W}t} d_{\mathcal{W}} + \sum_{\mathcal{V}=1}^{N_{\mathcal{V}}} A_{n\mathcal{V}} \hat{P}_{\mathcal{V}} w_{\mathcal{V}t} d_{\mathcal{V}} + \sum_{\mathcal{H}=1}^{N_{\mathcal{H}}} A_{n\mathcal{H}} \hat{P}_{\mathcal{H}} w_{\mathcal{H}t} d_{\mathcal{H}} \Big) \geq P_{res} \qquad \forall_{k,\mathcal{W},\mathcal{V},\mathcal{H},t}$$

$$\sum_{n=1}^{N_B} \Big(\sum_{k=1}^{N_G} A_{nk}(P_{kt} - w_{kt}\underline{P_k}) + \sum_{\mathcal{W}=1}^{N_{\mathcal{W}}} A_{n\mathcal{W}} \hat{P}_{\mathcal{W}} d_{\mathcal{W}}(1 - w_{\mathcal{W}t}) + \sum_{\mathcal{V}=1}^{N_{\mathcal{V}}} A_{n\mathcal{V}} \hat{P}_{\mathcal{V}} d_{\mathcal{V}}(1 - w_{\mathcal{V}t}) + \dots \tag{24}$$

$$\dots + \sum_{\mathcal{H}=1}^{N_{\mathcal{H}}} A_{n\mathcal{H}} \tilde{P}_{\mathcal{H}} d_{\mathcal{H}}(1 - w_{\mathcal{H}t}) \Big) \geq P_{res} \qquad \forall_{k,\mathcal{W},\mathcal{V},\mathcal{H},t} \tag{25}$$

Equations 24 and 25 impose requirements on the quantities of upward and downward load-following reserve requirements. Because wind, solar, and run-of-river hydro resources are semi-dispatchable by virtue of their curtailment capability, the amount of power from their maximum and minimum capacity values is included in the accounting of load following reserves.

$$
\begin{aligned}
&\sum_{n=1}^{N_B}\Big(\sum_{k=1}^{N_G} A_{nk}(w_{kt}\underline{R_k} - R_{kt}) + \sum_{m=1}^{N_D} A_{nm}(w_{mt}\overline{R_m} - R_{mt}) + \sum_{\mathcal{W}=1}^{N_{\mathcal{W}}} A_{n\mathcal{W}}(w_{\mathcal{W}t}\overline{R_{\mathcal{W}}} - R_{\mathcal{W}t}) + \dots \\
&\dots + \sum_{\mathcal{V}=1}^{N_{\mathcal{V}}} A_{n\mathcal{V}}(w_{\mathcal{V}t}\overline{R_{\mathcal{V}}} - R_{\mathcal{V}t}) + \sum_{\mathcal{H}=1}^{N_{\mathcal{H}}} A_{n\mathcal{H}}(w_{\mathcal{H}t}\overline{R_{\mathcal{H}}} - R_{\mathcal{H}t})\Big) \geq R_{res} \qquad \forall_{k,\mathcal{W},\mathcal{V},\mathcal{H},t} \qquad (26)
\end{aligned}
$$

$$
\begin{aligned}
&\sum_{n=1}^{N_B}\Big(\sum_{k=1}^{N_G} A_{nk}(R_{kt} - w_{kt}\underline{R_k}) + \sum_{m=1}^{N_D} A_{nm}(R_{mt} - w_{mt}\underline{R_m}) + \sum_{\mathcal{W}=1}^{N_{\mathcal{W}}} A_{n\mathcal{W}}(R_{\mathcal{W}t} - w_{\mathcal{W}t}\underline{R_{\mathcal{W}}}) + \dots \\
&\dots + \sum_{\mathcal{V}=1}^{N_{\mathcal{V}}} A_{n\mathcal{V}}(R_{\mathcal{V}t} - w_{\mathcal{V}t}\underline{R_{\mathcal{V}}}) + \sum_{\mathcal{H}=1}^{N_{\mathcal{H}}} A_{n\mathcal{H}}(R_{\mathcal{H}t} - w_{\mathcal{H}t}\underline{R_{\mathcal{H}}})\Big) \geq R_{res} \qquad \forall_{k,\mathcal{W},\mathcal{V},\mathcal{H},t} \qquad (27)
\end{aligned}
$$

Finally, Equations 26 and 27 are the upward and downward ramping constraints respectively. Similar to load-following constraints, these reserve constraints include contributions from solar, wind and run-of-river hydro resources.

2.3. SCED

This section provides the mathematical formulation for the security constrained economic dispatch (SCED). The SCED runs every 5 minutes to provide new set-points for dispatchable generators, wind, solar, hydro, and active demand-side resources. Similar to the SCUC, the objective function for SCED includes a quadratic penalty term to account for cases where nodal power balance can not be achieved with the existing set of energy resources. The SCED does not commit any new units. Instead it ramps up/down already committed dispatchable generators and sets new curtailment levels for solar, wind, run-of-river, and demand-side resources. Unlike the SCUC, the SCED does not re-optimize the energy storage setpoints, but rather uses those calculated in the execution of the SCUC. The SCED formulation minimizes the following objective function:

$$
\begin{aligned}
\min \quad & \frac{T_m}{60}\Big(\sum_{k=1}^{N_G}(C_{Lk}P_k + C_{Qk}P_k^2) + \sum_{\mathcal{L}=1}^{N_{\mathcal{L}}} C_{\mathcal{L}}(1 - w_{\mathcal{L}}d_{\mathcal{L}})\tilde{P}_{\mathcal{L}} + \sum_{s=1}^{N_s} C_{sp}P_s^+ - C_{sc}P_s^- + \dots \\
& \dots + \sum_{m=1}^{N_D}(C_{Lm}P_m + C_{Qm}P_m^2) + \sum_{\mathcal{W}=1}^{N_{\mathcal{W}}} C_{\mathcal{W}}(1 - w_{\mathcal{W}}d_{\mathcal{W}})\tilde{P}_{\mathcal{W}} + \dots \\
& \dots + \sum_{\mathcal{V}=1}^{N_{\mathcal{V}}} C_{\mathcal{V}}(1 - w_{\mathcal{V}}d_{\mathcal{V}})\tilde{P}_{\mathcal{V}} + \sum_{\mathcal{H}=1}^{N_{\mathcal{H}}} C_{\mathcal{H}}(1 - w_{\mathcal{H}}d_{\mathcal{H}})\tilde{P}_{\mathcal{H}} + \sum_{x=1}^{N_x} C_{Qx}P_x^2\Big) \qquad (28)
\end{aligned}
$$

This objective function is similar to that of the SCUC except that it optimizes over a single time step every T_m minutes and eliminates the energy storage resource terms. The SCED objective is multiplied by a factor of $\frac{T_m}{60}$ to obtain a cost in dollars rather than \$/hr.

$$\sum_{k=1}^{N_G} A_{nk}P_k + \sum_{m=1}^{N_D} A_{nm}P_m - (1+\gamma)\sum_{\mathcal{L}=1}^{N_\mathcal{L}} A_{n\mathcal{L}}(1-w_\mathcal{L}d_\mathcal{L})\tilde{P}_\mathcal{L} + (1+\gamma)\sum_{\mathcal{H}=1}^{N_\mathcal{H}} A_{n\mathcal{H}}(1-w_\mathcal{H}d_\mathcal{H})\tilde{P}_\mathcal{H} + \dots \tag{29}$$

$$\dots + \sum_{s=1}^{N_s} A_{ns}(P_s^+ - P_s^-) + (1+\gamma)\sum_{\mathcal{W}=1}^{N_\mathcal{W}} A_{n\mathcal{W}}(1-w_\mathcal{W}d_\mathcal{W})\tilde{P}_\mathcal{W} + (1+\gamma)\sum_{\mathcal{V}=1}^{N_\mathcal{V}} A_{n\mathcal{V}}(1-w_\mathcal{V}d_\mathcal{V})\tilde{P}_\mathcal{V} + \dots$$

$$\dots + \sum_{x=1}^{N_x} A_{nx}P_x^2 = \sum_{l=1}^{N_L} B_{nl}F_l \qquad \forall_{k,m,x,n,l,s,\mathcal{W},\mathcal{V},\mathcal{H},\mathcal{L}} \tag{30}$$

Similarly, the nodal-power balance constraint in 30 is expressed for a single moment in time.

$$w_k\underline{P_k} \le P_k \le w_k\overline{P_k} \qquad \forall_k \tag{31}$$

$$\underline{P_m} \le P_m \le \overline{P_m} \qquad \forall_m \tag{32}$$

Equations 31 and 32 are the capacity constraints for the dispatchable generators and the active demand response units.

$$\underline{R_k} \le \frac{P_k - P_k^0}{T_m} \le \overline{R_k} \qquad \forall_k \tag{33}$$

$$\underline{R_m} \le \frac{P_m - P_m^0}{T_m} \le \overline{R_m} \qquad \forall_m \tag{34}$$

$$\underline{R_\mathcal{W}} \le \frac{\tilde{P}_\mathcal{W}(1-w_\mathcal{W}d_\mathcal{W}) - \tilde{P}_\mathcal{W}^0}{T_m} \le \overline{R_\mathcal{W}} \qquad \forall_\mathcal{W} \tag{35}$$

$$\underline{R_\mathcal{V}} \le \frac{\tilde{P}_\mathcal{V}(1-w_\mathcal{V}d_\mathcal{V}) - \tilde{P}_\mathcal{V}^0}{T_m} \le \overline{R_\mathcal{V}} \qquad \forall_\mathcal{V} \tag{36}$$

$$\underline{R_\mathcal{H}} \le \frac{\tilde{P}_\mathcal{H}(1-w_\mathcal{H}d_\mathcal{H}) - \tilde{P}_\mathcal{H}^0}{T_m} \le \overline{R_\mathcal{H}} \qquad \forall_\mathcal{H} \tag{37}$$

Finally, Equations 33, 34, 35, 36, and 37 are the ramping constraints for the dispatchable generators, the active demand response, wind, solar, and run-of-river hydro resources respectively.

2.4. Regulation Reserves

Regulation reserves are provided by generation units with automatic generation control (AGC) capability. As described previously in detail[58], the enterprise control methodology simulates in 1-minute increments. The regulation service generators respond to imbalances by varying their output in the direction opposite to the imbalance until the imbalance is mitigated or the available regulation is exhausted. The enterprise control simulator also uses a virtual slack generator that consumes any mismatch between generation and load to make the steady state power flow equations feasible. The power system imbalances are quantified as the output of the slack generator.

2.5. Model of Physical Energy and Water Flows in the Electricity Supply System

In order apply the enterprise control model described above to the techno-economic assessment of the energy-water nexus, the physical grid model must be extended so as to quantify the energy and water flows. More specifically, this section provides a methodology by which to calculate the energy and water flows (A through K, and W) that cross the yellow system boundary depicted in Figure 1. For simplicity, all calculations are done in SI units as indicated in the nomenclature.

2.5.1. DC Power Flow Analysis Model

The heart of the electricity supply system model is a DC power flow analysis model that is solved at each minute time step. In that regard, for a given minute-time step t, the flow of electric power is assumed to follow Equation 30 in Section 2.3. This model couples all of the system's electrical variables in generation, transmission, and consumption. The remainder of this section, relates the energy and water flows in Figure 1 to these electrical variables.

2.5.2. C: Processed Fuel Used

One of the main roles of the electricity supply system is to convert processed fuels (C) into electrical energy and deliver it to meet electrical end-uses (E,F,G,H). The fuel flow rate $C_k(t)$ (kg/min) for a given dispatchable generator k is extracted from the generator's fuel curve used in the objective function of the SCUC (Equation 28).

$$C_k(t) = \frac{C_{Qk}P_k^2 + C_{Lk}P_k + w_{Gk}C_{Fk}}{60\mathbb{C}_F D_{fk}} \qquad \forall k \tag{38}$$

where P_k is the real-time power generation of generator k, $\mathbb{C}_F$ is the fuel cost in $\$/MJ$, D_{fk} (MJ/kg) is the fuel energy density and 60 is the conversion from hours to minutes.

2.5.3. D: Renewable Energy Delivered

In the enterprise control simulator, the real-time solar PV $P_{\mathcal{V}}(t)$, run-of-river hydro $P_{\mathcal{H}}(t)$, and wind generation $P_{\mathcal{W}}(t)$ are exogeneous quantities drawn from input temporal profile data. This data is scaled by varying five parameters: *penetration level* (π), *capacity factor* (γ), *variability* (A), *day- ahead forecast error* $(\hat{\epsilon})$ and *short-term* $(\tilde{\epsilon})$ *forecast error*. The penetration level and capacity are used to determine actual output of the variable energy resource (VER). The VER output is normalized to a unit capacity factor. The day ahead (mean absolute) forecast error with a 1-hour resolution is used in the SCUC formulation while the short-term (mean absolute) forecast error with a 5-minute resolution is used in the SCED formulation. The interested reader is referred to earlier works for further details[58]We need aramazd's reserves paper here. Both solar and wind can be curtailed in order to balance the grid in the real-time. In this work, the renewable energy delivered (D) (to the electric grid) is the sum of the curtailed wind and solar generation as *endogeneous* results of the SCED (2.3) and SCUC (2.2) models.

$$D(t) = \sum_{\mathcal{V}=1}^{N_{\mathcal{V}}}(1 - w_{\mathcal{V}t}d_{\mathcal{V}})P_{\mathcal{V}}(t) + \sum_{\mathcal{W}=1}^{N_{\mathcal{W}}}(1 - w_{\mathcal{W}t}d_{\mathcal{W}})P_{\mathcal{W}}(t) \tag{39}$$

Equation 39 represents the total renewable energy delivered in (MW) at each minute time-step t.

2.5.4. E: Electrical Energy for Water Supply System

The electrical energy consumed by the water supply system (E) is a fraction $d_{\mathcal{L}w}$ of the total electricity demand, and is consequently an exogeneous quantity drawn from input temporal profile data. This portion of the demand acts as a virtual power plant and can be incentivized downwards as part of the demand response scheme integrated into the SCUC and SCED models above.

$$E(t) = \sum_{\mathcal{L}w=1}^{N_{\mathcal{L}w}} (1 - w_{\mathcal{L}wt} d_{\mathcal{L}w}) P_{\mathcal{L}w}(t) \tag{40}$$

The final electrical energy consumed by the water supply system in MW is shown in Equation 40 as the curtailed amount of water supply electricity demand. AMRO HAS REVISED BLUETEXT.

2.5.5. F: Thermal Energy for Water Desalination

No multi-stage flash desalination units were included in this study. Why NOT?

2.5.6. G: Electrical Energy for Wastewater Management System

Similar to flow E, the electrical energy delivered to the wastewater management system (G) is an exogeneous input to the EPECS simulator and can be incentivized downwards as part of the demand response scheme integrated into the SCUC and SCED models above.

$$G(t) = \sum_{\mathcal{L}ww=1}^{N_{\mathcal{L}ww}} (1 - w_{\mathcal{L}wwt} d_{\mathcal{L}ww}) P_{\mathcal{L}ww}(t) \tag{41}$$

The final electrical energy consumed by the wastewater management system is shown in Equation 41 as the curtailed wastewater management electricity demand in MW.

2.5.7. H: Electrical Energy for End Use

The electrical energy delivered for end use (H) is calculated as the total demand minus the electrical demand for the water supply and wastewater management systems as shown in Equation 42.

$$H(t) = \sum_{\mathcal{L}=1}^{N_{\mathcal{L}}} P_{\mathcal{L}}(t) - G(t) - E(t) \tag{42}$$

2.5.8. I: Electrical Losses

The DC power flow analysis model described in Section **??** assumes zero electrical losses.

2.5.9. J: Thermal Losses

The thermal losses J_k of a given power plant k shown in Equation 43 includes all the heat lost to cooling and flue gases. It is calculated from input fuel flow net the work for the electrical energy generation.

$$J_k(t) = \frac{C_k(t) D_{fk}}{60} - P_k(t) \tag{43}$$

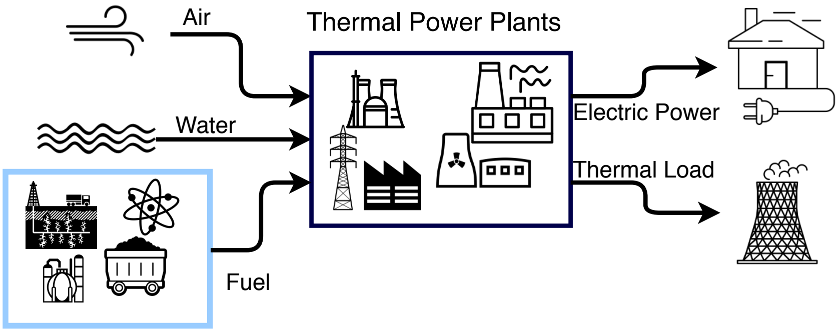

Figure 3: Input/Output model for thermal power plants.

2.5.10. A: Portable Water Withdrawal for Electricity Supply System

To study the portable water withdrawal for thermal power plants, this work adopts the system-level generic model (S-GEM) introduced in [64]. The S-GEM was developed to study the water use of fossil fuel, nuclear, geothermal and solar thermal power plants using either steam or combined cycle technologies. The S-GEM model captures the essential physics of cooling processes while minimizing the number of required input parameters and computational complexity. The model is also geography and case-independent; making it ideal for application in this work. Three main cooling processes are applied in this paper: once-through cooling, wet tower cooling and dry-air cooling.

2.5.10.1 Once-Through Cooling Systems

Figure 4 represents a once through cooling system. Once through cooling, also known as open-loop cooling, draws cool water from a water body, passes it through a heat exchanger to cool the thermal load Q_{Tkt} and returns the warm water back to the same water body. Although this system is simple and has a low cost, it withdraws large quantities of water from the surface environment which may endanger acquatic life through entrainment. It also discharges waste-heat and anti-corrosion, scaling, and bio-fouling chemicals back to the water source[?]. Evaporative losses through these cooling systems are often negligible and are, therefore, assumed to be zero. Due to its potentially harmful ecological impacts, once-through cooling systems are less popular for newer generation plants. That said, a lot of older coal, oil and nuclear plants generation still use once-through cooling to dissipate their waste heat.

$$Q_{Tk}(t) = J_k(t)(1 - \eta_{k,other}) \tag{44}$$

$$M_w(t) = \frac{60 Q_{Tk}(t)}{c_{p,w} \Delta T_{cond}} = 60 J_k(t)(1 - \eta_{k,other}) \frac{1}{c_{p,w} \Delta T_{cond}} \tag{45}$$

Equation 44 represents the thermal load Q_{Tkt} for a generator k at time t that requires cooling, where $\eta_{k,other}$ represents the fraction of the thermal load J_{kt} that is lost through other means (e.g. flue gases). Equation 45 shows the mass flow rate of water in kg/min from the water body where $c_{p,w}$ is the specific heat capacity of water in $MJ/kg \cdot K$ while ΔT_{cond} is the temperature difference between the cooling water and the process hot water.

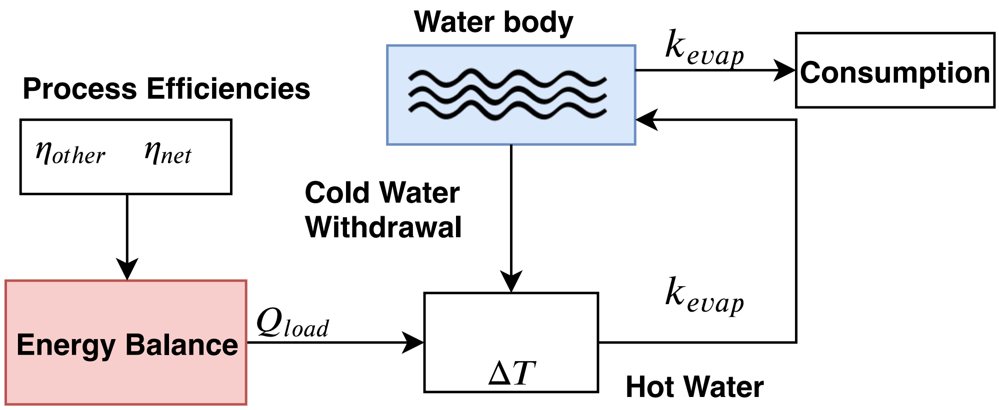

Figure 4: Once-through cooling system.

2.5.10.2 Recirculating Wet Tower Cooling Systems

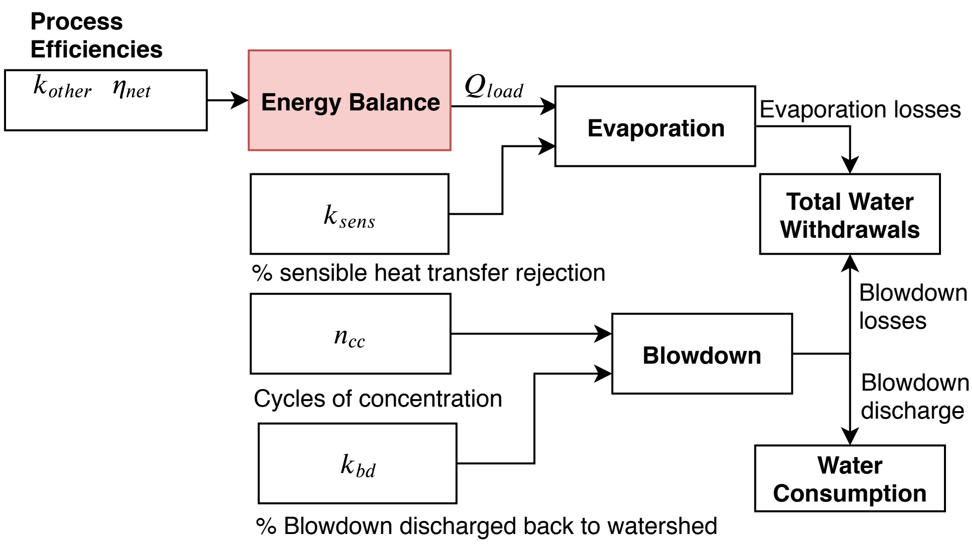

Figure 5: Wet tower cooling also known as a recirculating cooling system.

Figure 5 depicts a recirculating wet tower cooling system. A recirculating loop of cooling water is sent through the system. After cooling water passes through the waste heat exchanger, the now warm water is sprayed down through a lattice-like fill material which increases the surface area through which the water must flow down in the cooling tower. As the warm water is sprayed down through the fill, a fan or natural draft draws in air from the bottom of the tower up through the fill and out to the environment. The water and air flow through the tower serves as a heat exchanger to cool the water down before it is recirculated back in the system.

The bulk of the heat is lost through convective heat transfer from the hot water to the air. k_{sens} represents the fraction of heat lost through sensible heat transfer between air and water. It largely depends on the temperature of the incoming air and less so on other factors such as humidity and atmospheric pressure. In addition to sensible heat transfer, some of the water evaporates and the latent heat of this evaporation process results in further cooling. A bulk of water consumption in a recirculating cooling system is mainly due to evaporation from the cooling tower Please reference the IPPC cooling system BAT doc in this section.

Additionally, a small percentage of blowdown water is occasionally flushed out of the system to avoid any build up of contaminants. The blowdown may be consumed through evaporation or treated and sent back to the natural surface water system. This study assumes that the entire blowdown is treated and sent back to the natural environment. Recirculating systems do not withdraw nearly as much water as once-through systems. However, a significant amount of water is consumed through evaporation.

Given the recirculating nature of this type of cooling system, the total water withdrawal for a recirculating system is assumed to equal the amount of water lost through evaporation and blowdown. Figure 5 best illustrates the process flows for recirculating systems.

$$\dot{M}_{evap,k}(t) = 60Q_{Tk}(t)\frac{(1-k_{sens,t})}{h_{fg}} \tag{46}$$

The rate of water loss, kg/min, through evaporation is computed as shown in Equation 46 where k_{sens} is the energy fraction transferred from the hot water to the cool air while h_{fg} is the latent heat of vaporization in units of MJ/kg.

$$\dot{M}_{bd,k}(t) = \dot{M}_{evap,k}(t)\left(\frac{1}{n_{cc}-1}\right) \tag{47}$$

The rate of blowdown is represented by Equation 47. Note that the blowdown rate is related to the rate of evaporation $\dot{M}_{evap}$ and the cycles of concentration n_{cc}. n_{cc} is a parameter that describes the concentration of impurities in the water circulating through the cooling system relative to that of the makeup water. Typical n_{cc} values used for North American systems range between 2 and 10 cycles of concentration. In this study, an average n_{cc} value of 6 was used.

$$\dot{M}_{wrecirc}(t) = 60Q_{Tk}(t)\left(\frac{1-k_{sens}}{h_{fg}}\right)\left(1+\frac{1}{n_{cc}-1}\right) \tag{48}$$

The rate of water lost in kg/min from the cooling tower can be found by combining equations 43, 46, and 47 as shown in Equation 48.

2.5.10.3 Dry Air Cooling Systems

Dry air cooling systems reject waste heat by releasing it directly into the atmosphere without any water withdrawals or consumption. Given the lack of water withdrawal and consumption, the water footprint of dry cooling was set to zero in this study. Dry cooling systems require large heat exchangers making them significantly more expensive than recirculating cooling systems. Additionally, their efficiency depends greatly on ambient air temperatures and makes them less suitable during hot days when electricity demand is often at its highest. You should know that the SHAMS-1 concentrated solar power plant which was the largest in the world in 2015, was built 100km inland in the desert from

Abu Dhabi with an air cooling system. This design was chosen to minimize water losses but sacrificed efficiency of the steam cycle.

2.5.11. K: Evaporative Losses

2.5.11.1 Once-Through System

In once-through cooling systems, the fraction of water consumed downstream through evaporation, k_{evap} is considered negligible. Consequently, the total water consumption for once-through cooling systems is set to zero.

2.5.11.2 Recirculating System

Water consumed by recirculating cooling systems is expressed as follows:

$$K_k(t) = 60Q_{Tk}(t)\left(\frac{1-k_{sens}}{h_{fg}}\right)\left(1+\frac{1-k_{bd}}{n_{cc}-1}\right) \tag{49}$$

where k_{bd} represents the fraction of the blowdown that is treated and sent back to the water source. In this study, it is assumed that all of the blowdown is treated and returned to the watershed. Therefore, Equation 49 becomes:

$$K_k(t) = C_k(t)\left(\frac{1-\eta_k-\eta_{other}}{D_{fk}}\right)\left(\frac{1-k_{sens}}{h_{fg}}\right) \tag{50}$$

2.5.12. B: Non-Portable Water Withdrawal for Electrical Supply System

Although it presents a significant opportunity for developing energy-water nexus synergies[?], this study assumes that none of the water withdrawals are from non-potable water sources.

3. A Case Study: The RTS-96 GMLC Test Case

The enterprise control methodology summarized in sections 2.2-2.5 has been tested and validated on slight modifications of the IEEE RTS-96 test case[58, 59] originally presented in [65]. In this paper, a more recent version of the IEEE Reliability Test System (RTS-96) called the Reliability Test System Grid Modernization Laboratory Consortium (RTS-GMLC) was be used to test and validate our methodology. The original IEEE RTS-96 comprised 3 control areas, 73 buses, 99 generators and an 8550MW peak load. The new modernized RTS-GMLC includes wind, utility PV, rooftop PV, and hydro generation profiles. This test case also evolves the generation mix to reflect current grid generation mixes. For example, some of the oil and coal units are replaced with combined-cycle natural gas units both to minimize emissions and to support a high penetration of solar and winds.

3.1. Overview

In this paper, the water infrastructure is studied based on the amount of flexibility it can provide the electricity supply system. The novelty of the enterprise control methodology is in its accurate determination of operating reserves such as regulation, load-following and ramping reserves. Flexible control of water resources such as run-of-river

Parameter	Values	Units
k_{os} others	20	%
k_{os} nuclear	0	%
k_{os} combined cycle	12	%
n_{cc}	6	-
$c_{p,w}$	4.142	MJ/kg· K
h_{fg}	2.54	MJ/kg
ρ_w	0.998	kg/m^3
Δ_T	10	°K
k_{bd}	0	%
k_{evap}	0	%

Table 1: Table of parameters values.

Resource Type	Cost	Units
Natural gas	3.8872	$/MMBTU
Oil	10.3494	$/MMBTU
Coal	2.1139	$/MMBTU
Nuclear	0.8104	$/MMBTU
Curtailable load	50	$/MW
Curtailable Hydro	2.5	$/MW
Curtailable Wind	0	$/MW
Curtailable Solar	1	$/MW
Active Demand Response	50	$/MW
Storage	0	$/MWh

Table 2: Table of fuel, curtailment, active demand response and storage costs.

hydro, conventional hydro, water and wastewater treatment facilities is considered. For any given variable profile (could be hydro, solar, or wind), the ability to curtail the resource is analyzed. Two scenarios are considered. In the first case, water and wastewater treatment facilities can provide demand response while run-of-river and conventional hydro resources are treated as curtailable resources, that is, they provide load-following and ramping reserves through curtailment. In the second case, all water resources are considered inflexible. That is, run-of-river and conventional hydro are not curtailable, and water and wastewater treatment facilities cannot provide demand response. Based on the simulation results for the year, the amount of thermal generation is calculated and the resulting water withdrawals, and consumption is obtained. Additionally, the model can also estimate the amount of fuel used and subsequently the CO_2 emissions.

3.1.1. Power and water resources

The RTSGMLC consists of 73 buses, 73 thermal generators, 20 hydro generating units, 56 solar units, 4 wind generators, 1 storage unit, supplying a peak load of 7979.5MW. Water resources considered in the study include all hydroelectric power plants as well as the electricity demand profile of water and wastewater treatment facilities. The load profile of water and wastewater treatment facilities was taken to be a fraction of the load profile eligible for curtailment and active demand response. The thermal generators were split between the two cooling systems: once-through and recirculating cooling systems. Table 1 represents the assumed constants used in the calculation of water withdrawals and consumption as well as the total fuel consumed.

3.1.2. Heating Rate curves

Heating curves for thermal generators are used to compute the fixed, linear and quadratic costs for generating electricity. These heating rate curves are later used to compute the fuel consumption and thermal load of thermal

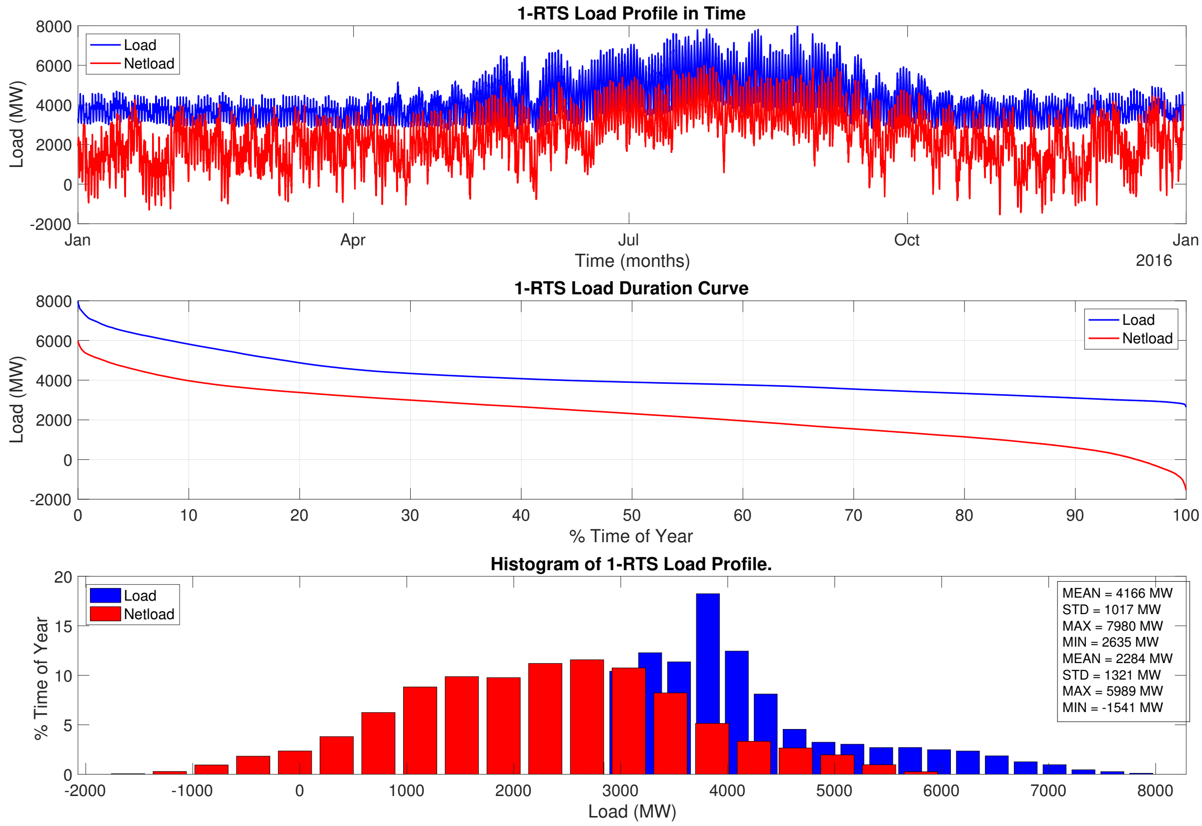

Figure 6: Load and net Load profile for RTS-GMLC.

generating units. Table 2 provides the assumed fuel cost of all the resources used in this study.

3.1.3. Time profiles

Real-time and day-ahead time profiles for solar, wind, load and hydro generating facilities are also provided. These profiles are used to compute the day-ahead and real-time forecasts which are then used as inputs to the optimization programs. As stated in Section **??**, variable energy resources are analyzed based on the implementation introduced in [56]. Given the actual generation profile and expected errors, the day-ahead and real-time forecasts are computed.

Figure 6 represents the net load distribution used in the RTS-GMLC test case. The first subplot represents the load profile in blue and the net load profile in red. Notice that in periods of low demand in the Spring and Fall months, the net load is very low and in some case less below zero MW. Negative net load represents cases when the generation exceeds the demand. Due to high amounts of variable renewable generation, the histogram of the net load in sub-figure 3 is shifted further to the left and is less than is negative for x% of the time.

4. Results

4.1. Load-Following Reserves

Upward and downward load-following reserves are procured in the day-ahead market (SCUC). These reserves are then used in the real-time market to balance any variability in the net load. In this study, wind, solar and dispatchable generators contribute towards load-following reserves in the conventional case. While in the flexible case run-of-river and conventional hydro also contribute towards load-following reserves. Both downward and upward load-following reserves are equally important to ensure reliable operation in a system with high amounts of variable renewable energy. Therefore, it is important that neither the upward or downward load-following reserves are depleted. Figure 7 shows a histogram of the load-following profile for both the conventional and flexible cases. From Figure 7, it is clear that flexible water resources greatly improve both upward and downward load-following reserves.

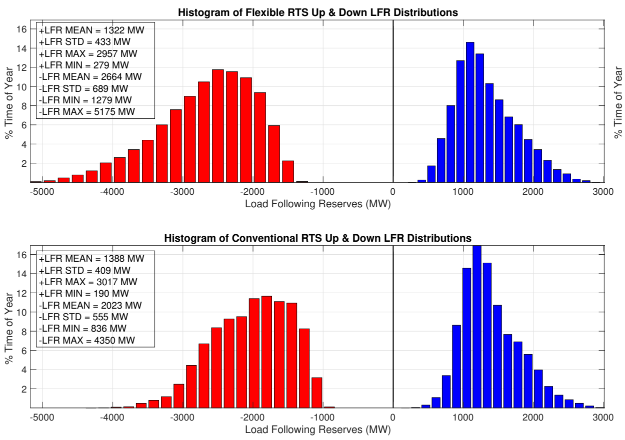

Figure 7: Histogram of load-following reserves for RTS-GMLC

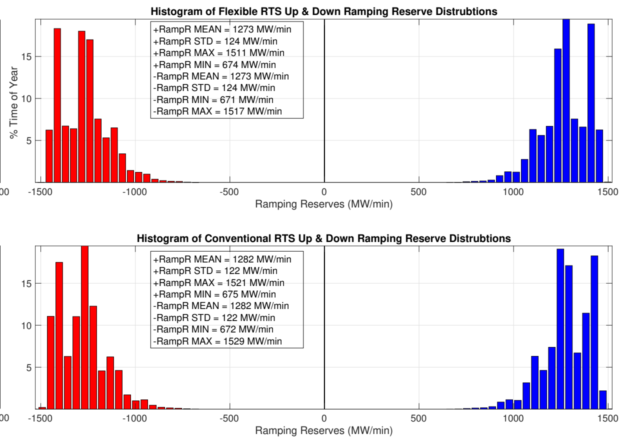

Figure 8: Histogram of ramping reserves for RTS-GMLC

4.2. Ramping Reserves

Similar to load-following reserves, upward and downward ramping reserves are also procured in the day-ahead market and used in the real-time market to balance variability in the net load.

4.3. Regulation

4.4. Curtailment

4.5. Water Withdrawals and Consumption

4.6. Production Costs

5. Conclusion

References

[1] J. Rogers, K. Averyt, S. Clemmer, M. Davis, F. Flores-Lopez, D. Kenney, J. Macknick, N. Madden, J. Meldrum, S. Sattler, and E. Spanger-Siegfried, "Water-Smart Power: Strengthening the U.S. Electricity System in a Warming World," Union for Concerned Scientists, Cambridge,

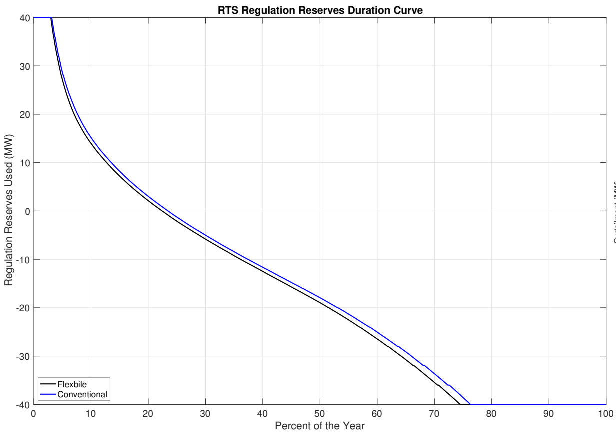

Figure 9: Regulation Reserves Duration Curve for RTS-GMLC

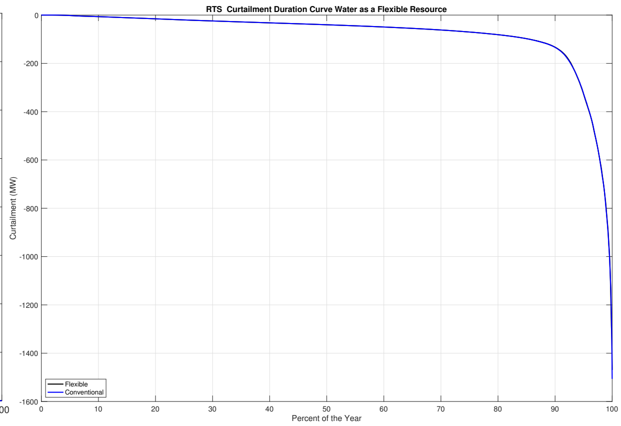

Figure 10: Curtailment Duration Curve for RTS-GMLC

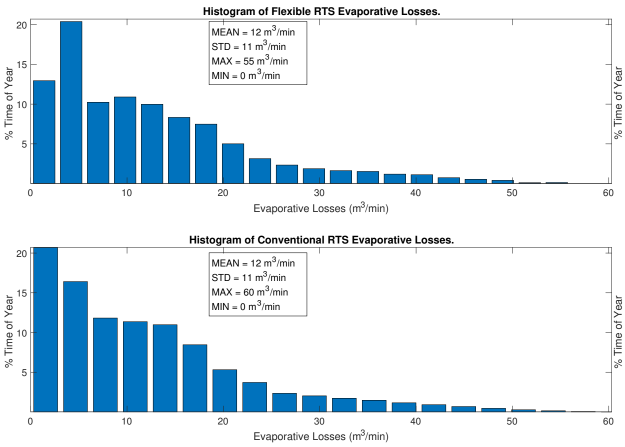

Figure 11: Histogram of evaporative losses.

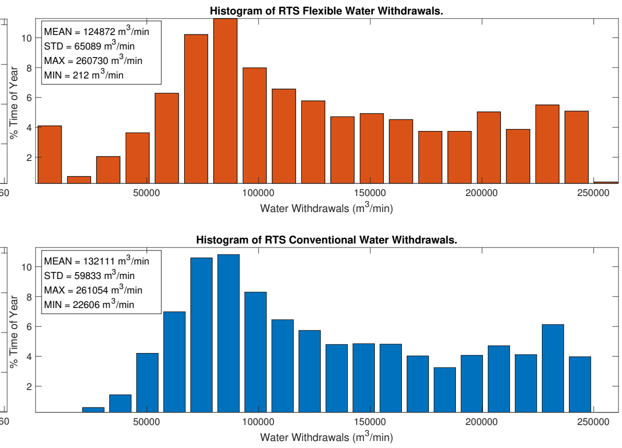

Figure 12: Histogram of water withdrawals.

MA, Tech. Rep., 2013.

[2] T. Kanyerere, S. Tramberend, A. D. Levine, P. Mokoena, P. Mensah, W. Chingombe, J. Goldin, S. Fatima, and M. Prakash, "Water futures and solutions: Options to enhance water security in sub-saharan africa," in *Systems Analysis Approach for Complex Global Challenges*. Springer, 2018, pp. 93–111.

[3] K. Averyt, J. Macknick, J. Rogers, N. Madden, J. Fisher, J. Meldrum, and R. Newmark, "Water use for electricity in the united states: an analysis of reported and calculated water use information for 2008," *Environmental Research Letters*, vol. 8, no. 1, p. 015001, Jan 2013.

[4] R. S. Dodder, J. T. Barnwell, and W. H. Yelverton, "Scenarios for low carbon and low water electric power plant operations: Implications for upstream water use," *Environmental science & technology*, vol. 50, no. 21, pp. 11 460–11 470, 2016.

[5] N. R. Armstrong, R. C. Shallcross, K. Ogden, S. Snyder, A. Achilli, and E. L. Armstrong, "Challenges and opportunities at the nexus of energy, water, and food: A perspective from the southwest united states," *MRS Energy & Sustainability*, vol. 5, 2018.

[6] IEA, "Key world energy statistics," Tech. Rep., September 2017.

[7] K. T. Sanders, M. F. Blackhurst, C. W. King, and M. E. Webber, "The impact of water use fees on dispatching and water requirements for water-cooled power plants in texas," *Environ. Sci. Technol.*, vol. 48, no. 12, p. 140602120931006, Jun 2014.

[8] F. Y. Al-Aboosia and M. M. El-Halwagia, "An integrated approach to water-energy nexus in shale-gas production," *Processes*, vol. 6, p. 52, 2018.

[9] J. R. Dierauer, D. M. Allen, and P. H. Whitfield, "Exploring future water demand and climate change impacts on water availability in the peace region of british columbia, canada," in *The Water-Energy-Food Nexus*. Springer, 2018, pp. 45–54.

[10] A. Al-Douri, D. Sengupta, and M. El-Halwagi, "Shale gas monetization - a review of downstream processing to chemicals and fuels," *Journal of Natural Gas Science and Engineering*, 2017. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S1875510017302299

[11] A. Kiaghadi, R. S. Sobel, and H. S. Rifai, "Modeling geothermal energy efficiency from abandoned oil and gas wells to desalinate produced water," *Desalination*, vol. 414, pp. 51 – 62, 2017. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S001191641631757X

[12] K. Nichols, J. Sawyer, J. Bruening, B. Halldorson, K. Madhavan *et al.*, "Development of a Large Scale Water Recycling Program for the Delaware Basin, New Mexico," in *SPE Health, Safety, Security, Environment, & Social Responsibility Conference-North America*. Society of Petroleum Engineers, 2017, pp. 1–12.

[13] Y. Chang, R. Huang, R. J. Ries, and E. Masanet, "Life-cycle comparison of greenhouse gas emissions and water consumption for coal and shale gas fired power generation in China," *Energy*, vol. 86, no. 0, pp. 335–343, 2015. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0360544215004880

[14] A. Siddiqi, A. Kajenthira, and L. D. Anadon, "Bridging decision networks for integrated water and energy planning," *Energy Strategy Reviews*, vol. 2, no. 1, pp. 46 – 58, 2013, agricultural sector;Boundary spanning;Integrated resources;Inter-organizational network;International donors;Reuse of wastewater;Strategic objectives;Water-energy nexus;. [Online]. Available: http://dx.doi.org/10.1016/j.esr.2013.02.003

[15] Z. Zhang, X. Feng, and F. Qian, "Studies on resilience of water networks," *Chemical Engineering Journal*, vol. 147, no. 2-3, pp. 117–121, 2009. [Online]. Available: http://dx.doi.org/10.1016/j.cej.2008.06.026

[16] C. Baranowski, "Climate resilience evaluation and awareness tool BT ," in *Water Quality Technology Conference and Exposition 2010, November 14, 2010 - November 18, 2010*, ser. Water Quality Technology Conference and Exposition 2010. Savannah, GA, United states: American Water Works Association, 2010, pp. 1167–1181.

[17] R. Banos, J. Reca, J. Martinez, C. Gil, and A. L. Marquez, "Resilience Indexes for Water Distribution Network Design: A Performance Analysis Under Demand Uncertainty," *Water Resources Management*, vol. 25, no. 10, pp. 2351–2366, 2011. [Online]. Available: http://dx.doi.org/10.1007/s11269-011-9812-3

[18] T. Asefa, J. Clayton, A. Adams, and D. Anderson, "Performance evaluation of a water resources system under varying climatic conditions: Reliability, Resilience, Vulnerability and beyond," *Journal of Hydrology*, vol. 508, pp. 53–65, 2014. [Online]. Available: http://dx.doi.org/10.1016/j.jhydrol.2013.10.043

[19] F. Arreguin-Sanchez, "Measuring resilience in aquatic trophic networks from supply-demand-of-energy relationships," *Ecological Modelling*, vol. 272, pp. 271–276, 2014. [Online]. Available: http://dx.doi.org/10.1016/j.ecolmodel.2013.10.018

[20] M. R. Altaweel, L. N. Alessa, and A. D. Kliskey, "Forecasting Resilience in arctic societies: Creating tools for assessing social-hydrological systems," *Journal of the American Water Resources Association*, vol. 45, no. 6, pp. 1379–1389, 2009. [Online]. Available: http://dx.doi.org/10.1111/j.1752-1688.2009.00370.x

[21] A. R. Farhan and S. Lim, "Resilience assessment on coastline changes and urban settlements: A case study in Seribu Islands, Indonesia," *Ocean and Coastal Management*, vol. 54, no. 5, pp. 391–400, 2011. [Online]. Available: http://dx.doi.org/10.1016/j.ocecoaman.2010.12.003

[22] E. B. Connelly, J. Akanji, M. E. Goodsite, M. Kodack, K. D. Mikkelsen, K. M. Stoughton, and J. H. Lambert, "Advances in the net-zero paradigm and resilience of net-zero strategic plans for water systems," in *Green Defense Technology*. Springer, 2017, ch. 10, pp. 171–218.

[23] M. Al-Saidi and A. Hefny, "Institutional arrangements for beneficial regional cooperation on water, energy and food priority issues in the eastern nile basin," *Journal of Hydrology*, 2018.

[24] J. Meldrum, S. Nettles-Anderson, G. Heath, and J. Macknick, "Life cycle water use for electricity generation: a review and harmonization of literature estimates," *Environmental Research Letters*, vol. 8, no. 1, p. 015031, Mar 2013.

[25] K. Burnett and C. A. Wada, "Accounting for externalities in the water energy food nexus," in *The Water-Energy-Food Nexus*. Springer, 2018, pp. 261–272.

[26] A. Eren, "Transformation of the water-energy nexus in turkey: re-imagining hydroelectricity infrastructure," *Energy Research & Social Science*, 2018.

[27] J. J. Gurdak, "The water-energy-food nexus and california's sustainable groundwater management act," in *The Water-Energy-Food Nexus*. Springer, 2018, pp. 145–155.

[28] P. Gleick, "Impacts of California's Five-Year (2012-2016) Drought on Hydroelectricity Generation," Pacific Institute, Oakland, California, Tech. Rep., 2017.

[29] S. Pincetl, R. Graham, S. Murphy, and D. Sivaraman, "Analysis of high-resolution utility data for understanding energy use in urban systems: The case of los angeles, california," *Journal of Industrial Ecology*, 2015.

[30] A. Escriva-Bou, J. R. Lund, and M. Pulido-Velazquez, "Optimal residential water conservation strategies considering related energy in california," *Water Resources Research*, vol. 51, no. 6, pp. 4482–4498, 2015. [Online]. Available: http://dx.doi.org/10.1002/2014WR016821

[31] GEI Consultants, "California's water-energy nexus pathways to implementation," Water-Energy Team of the Governor's Climate Action Team, Tech. Rep., 2012.

[32] K. E. Haynes and T. D. Georgianna, "Risk assessment of water allocation and pollution treatment policies in a regional economy: reliability, vulnerability and resiliency in the Yellowstone Basin of Montana," *Computers, Environment and Urban Systems*, vol. 13, no. 2, pp. 75–94, 1989. [Online]. Available: http://dx.doi.org/10.1016/0198-9715(89)90036-7

[33] Y. E. Mahgary and E. Tamminen, "Relevant methods for planning and optimization of power and water production systems of the Gulf countries BT - Proceedings of DESAL '92 Arabian Gulf Regional Water Desalination Symposium, November 15, 1992 - November 17, 1992," *Desalination*, vol. 92, no. 1-3, pp. 149–170, 1993. [Online]. Available: http://dx.doi.org/10.1016/0011-9164(93)80079-3

[34] K. T. M. Formiga, F. H. Chaudhry, P. B. Cheung, and F. R. Luisa, "Optimal design of water distribution system by multiobjective evolutionary methods," in *Evolutionary Multi-Criterion Optimization*. Berlin, Germany: Springer Berlin Heidelberg, 2003, pp. 677–691.

[35] A. Diniz and M. Maceira, "A four-dimensional model of hydro generation for the short-term hydrothermal dispatch problem considering head and spillage effects," *IEEE Trans. Power Syst.*, vol. 23, no. 3, pp. 1298–1308, Aug 2008.

[36] J. Macknick, R. Newmark, G. Heath, and K. C. Hallett, "Operational water consumption and withdrawal factors for electricity generating technologies: a review of existing literature," *Environmental Research Letters*, vol. 7, no. 4, p. 045802, Dec 2012.

[37] J. Macknick, S. Sattler, K. Averyt, S. Clemmer, and J. Rogers, "The water implications of generating electricity: water use across the united states based on different electricity pathways through 2050," *Environmental Research Letters*, vol. 7, no. 4, p. 045803, Dec 2012.

[38] K. Averyt, J. Fisher, A. Huber-Lee, A. Lewis, J. Macknick, N. Madden, J. Rogers, and S. Tellinghuisen, "Freshwater use by us power plants: Electricity's thirst for a precious resource," Union of Concerned Scientists, Cambridge, MA, USA, Tech. Rep., 2011.

[39] S. A. Bagloee, M. Asadi, and M. Patriksson, "Minimization of water pumps' electricity usage: a hybrid approach of regression models with optimization," *Expert Systems with Applications*, 2018.

[40] A. M. Bagirov, A. Barton, H. Mala-Jetmarova, A. Al Nuaimat, S. Ahmed, N. Sultanova, and J. Yearwood, "An algorithm for minimization of pumping costs in water distribution systems using a novel approach to pump scheduling," *Mathematical and Computer Modelling*, vol. 57, no. 3-4, pp. 873–886, 2013.

[41] B. Ulanicki, J. Kahler, and H. See, "Dynamic optimization approach for solving an optimal scheduling problem in water distribution systems," *Journal of Water Resources Planning and Management*, vol. 133, no. 1, pp. 23–32, 2007.

[42] M. López-Ibáñez, T. D. Prasad, and B. Paechter, "Ant colony optimization for optimal control of pumps in water distribution networks," *Journal of Water Resources Planning and Management*, vol. 134, no. 4, pp. 337–346, 2008.

[43] Z. Ghelichi, J. Tajik, and M. S. Pishvaee, "A novel robust optimization approach for an integrated municipal water distribution system design under uncertainty: A case study of mashhad," *Computers & Chemical Engineering*, vol. 110, pp. 13–34, 2018.

[44] R. Menke, E. Abraham, P. Parpas, and I. Stoianov, "Exploring optimal pump scheduling in water distribution networks with branch and bound methods," *Water Resources Management*, vol. 30, no. 14, pp. 5333–5349, 2016.

[45] W. N. Lubega and A. M. Farid, "A Reference System Architecture for the Energy-Water Nexus," *IEEE Systems Journal*, vol. PP, no. 99, pp. 1–11, 2014. [Online]. Available: http://dx.doi.org/10.1109/JSYST.2014.2302031

[46] H. Abdulla and A. M. Farid, "Extending the energy-water nexus reference architecture to the sustainable development of agriculture, industry & commerce," in *First IEEE International Smart Cities Conference*, Guadalajara, Mexico, 2015, pp. 1–7. [Online]. Available:

http://dx.doi.org/10.1109/ISC2.2015.7366166
[47] W. N. Lubega and A. M. Farid, "Quantitative Engineering Systems Model and Analysis of the Energy-Water Nexus," *Applied Energy*, vol. 135, no. 1, pp. 142–157, 2014. [Online]. Available: http://dx.doi.org/10.1016/j.apenergy.2014.07.101
[48] A. Santhosh, A. M. Farid, and K. Youcef-Toumi, "Optimal Network Flow for the Supply Side of the Energy-Water Nexus," in *2013 IEEE International Workshop on Intelligent Energy Systems*, Vienna, Austria, 2013, pp. 1–6. [Online]. Available: http://dx.doi.org.libproxy.mit.edu/10.1109/IWIES.2013.6698578
[49] A. Santhosh, A. M. Farid, A. Adegbege, and K. Youcef-Toumi, "Simultaneous Co-optimization for the Economic Dispatch of Power and Water Networks," in *The 9th IET International Conference on Advances in Power System Control, Operation and Management*, Hong Kong, China, 2012, pp. 1–6. [Online]. Available: http://dx.doi.org/10.1049/cp.2012.2148
[50] W. Hickman, A. Muzhikyan, and A. M. Farid, "The Synergistic Role of Renewable Energy Integration into the Unit Commitment of the Energy Water Nexus," *Renewable Energy*, vol. 108, pp. 220–229, 2017. [Online]. Available: https://dx.doi.org/10.1016/j.renene.2017.02.063
[51] C. Diaz, F. Ruiz, and D. Patino, "Modeling and control of water booster pressure systems as flexible loads for demand response," *Applied Energy*, vol. 204, pp. 106–116, 2017.
[52] S. Takahashi, H. Koibuchi, and S. Adachi, "Water supply operation and scheduling system with electric power demand response function," *Procedia Engineering*, vol. 186, pp. 327–332, 2017.
[53] R. Menke, E. Abraham, P. Parpas, and I. Stoianov, "Extending the envelope of demand response provision though variable speed pumps," *Procedia Engineering*, vol. 186, pp. 584–591, 2017.
[54] ——, "Demonstrating demand response from water distribution system through pump scheduling," *Applied Energy*, vol. 170, pp. 377–387, 2016.
[55] A. M. Farid, B. Jiang, A. Muzhikyan, and K. Youcef-Toumi, "The Need for Holistic Enterprise Control Assessment Methods for the Future Electricity Grid," *Renewable & Sustainable Energy Reviews*, vol. 56, no. 1, pp. 669–685, 2015. [Online]. Available: http://dx.doi.org/10.1016/j.rser.2015.11.007
[56] A. Muzhikyan, A. M. Farid, and K. Youcef-Toumi, "An Enhanced Method for Determination of the Ramping Reserves," in *IEEE American Control Conference*, Los Angeles, CA, USA, 2015, pp. 1–8. [Online]. Available: http://dx.doi.org/10.1109/ACC.2015.7170863
[57] ——, "An Enhanced Method for Determination of the Regulation Reserves," in *IEEE American Control Conference*, Los Angeles, CA, USA, 2015, pp. 1–8. [Online]. Available: http://dx.doi.org/10.1109/ACC.2015.7170866
[58] ——, "An Enterprise Control Assessment Method for Variable Energy Resource Induced Power System Imbalances Part 1: Methodology," *IEEE Transactions on Industrial Electronics*, vol. 62, no. 4, pp. 2448–2458, 2015. [Online]. Available: http://dx.doi.org/10.1109/TIE.2015.2395391
[59] ——, "An Enterprise Control Assessment Method for Variable Energy Resource Induced Power System Imbalances Part 2: Results," *IEEE Transactions on Industrial Electronics*, vol. 62, no. 4, pp. 2459 – 2467, 2015. [Online]. Available: http://dx.doi.org/10.1109/TIE.2015.2395380
[60] ——, "Relative Merits of Load Following Reserves and Energy Storage Market Integration Towards Power System Imbalances," *International Journal of Electrical Power and Energy Systems*, vol. 74, no. 1, pp. 222–229, 2016. [Online]. Available: http://dx.doi.org/10.1016/j.ijepes.2015.07.013
[61] ——, "An A Priori Analytical Method for Determination of Operating Reserves Requirements," *International Journal of Energy and Power Systems*, vol. 86, no. 3, pp. 1–11, 2016. [Online]. Available: http://dx.doi.org/10.1016/j.ijepes.2016.09.005
[62] A. M. Farid, "2017 iso new england system operational analysis and renewable energy integration study (soares): Study methodology," in *ISO New England Planning Advisory Committee*, Westborough, MA, 2017.
[63] ——, "2017 iso new england system operational analysis and renewable energy integration study (soares): Scenario results," in *ISO New England Planning Advisory Committee*, Westborough, MA, 2017.
[64] M. J. Rutberg, A. Delgado, H. J. Herzog, and A. F. Ghoniem, "A system-level generic model of water use at power plants and its application to regional water use estimation," in *ASME 2011 International Mechanical Engineering Congress and Exposition*. American Society of

Mechanical Engineers, 2011, pp. 513–523.

[65] C. Grigg, P. Wong, P. Albrecht, R. Allan, M. Bhavaraju, R. Billinton, Q. Chen, C. Fong, S. Haddad, S. Kuruganty, W. Li, R. Mukerji, D. Patton, N. Rau, D. Reppen, A. Schneider, M. Shahidehpour, and C. Singh, "The IEEE Reliability Test System-1996. A report prepared by the Reliability Test System Task Force of the Application of Probability Methods Subcommittee," *Power Systems, IEEE Transactions on*, vol. 14, no. 3, pp. 1010–1020, 1999.