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The impact of storage facility capacity and ramping capabilities on the supply side economic dispatch of the energy–water nexus

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ABSTRACT

Clean energy and water are two essential resources that any society must securely deliver in order to develop sustainably. Recently, the energy and water infrastructure value chains have gained attention as a single interlinked system of global concern called the energy–water nexus. In light of these couplings, energy and water, as two valuable resources require co-optimization. Recently, one such simultaneous co-optimization method has been contributed for the economic dispatch of networks that include water, power and co-production facilities. This paper builds upon this foundation with the introduction of plant ramping behavior. Furthermore, it investigates the impact of electrical energy and water storage as a technology that can help to alleviate binding constraints and lead to more flat production and reduced cost levels. Three cases studies are presented; a base case, a second case inspired by Singapore's limited water storage availability, and a third case relevant to countries in the Middle East where water storage facilities can be readily constructed. Storage facilities are shown to reduce total operating costs by up to 38% and lead to less variable daily production suggesting that they have an important role to play in the optimization of the energy–water nexus.

1. Introduction

1.1. Motivation

Clean energy and water are two essential resources that any society must securely deliver in order to develop sustainably; i.e. meet its economic, social and environmental goals [1,2]. In the case of energy, the overuse of conventional resources has raised concerns over global climate change, smog and acid rain collectively [3]. Similarly, water use has grown substantially in recent years; tracking strongly with energy use and economic development and leading to depleted water tables in many geographic regions [4]. And yet, these two essential resources are intrinsically linked in that the production, distribution and consumption of one often requires the other [5]. This interlinked meta-system is often called the energy–water nexus and is defined here as:

Definition 1. *Energy–water nexus* [6–9]: *A system-of-systems composed of one infrastructure system with the artifacts necessary to describe a full energy value chain and another infrastructure system with the artifacts necessary to describe a full water value chain.*

1.2. Scope

Recently, the energy–water nexus has gained attention as a single interlinked system from policy, systems engineering and technical perspectives. While some works have developed holistic engineering system models [6–8], the primary focus of the literature has been to analyze and design for the individual energy–water couplings summarized in Table 1. The greatest attention has been given to the cross-interactions of energy supply to water demand or vice versa. Many empirical methods have attempted to quantitatively assess the water consumption requirements of thermal power generation facilities [10]. For example, in the United States, the condensers found in the Rankine cycle of thermal cogeneration plants account for 49% of the country's natural water resource consumption [11]. Similarly, energy management has become an important concern for utilities that use electrical pumping energy to deliver water for residential, industrial and irrigational purposes [12,13]. On the demand side, the residential,

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Nomenclature

σ_v	water level of the vth water storage plant
A_{ck}	quadratic prod. cost function coeff. of kth power plant
A_{pi}	quadratic prod. cost function coeff. of ith power plant
A_{wj}	quadratic prod. cost function coeff. of jth water plant
B_{ck}	linear production cost function coeff. of kth power plant
B_{pi}	linear production cost function coeff. of ith power plant
B_{wj}	linear production cost function coeff. of jth water plant
C_G	production cost function
C_{ck}	cost function for kth coproduction plant
C_{pi}	cost function for ith power generation plant
C_{wj}	cost function for jth water production plant
n_σ	number of water storage plants
n_c	number of coproduction plants
n_p	number of power generation plants
n_s	number of electrical energy storage plants
n_w	number of water production plants
r_k^{lower}	lower bound of kth coproduction ratio
r_k^{upper}	upper bound of kth coproduction ratio
S_u	state of electrical charge of the uth energy storage plant
$x_{\sigma v}$	Water released by vth water storage plant
K_{ck}	constant prod. cost function coeff. of kth power plant
K_{pi}	constant prod. cost function coeff. of ith power plant
K_{wj}	constant prod. cost function coeff. of jth water plant
D_p	electrical power demand
D_w	water demand
$\mathrm{maxDRRCP}_k$	max. power down ramp of kth coproduction plant
$\mathrm{maxDRRCW}_k$	max. water down ramp of kth coproduction plant
$\mathrm{maxDRRP}_i$	max. down ramp of the ith power plant
$\mathrm{maxDRRW}_j$	max. down ramp of the jth water plant
$\mathrm{maxGen}\sigma_v$	max. capacity limit of the vth water storage plant
$\mathrm{maxGenC}_k$	max. capacity limit of the kth coproduction plant
$\mathrm{maxGenP}_i$	max. capacity limit of the ith power plant
$\mathrm{maxGenS}_u$	max. capacity limit of the uth energy storage plant
$\mathrm{maxGenW}_j$	max. capacity limit of the jth water plant
$\mathrm{maxStore}\sigma_v$	max. storage limit of the vth water storage plant
$\mathrm{maxStoreS}_u$	max. storage limit of the uth energy storage plant
$\mathrm{maxURRCP}_k$	max. power up ramp of the kth coproduction plant
$\mathrm{maxURRCW}_k$	max. water up ramp of the kth coproduction plant
$\mathrm{maxURRP}_i$	max. up ramp of the ith power plant
$\mathrm{maxURRW}_j$	max. up ramp of the jth water plant
$\mathrm{minGen}\sigma_v$	min. capacity limit of the vth water storage plant
$\mathrm{minGenC}_k$	min. capacity limit of the kth coproduction plant
$\mathrm{minGenP}_i$	min. capacity limit of the ith power plant
$\mathrm{minGenS}_u$	min. capacity limit of the uth energy storage plant
$\mathrm{minGenW}_j$	min. capacity limit of the jth water plant
$\mathrm{minStore}\sigma_v$	min. storage limit of the vth water storage plant
$\mathrm{minStoreS}_u$	min. storage limit of the uth energy storage plant
x_{cpk}	power generated at the kth coproduction plant
x_{cwk}	water produced at kth coproduction plant
x_{pi}	power generated at the ith power plant
x_{su}	power discharged by uth electric energy storage plant
x_{wj}	water produced at the jth water plant

commercial, and industrial use of electric heating and cooling for water consumption presents a major coupling [13].

This paper restricts its scope to the real-time economic dispatch of the supply-side of the engineered electricity and water systems. This includes the couplings manifested by the operations management of hydroelectric and thermal desalination facilities. Hydro-electric facilities have a hydro-power production function that ties the output power to the spillage [14–17]. Meanwhile, thermal desalination facilities require a steam balance that couples the heat by-product of power generation to the production of potable water [18–20].

1.3. Relevance

The optimization of the supply side coupling is of greatest interest in the GCC (Gulf Cooperation Council) countries. The hot and arid climates found in the GCC cause a heavy reliance on desalination technology to alleviate the scarcity of potable ground water. The additional reliance on climate-controlled buildings further exacerbates power dispatch with sharp peak loads. Fortunately, most GCC nations operate their water and power utilities within a single organization and therefore the optimization program presented in this work is of direct industrial applicability [21]. Similar combined water and power utilities may be found in other regions of the world. Furthermore, the presence of a co-optimization program can highlight potential efficiencies if separated power and water utilities were to coordinate their activities. The ultimate goal of the optimization program presented in this work would be the development of an integrated energy–water market not unlike deregulated energy markets found in European and North American nations.

Table 1
Supply & demand side energy–water nexus couplings.

	Power supply	Power demand
Water supply	Co-generation • Thermal desalination • Hydroelectric	• Pumped water • Water distribution • Wastewater recycling
Water demand	Thermal-power generation facilities	Residential, commercial, & industrial use of electric heating & cooling of water

1.4. Contribution

This paper builds upon previous work in which supply-side energy–water nexus couplings were optimized in the operations time scale. The first works developed an optimization program for the simultaneous economic dispatch of systems that consist of power generation, co-production, and potable water production plants [22,23]. There, it was found that the presence of co-production facilities introduce not only the typical capacity limits but also process constraints on the ratio of power to water produced. This formulation, however, did not address recent trends in renewable energy integration which have motivated the need for fast ramping power generation facilities and energy storage [24–29]. In light of this trend, the simultaneous economic co-dispatch was further developed to include ramping constraints and storage facilities [22,30]. This paper utilizes this optimization program to study three cases: a base case, a case inspired by Singapore's limited water storage availability, and a third relevant to Middle East Countries where storage facilities can be readily constructed.