The Impact of Storage Facility Capacity and Ramping Capabilities on the Supply Side Economic Dispatch of the Energy-Water Nexus

Apoorva Santhosh, Amro M. Farid, Kamal Youcef-Toumi

Abstract

Clean energy and water are two essential resource 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. Futhemore, it investigates the impact of electrical energy and water storage as a technology that can help 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.

NOMENCLATURE

σ_v	Water level of the v^{th} water storage plant
A_{ck}	Quadratic prod. cost function coeff. of k^{th} power plant
A_{pi}	Quadratic prod. cost function coeff. of i^{th} power plant
A_{wj}	Quadratic prod. cost function coeff. of j^{th} water plant
B_{ck}	Linear production cost function coeff. of k^{th} power plant
B_{pi}	Linear production cost function coeff. of i^{th} power plant
B_{wj}	Linear production cost function coeff. of j^{th} water plant
C_G	Production cost function
C_{ck}	Cost function for k^{th} coproduction plant
C_{pi}	Cost function for i^{th} power generation plant
C_{wj}	Cost function for j^{th} 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 k^{th} coproduction ratio
r_k^{upper}	Upper bound of k^{th} coproduction ratio
S_u	State of electrical charge of the u^{th} energy storage plant

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$x_{\sigma v}$ Water released by v^{th} water storage plant
$\mathcal{K}_{ck}$ Constant prod. cost function coeff. of k^{th} power plant
$\mathcal{K}_{pi}$ Constant prod. cost function coeff. of i^{th} power plant
$\mathcal{K}_{wj}$ Constant prod. cost function coeff. of j^{th} water plant
D_p Electrical power demand
D_w Water demand
$\mathrm{maxDRRCP}_k$ Max. power down ramp of k^{th} coproduction plant
$\mathrm{maxDRRCW}_k$ Max. water down ramp of k^{th} coproduction plant
$\mathrm{maxDRRP}_i$ Max. down ramp of the i^{th} power plant
$\mathrm{maxDRRW}_j$ Max. down ramp of the j^{th} water plant
$\mathrm{maxGen}_{\sigma v}$ Max. capacity limit of the v^{th} water storage plant
$\mathrm{maxGenC}_k$ Max. capacity limit of the k^{th} coproduction plant
$\mathrm{maxGenP}_i$ Max. capacity limit of the i^{th} power plant
$\mathrm{maxGenS}_u$ Max. capacity limit of the u^{th} energy storage plant
$\mathrm{maxGenW}_j$ Max. capacity limit of the j^{th} water plant
$\mathrm{maxStore}\sigma_v$ Max. storage limit of the v^{th} water storage plant
$\mathrm{maxStoreS}_u$ Max. storage limit of the u^{th} energy storage plant
$\mathrm{maxURRCP}_k$ Max. power up ramp of the k^{th} coproduction plant
$\mathrm{maxURRCW}_k$ Max. water up ramp of the k^{th} coproduction plant
$\mathrm{maxURRP}_i$ Max. up ramp of the i^{th} power plant
$\mathrm{maxURRW}_j$ Max. up ramp of the j^{th} water plant
$\mathrm{minGen}_{\sigma v}$ Min. capacity limit of the v^{th} water storage plant
$\mathrm{minGenC}_k$ Min. capacity limit of the k^{th} coproduction plant
$\mathrm{minGenP}_i$ Min. capacity limit of the i^{th} power plant
$\mathrm{minGenS}_u$ Min. capacity limit of the u^{th} energy storage plant
$\mathrm{minGenW}_j$ Min. capacity limit of the j^{th} water plant
$\mathrm{minStore}\sigma_v$ Min. storage limit of the v^{th} water storage plant
$\mathrm{minStoreS}_u$ Min. storage limit of the u^{th} energy storage plant
x_{cpk} Power generated at the k^{th} coproduction plant
x_{cwk} Water produced at k^{th} coproduction plant
x_{pi} Power generated at the i^{th} power plant
x_{su} Power discharged by u^{th} electric energy storage plant
x_{wj} Water produced at the j^{th} water plant

I. INTRODUCTION

A. 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.

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

TABLE I
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

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].

C. Relevance

The optimization of the supply side coupling is of greatest interest in the Gulf Cooperation Council (GCC) 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.

D. 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.

E. Relevant Literature

The background literature to this work is drawn from a number of relevant sources: 1.) the co-dispatch of the dual products of combined heat & power 2.) the co-dispatch of power and water 3.) the dispatch of power and pumped water storage facilities and 4.) the mitigation of renewable energy variability with various types of energy storage systems. In regards to the first, the first work on dual-product dispatch arose from the need to extract two useful products in the form of power and heat from combined cycle facilities [31]–[34]. In regards to the second, comparatively greater attention has been given to hydroelectric facilities versus desalination facilities. One author, however, directly addresses the economic dispatch of a single specific desalination facility composed of a number of sub-units but neither generalizes the formulation nor applies it to all the water and production units in a combined water and power grid [35]. In contrast, a number of robust optimization methods have been recently applied to hydrothermal systems [14], [36]–[41], but they do not specifically include the potable water demand from the water utility. Variations of this work utilize the water reservoirs behind the hydroelectric facilities for pumped energy storage [14], [28], [29], [42], [43]. Finally, extensive attention has been devoted to the dispatch of energy storage systems in the presence of renewables [25]–[29], [44].

The remainder of the paper develops in five sections. Section II describes the modeling methodology for the formulation of the optimization program. Section III then explains the simulation methodology for the case studies in the following section. The paper concludes in Section V.

II. Modeling Methodology

This section describes the modeling methodology for the formulation of an optimization program to simultaneously dispatch power and water. Subsection II-A describe the system model. The remaining subsections recount the optimization program presented in [30] whose goal is to provide dispatch setpoints that individual facilities can use for single-plant target optimizations. Given the ultimate goal of an integrated energy-water market, the optimization program introduces symmetry between the electrical energy and water variables so as to maintain a level of complexity similar to that found in traditional deregulated electrical energy markets.

A. Conceptual Model

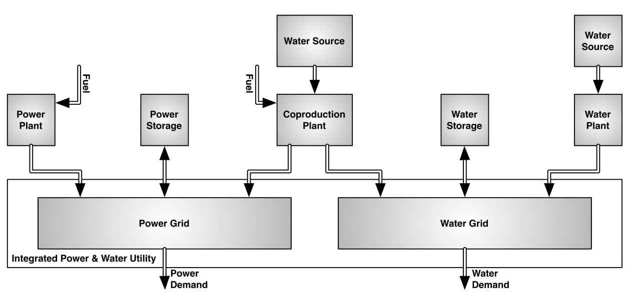

Fig. 1. Model for the Co-Dispatch of Power and Water Supply

Figure 1 provides a graphical representation of the conceptual model that serves as the basis for the development of the optimization program. It consists of an integrated power & water utility that is interested in simultaneously serving an electrical power demand as well as a potable water demand. The respective grids are modeled as single nodes. The utility dispatches power, electrical energy storage, water, water storage, and co-production facilities that may be independent or vertically integrated. The dispatchable power plant requires a fuel source. The co-production facility may be either hydroelectric or thermal desalination; requiring fuel in the latter case. They couple the respective grids by virtue of their production cost functions and their process constraints. The water plant may be a ground or surface pumping station or a reverse osmosis desalination plant. Each water and co-production facility is assumed to draw from its own independent water source. The model also applies to a single aggregate water source; as in the practical case of the Persian Gulf serving all desalination facilities in the U.A.E. Hydrologically speaking, the water sources are assumed to be able to support the maximum water flow capacities of the water production facilities that they serve. The electrical energy and water storage are assumed to draw and inject exclusively from their respective grids. The power and water demands are measured net of any power and water requirements to the dispatched facilities and are ultimately delivered to the utility's power and water customers.

B. Objective Function

The production cost function $C_G(t)$ is to be minimized with respect to the produced quantities of power and water over a over the discrete-time interval t = [1,. . . ,T].

$$\begin{aligned} min \sum_{t=1}^{T} C_G(X_{pi}(t), X_{wj}(t), X_{ck}(t)) = \sum_{t=1}^{T} \\ \left[\sum_{i=1}^{n_p} C_{pi}(X_{pi}(t)) + \sum_{j=1}^{n_w} C_w(X_{wj}(t)) + \sum_{k=1}^{n_c} C_{ck}(X_{ck}(t)) \right] \end{aligned} \tag{1}$$

Here, the individual production quantities are organized into two-vectors to address the two products simultaneously. X_{pi} = [x_{pi},0]^T, X_{wj} =[0, x_{wj}]^T, X_{ck} =[x_{cpk} , x_{cwk}]^T, X_{su} =[x_{su} ,0]^T, $X_{\sigma v} = [0, x_{\sigma v}]^T$. The objective function must consider the cost function of each time block simultaneously because the electrical and water storage facilities couple them together. Each storage facility either has a state of charge or water level state that will depend on each time block's respective injection or withdrawal of electricity or water. In this regard, this optimization program strongly resembles the "look-ahead dispatch" models implemented in some North American real-time power markets [45].

The cost functions C_{pi} , C_{wj} , C_{ck} are assumed to exhibit a quadratic structure in their respective production variables.

$$\begin{aligned} C_{pi} &= X_{pi}^T A_{pi} X_{pi} + B_{pi} X_{pi} + \mathcal{K}_{pi} \\ C_{wj} &= X_{wj}^T A_{wj} X_{wj} + B_{wj} X_{wj} + \mathcal{K}_{wj} \\ C_{ck} &= X_{ck}^T A_{ck} X_{ck} + B_{ck} X_{ck} + \mathcal{K}_{ck} \end{aligned} \tag{2}$$

The cost function coefficients are appropriately sized positive constant matrices based upon the heat rate characteristics of their respective production units.

C. Capacity Constraints

The objective function is minimized subject to minimum and maximum power and water flow capacity constraints of each of the facilities.

$$\begin{aligned} minGenP_i \leq X_{pi} \leq maxGenP_i \quad & \forall i = 1 \dots n_p \\ minGenW_i \leq X_{wj} \leq maxGenP_j \quad & \forall j = 1 \dots n_w \\ minGenC_k \leq X_{ck} \leq maxGenC_k \quad & \forall k = 1 \dots n_c \\ minGenS_u \leq X_{su} \leq maxGenS_u \quad & \forall u = 1 \dots n_s \\ minGen\sigma_v \leq X_{\sigma v} \leq maxGen\sigma_v \quad & \forall v = 1 \dots n_\sigma \end{aligned} \tag{3}$$

As is typically found in economic power dispatch problem, it is important to note that Equation 3 limits the *flow rate* capacity of power and water including for storage facilities. The maximal water flow rate capacities may be interpreted as the plant's upper production limit, or alternatively from a hydrological perspective as the plant's environmental license limit. As such, it may be viewed as a policy instrument for shifting hydrological impact from one water source to another.

D. Storage Limit Constraints

In contrast, the second group of constraints found in Equation 4 govern the minimum and maximum capacity on the *stock* of energy and water stored.

$$\begin{aligned} minStoreS_u \leq S_u(t) \leq maxStoreS_u \quad & \forall t, \forall u = 1 \dots n_s \\ minStore\sigma_v \leq \sigma_v(t) \leq maxStore\sigma_v \quad & \forall t, \forall v = 1 \dots n_\sigma \end{aligned} \tag{4}$$

E. Power & Water Demand Constraints

The next constraint shown in Equation 5 shows the power and water demand constraint that includes the terms from the two types of storage facilities.

$$\forall t = 1 \dots T \ D(t) = \sum_{i=1}^{n_p} X_{pi}(t) + \sum_{j=1}^{n_w} X_{wj}(t) + \sum_{k=1}^{n_c} X_{ck}(t) + \sum_{u=1}^{n_s} X_{su}(t) + \sum_{v=1}^{n_\sigma} X_{\sigma v}(t) \quad (5)$$

where $D(t) = [D_p(t), D_w(t)]$. Here, the power and water demands are aggregated to reflect the entirety of the utility's customer base.

F. Co-Production Process Constraints

Equation 6 represents a process constraint for coproduction facilities.

$$r_k^{lower} \leq \frac{x_{cpk}}{x_{cwk}} \leq r_k^{upper} \quad \forall k = 1 \dots n_{cp} \quad (6)$$

Here, the process constraints do not model the physical flows of power and water for cogeneration facilities, as this would be intractable for all facilities. Instead, they represent the reasonable limits of safe operation of the co-production process. Such an approach lends itself to market implementation as it encapsulates process-specific details from the public and allows individual facilities to optimize their own processes to the market dispatch setpoints as targets.

G. Ramping Constraints

Equation 7 represents the ramping constraints of the three types of production facilities.

$$\begin{aligned} &\forall i = 1 \dots n_{pp} \\ &\begin{bmatrix} -maxDRRP_i \\ 0 \end{bmatrix} \leq X_{pi}(t) - X_{pi}(t-1) \leq \begin{bmatrix} maxURRP_i \\ 0 \end{bmatrix} \\ &\forall j = 1 ... n_{wp} \\ &\begin{bmatrix} 0] \\ -maxDRRW_j \end{bmatrix} \leq X_{wj}(t) - X_{wj}(t-1) \leq \begin{bmatrix} 0 \\ maxURRW_j \end{bmatrix} \\ &\forall j = 1 ... n_{cp} \\ &\begin{bmatrix} -maxDRRCP_k \\ -maxDRRCW_k \end{bmatrix} \leq X_{ck}(t) - X_{ck}(t-1) \leq \begin{bmatrix} maxURRCP_k \\ maxURRCW_k \end{bmatrix} \end{aligned} \quad (7)$$

As mentioned in Subsection II-B, the ramping constraints serve to couple the optimization time block and give preference to facilities that can ramp easily to meet demand variability.

H. Storage Continuity Relations

Equation 8 captures the power and water storage facility continuity relations as constraints.

$$\begin{aligned} S_u(t) &= S_u(t-1) - X_{su}(t) \quad \forall t, \forall u = 1 ... n_s \\ \sigma_v(t) &= \sigma_v(t-1) - X_{\sigma v}(t) \quad \forall t, \forall v = 1 ... n_\sigma \end{aligned} \quad (8)$$

As in the ramping constraints, these storage continuity relations also couple the dispatch of the optimization time blocks.

I. Initial Conditions

Finally, the initial conditions of the two types of storage facilities are taken as constraints in Equation 9.

$$\begin{aligned} S_u(t) &= 0 \quad \forall u = 1 ... n_s \\ \sigma_v(t) &= 0 \quad \forall v = 1 ... n_\sigma \end{aligned} \quad (9)$$

These may be adjusted over multiple days or seasons to reflect the need for medium-term and long term water management goals.

TABLE II
PLANT AND COST DATA [23], [30]

Plant Type	Index	Max Power Capacity (MW)	Max Water Capacity (m^3/hr)	Min Power Capacity (MW)	Min Water Capacity (m^3/hr)	Max Power Up Ramp Rate (MW/hr)	Max Power Down Ramp Rate (MW/hr)	Minimum Water Up Ramp Rate (m^3/hr^2)	Minimum Water Down Ramp Rate (m^3/hr^2)
Power	i_1	500	0	0	0	200	100	0	0
Power	i_2	400	0	0	0	200	100	0	0
Power	i_3	400	0	0	0	200	100	0	0
Power	i_4	350	0	0	0	200	100	0	0
Coproducts	k_1	800	200	160	30	200	100	100	100
Coproducts	k_2	600	150	120	23	200	100	50	50
Coproducts	k_3	400	100	80	15	200	100	50	50
Water	j_1	0	250	0	0	0	0	50	50

Power Plant Cost Coefficients

A_p	B_p	C_p
2.069e-4	-1.483e-1	5.711e+1
3.232e-4	-1.854e-1	5.711e+1
1.065e-3	-6.026e-1	1.268e+2
4.222e-4	-2.119e-1	5.711e+1

Water Plant Cost Coefficients

A_w	B_w	C_w
1.816e-2	-7.081	7.374

Coproduction Plant Cost Coefficients

A_{c11}	A_{c12}	A_{c22}	B_{c1}	B_{c2}	C_c
4.433e-4	3.546e-3	7.093e-3	-1.106	-4.426	7.374e+2
7.881e-4	6.305e-3	1.261e-2	-1.475	-5.901	7.374e+2
1.773e-3	1.419e-2	2.837e-2	-2.213	-8.851	7.374e+2

J. Discussion of Optimization Model

The optimization model as presented may be classified as a nonlinear mathematical program subject to smooth monotonic constraints. With the exception of the process constraints, these constraints are linear. Therefore, this mathematical program is a practical candidate for existing off-the-shelf nonlinear optimization engines and has a high potential for industrial implementation.

III. SIMULATION METHODOLOGY

The optimization program in the previous section was demonstrated on a hypothetical test case drawn from the literature [23], [30]. This data is selected for two reasons: 1.) The timing of power and water demand peaks and troughs is typical in the GCC. 2.) the range of the power and water demands is exaggerated to demonstrate the convergence capability of the selected optimization engine. The hypothetical test case is composed of 4 power plants, 3 co-production desalination facilities, and 1 reverse osmosis water plant. The associated plant and cost data is summarized in Table II. Table III includes 24 hours of power and water demand data. The scenario also includes three electrical energy and two water storage facilities. For the purposes of analyzing the impacts of storage quantities and charging rates, this paper varies the capacities and charging rates of these facilities according to the data found in Table IV.

This data facilitates the study of three test cases which demonstrate the effect of storage capacity and charging rate on this hypothetical system. The first "Base Case" has limited storage facilities and limited charging and discharging capability. This case serves to show the immediate effects gained from even a modest introduction of storage facilities. It also serves as the basis of comparison for the other two cases. The second case is inspired by Singapore where limited land mass has constrained the total availability of water storage [46]–[48]. Therefore, the case maintains limit storage capacity but large charging and discharging abilities; especially in the case of water storage. The final case is inspired the middle east where the ability to build storage facilities is relatively unconstrained. Therefore, large storage capacities and discharge rates were allowed.

Given the relatively well-behaved functional forms of the optimization program, it was sufficient to implement the optimization program with existing optimization engines for the numerical solution. The MATLAB and GAMS

TABLE III
POWER & WATER DEMAND DATA [23], [30]

Hour	Power Demand (MW)	Water Demand (m^3)
1	1250	150
2	1125	130
3	875	100
4	750	150
5	950	200
6	1440	350
7	1500	300
8	1750	200
9	2000	300
10	2250	400
11	2500	500
12	2750	600
13	2875	400
14	3250	400
15	2750	500
16	2500	550
17	2125	550
18	2375	500
19	2250	400
20	1975	350
21	1750	300
22	1625	250
23	1500	200
24	1376	150

TABLE IV
STORAGE CAPACITY AND CHARGING RATES

	$\mathbf{maxGenS}$ units(MW)	$\mathbf{maxGen}\sigma$ units(m3)	$\mathbf{maxStoreS}$ units (MW/hr)	$\mathbf{maxStore}\sigma$ units (m3/hr)
Base Case	1000.00 2500.00 2700.00	500.00 1000.00	200.00 300.00 400.00	25.00 25.00
Singapore Case	500.00 1250.00 1350.00	250.00 500.00	400.00 600.00 1000.00	200.00 200.00
Middle East Case	1000.00 2500.00 2700.00	500.00 1000.00	400.00 600.00 1000.00	200.00 200.00

languages were used together; the former for data handling and visualization and the latter for optimization. The in-built CONOPT solver was used. The code was executed on a Macbook Laptop with a 2.8 GHz Intel Core i7 processor in approximately 0.3 seconds.

IV. RESULTS

This section presents the results for three case studies: a base case of limited storage capacity and charging capability, a Singapore inspired case of limited storage capacity but large charging capability, and Middle East inspired case with large storage capacity and change capability. In each case, six figures are presented: (1) & (2) the electrical power and water dispatch, (3) the total production costs, (4) the coproduction power to water ratios, and (5) & (6) the electrical energy and water stored.

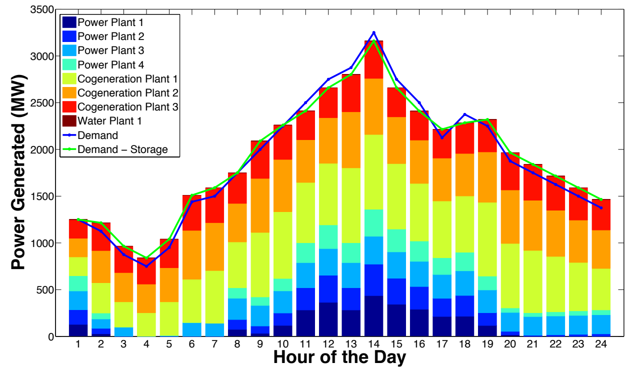

Fig. 2. Power Generation and Demand Profile Over 24 Hour Period

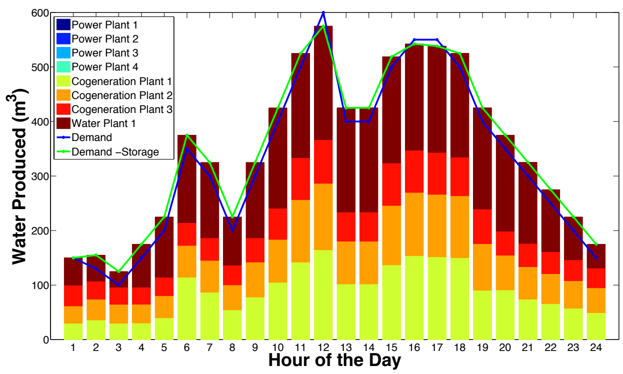

Fig. 3. Water Production and Demand Profile Over 24 Hour Period

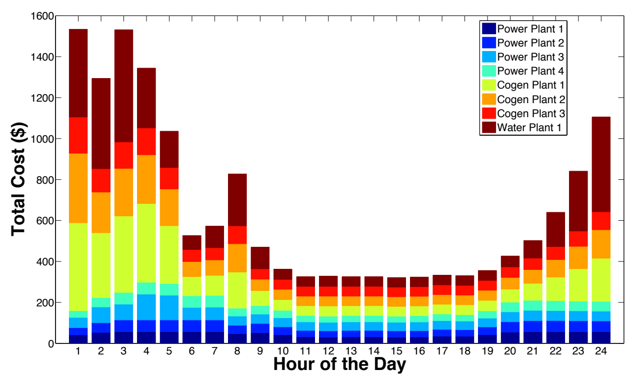

Fig. 4. Total Production Cost Over 24 Hour Period

A. Base Case - Limited Storage, Limited Ramping Abilities

Figures 2 and 3 show the power and water generation profiles over the 24 hours respectively. The optimization successfully completed in spite of a more than 4x variation in power demand over the course of the day. Such a demand profile represents more exaggerated optimization conditions than those commonly found in power demand profiles found in real life dispatch. Interestingly, the co-production facilities act as units of 'first-choice'. The single product power and water plants are essentially being used as peaking plants; coming into operation only to meet periods of high demand. In this sense, this work confirms the results found previously where ramp rates and storage facilities were not included [23]. The figures also show the modest quantities of energy and water storage as evidenced by the difference between the blue and green lines.

Figure 4 elucidates one cause of the cogeneration facilities being used as units of 'first-choice'. As a first observation, the total costs seem to be higher during periods of low demand. This atypical result originates from

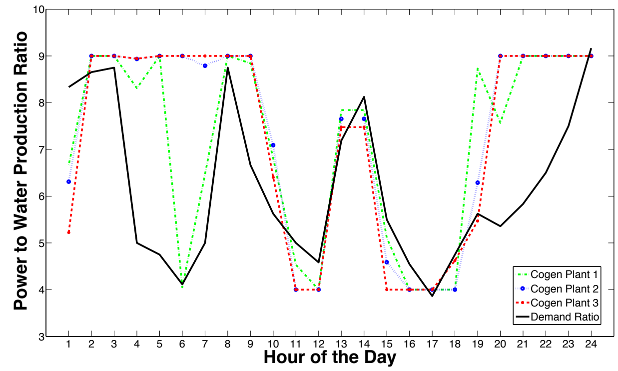

Fig. 5. Coproduction Power to Water Ratio Over 24 Hour Period

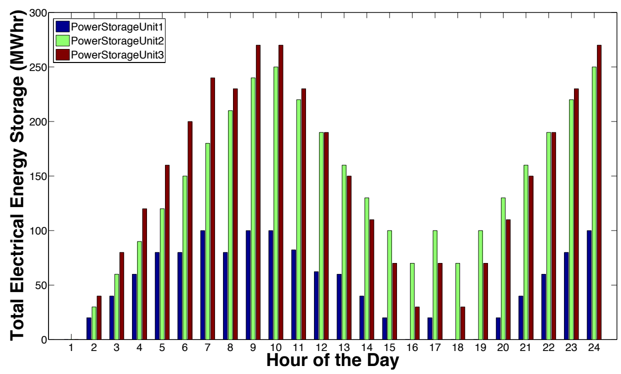

Fig. 6. Electrical Energy Storage Profile Over 24 Hour Period

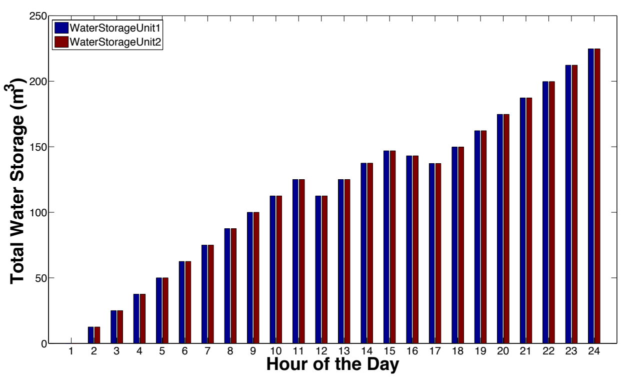

Fig. 7. Water Storage Profile Over 24 Hour Period

the fact that the cost curves used for the power, water and co-production facilities were strongly quadratic leading to significantly reduced per unit costs at near full capacities. Such a result may be found in real life with power generation fleets that rely exclusively on ‘base-load’ technologies like nuclear and coal power [49]. This strongly quadratic cost curve data is particularly noticeable in the coproduction facilities; causing them to be dispatched as close to full capacity as possible. The base case total costs amount to 15,981 dollars which is used for comparison in the next two cases.

Figure 5 further elucidates another cause that the cogeneration facilities are being used as units of ‘first-choice’. As the power to water demand ratio swings over the course of the day, the cogeneration facilities are not just incentivized to run as close to full capacity as possible but also are constrained by their product ratio process constraint of $4 \leq R \leq 9$ MW/m3. Provided that the cogeneration plants have sufficient capacity to meet this ratio, they track the ratio. Interestingly, storage facilities – especially as presented in this paper with zero costs in the objective function – help alleviate this need for tracking and allow for incrementally more flat production.

Finally, Figures 6 and 7 show the storage of electrical energy and water over the 24 hour period. As expected, the storage begins at the zero initial conditions, grows during periods of low demand and is subsequently used during periods of high demand. Overall, the quantities of energy and water storage grow over the course of the day given the incentives provided by the strongly quadratic cost curves. Nevertheless, the storage capacity and water do not seem to saturate; suggesting that the storage facility are more constrained by the net charging flow of water and electrical power, rather than the stock capacity.

B. Singapore Inspired Case - Limited Storage, Large Charging Abilities

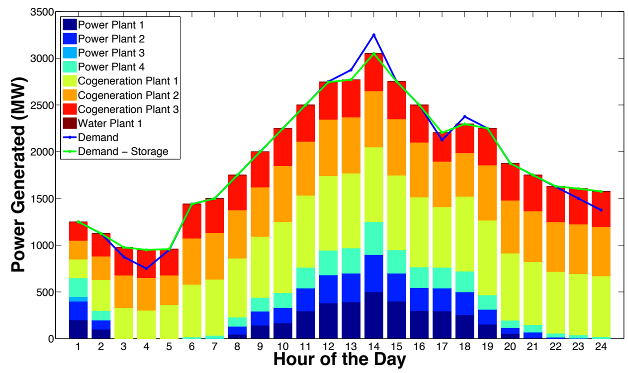

Fig. 8. Power Generation and Demand Profile Over 24 Hour Period

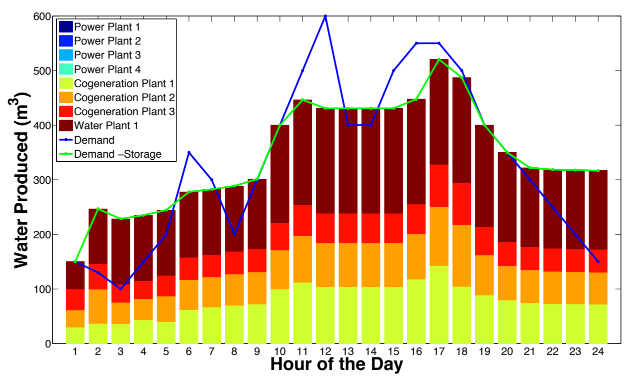

Fig. 9. Water Production and Demand Profile Over 24 Hour Period

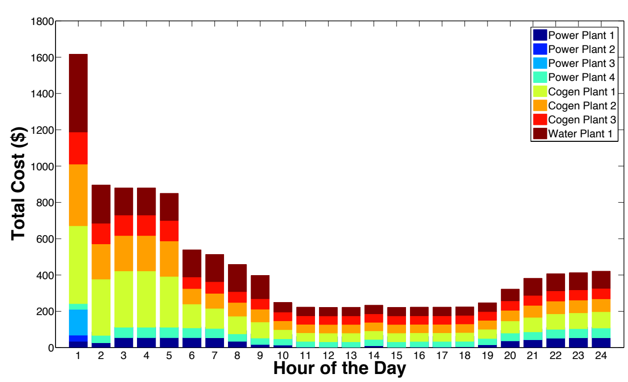

Fig. 10. Total Production Cost Over 24 Hour Period

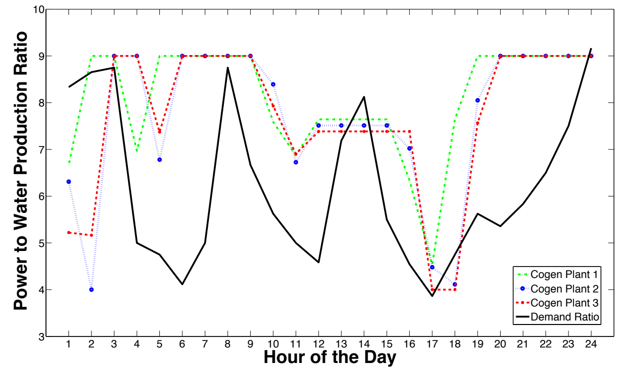

Fig. 11. Coproduction Power to Water Ratio Over 24 Hour Period

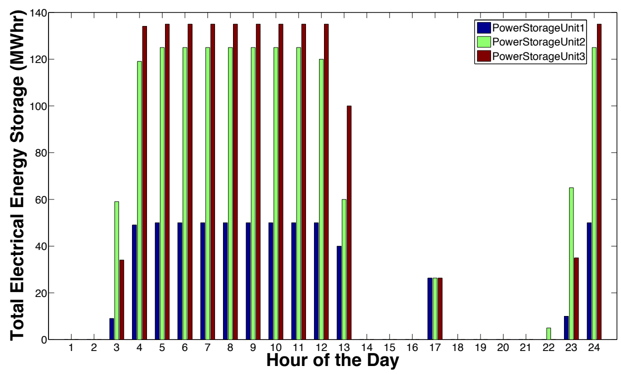

Fig. 12. Electrical Energy Storage Profile Over 24 Hour Period

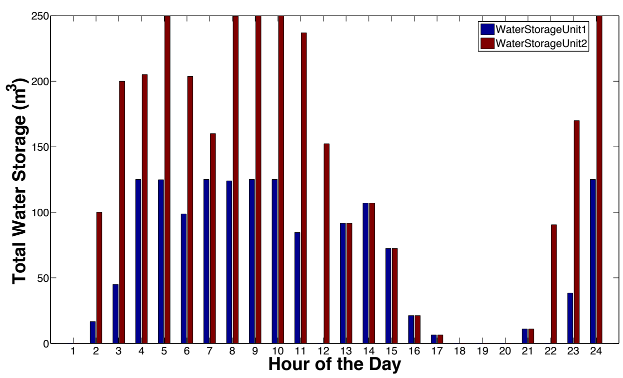

Fig. 13. Water Storage Profile Over 24 Hour Period

Singapore's water management challenges are well known [46]–[48]. As an island-nation with limited land mass, it has limited space for either natural water reserves or man-made water storage. It does, however, rely on water desalination and recycling. This case uses limited storage with high charging capabilities as is inspired by Singapore's situation.

To that effect, Figures 8 and 9 show the power and water production profile over 24 hours. While the power generation profiles shows energy storage quantities have remained relatively constant, the water production profiles shows a much more noticeable usage of water storage; as seen by the difference between the green and blue lines. In the base case, when storage capacity and charging capabilities of storage were limited, the production facilities were forced to meet the demand closely in each time period. This case demonstrates a more flat power generation profile in spite of the fact that storage is still relatively limited. Here the storage charging rates, or the constraints on the net power and water flows into the storage units have been increased sufficiently to permit their unimpeded utilization. Energy storage and water storage facilities charge during the morning hours and discharge during peak periods.

Figure 10 further demonstrates the value of the large charging rates on the storage units in terms of the cost of power and water production over the 24 hours. The total costs amount to $11,268; a 29.5% reduction over the base case. Much of the cost reduction occurs in the early morning and late night hours when the cogeneration facilities are particularly constrained. Therefore, the cost reductions can be attributed to the large charging rates on the storage facilities which allowed for more flat and efficient power and water production while simultaneously easing the strain on the over constrained cogeneration plants.

Interestingly, Figure 11 shows that electrical energy and water storage facilities have an additional benefit beyond simply peak demand shaving. They are able to alleviate the process constraints. In time periods of elevated power to water demand ratio, the electrical energy storage facilities can serve to complement the already strained process-limited co-production facilities. In time periods of low power to water demand ratio, the water storage facilities serve the same function.

The role of the large charging rates for the storage are further demonstrated in Figures 12 and 13 which show the energy and water storage over the 24 hour period. Here, morning storage and peak discharging behavior becomes apparent. Interestingly, the large charging rates now allow the power and water storage facilities to saturate during the morning hours; suggesting that the storage capacities are well utilized. The optimal solution also did not cause the end-of-day storage levels to return to the zero initial storage conditions. The cause of this behavior, again comes back to the shape of the cost curves which favor production as close to full capacity operation as possible. In principle, this implies that two days with similar profiles could potentially be subjected to very different "alleviation capability" by the storage facilities. Furthermore, the optimization program, as stated, does not exploit that natural cyclicity in daily demand. Perhaps an additional constraint on the equality of the initial and final conditions can be imposed, although operational considerations would ultimately affect the final choice of such parameters. As mentioned in Section II-I, such use of initial conditions can be applied in conjunction with optimization models that manage the medium and long-term use of the storage facilities.

C. Middle East Inspired Case - Large Storage, Large Charging Abilities

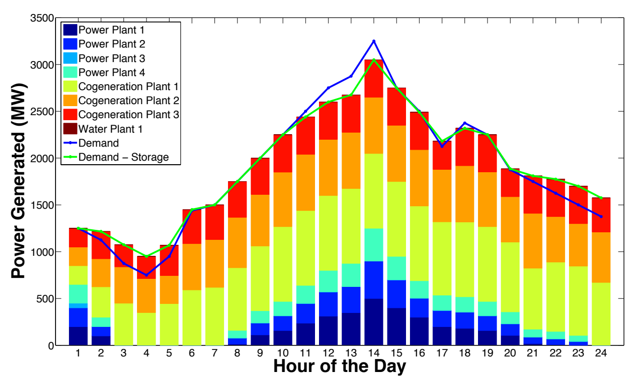

Fig. 14. Power Generation and Demand Profile Over 24 Hour Period

The Middle East, and especially countries within the Gulf Cooperation Council, have well known water scarcity challenges [50]. Fortunately, and contrary to the previous example, these countries typically have much open space in which to build water storage facilities. At the same time, GCC countries are investing heavily in solar energy [51] which introduce new dynamics to the power grid as variable energy resources [24]. Therefore, energy and water storage technologies present themselves as key enabling technologies for the successful management of the energy-water nexus. This case seeks to elucidate the full potential of energy and water technologies so as to direct itself towards this region.

To that effect, Figures 14 and 15 demonstrate the total power and water production over the next 24 hours. Here, the water storage capacity has been expanded significantly and disproportionately relative to the electrical energy storage. The observations made in the previous case are even more pronounced in this case. The water production is very strongly flattened over the course of the day.

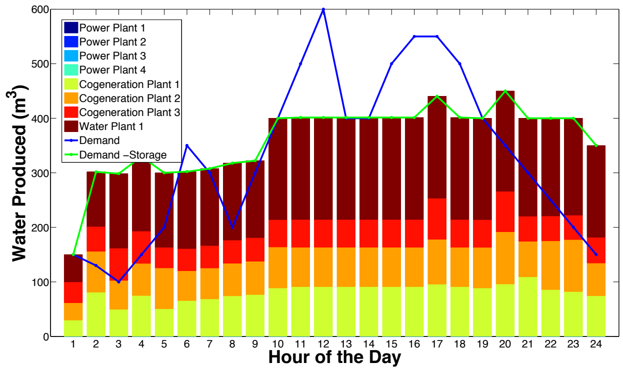

Fig. 15. Water Production and Demand Profile Over 24 Hour Period

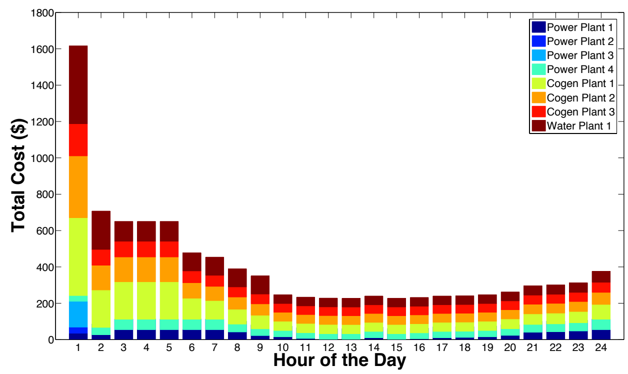

Fig. 16. Total Production Cost Over 24 Hour Period

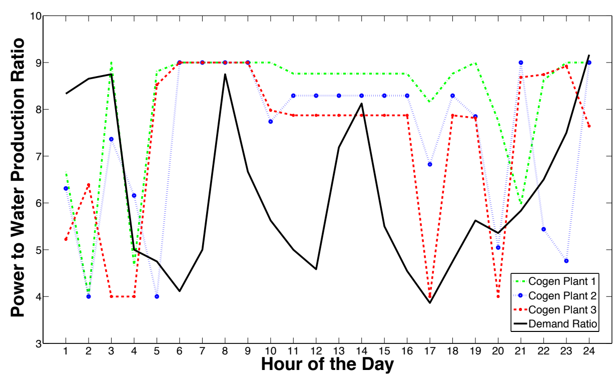

Fig. 17. Coproduction Power to Water Ratio Over 24 Hour Period

Figure 16 shows the associated costs of power and water production over the 24 hours. The availability of greater water storage leads to higher and more efficient production at periods of low water demand; thus bringing about greater cost efficiencies. In total, the production costs amount to $9861.5; a 12.5% reduction over the previous case and a 38.3% reduction over the base case.

Figure 17 shows a new operational challenge for the coproduction facilities as a result of the disproportionate increases in power and water storage capacities. While these facilities are no longer deeply constrained in terms of capacity and process constraints, the coproduction power to water ratios have to *ramp* significantly over the course of the day. Such ramps are most noticeable here between 16-18h and 19-21h. Thermodyanically speaking, this represents a massive change in the way the coproduction facilities are operated and likely are just as challenging as managing ramp events for single production facilities. This specific issue of cogeneration facility relative ramping rates has not be tackled specifically within this work but lends itself as a topic for further investigation.

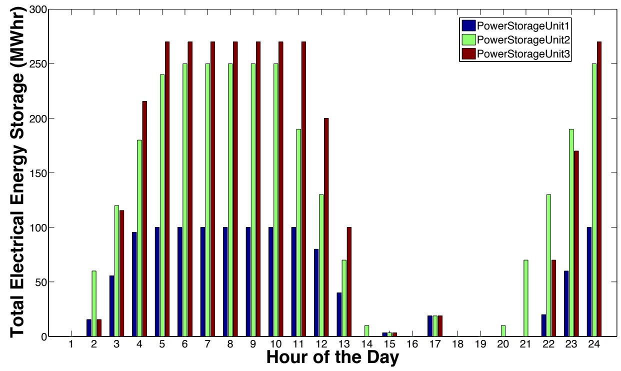

Fig. 18. Electrical Energy Storage Profile Over 24 Hour Period

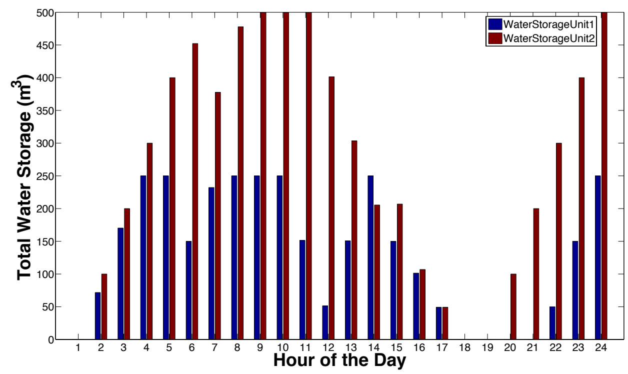

Fig. 19. Water Storage Profile Over 24 Hour Period

Finally, Figures 18 and 19 conclude the case study by demonstrating the energy and water storage profiles over the 24 hour period. Here, the expanded storage capacities in energy and water have lead to their greater utilization. Furthermore, relative to the previous case, the energy and water storage is less saturated; suggesting that their capacity limits are less binding.

V. Conclusions and Future Work

This work has analysed the impact of adding varying levels of storage to a co-optimization program for the simultaneous economic dispatch of water and power. It builds upon previous work [22], [23], [30] by introducing ramping constraints and storage facilities. The former reflects the limitations experienced by generation units in drastically increasing or decreasing their production in short intervals. The latter shows the significant benefit of demand peak shaving and trough filling in both the power and water domains on both physical production as well as total operating costs.

The work was demonstrated on three case studies. In all three, the cogeneration facilities were dispatched as ‘first resort’ units due to their economic efficiency in producing dual products. Nevertheless, this benefit was highly constrained due to the capacity, demand, and process ratio constraints. The incorporation of storage into the energy-water nexus system helped alleviate these constraints in all three cases, and therefore acts directly at the margin for maximal cost-efficiency. The second case was inspired by the water management challenges found in Singapore. Here, it was found that the when only limited storage capacity is available, it is critical to increase the storage charging capabilities to encourage their full utilization. This demonstrated a 29.5% cost reduction over the base case. The third case was inspired by the water management challenges found in the Midddle East. Here, it was found that the benefit becomes more pronounced with greater storage capacity because it allows the production units to operate in more flat regions of their respective cost curves. Thus, the storage facilities with large capacity and large ramping capabilties could further reduce costs. In this hypothetical case, costs were reduced another 12.5%.

The simultaneous co-optimization of power and water networks also leads to observations that are not readily apparent when each network is studied individually. For example, electrical energy storage facilities in interconnected power and water networks take on the added benefit of shifting the production in periods of high ratios of demanded power to water; while water storage facilities can be used for the opposite. Hence, these results suggest that energy and water storage facilities can have a particularly important role in balancing operations when the power and water grids are thought of as a single energy-water nexus grid. The storage facilities' function of alleviating constraints imposed on the coproduction facilities means that they are readily required to ramp their process ratio despite having relatively flat water production. This specific issue has not been tackled within this work but lends itself as a topic of future work.

An simultaneous economic dispatch applied to the supply-side of the energy-water nexus has three advantages: optimal use of resources, optimal production costs, and a formal approach to hydrological impact. This is especially relevant in geographic regions that depend heavily on coproduction facilities. The inclusion of both water and electrical energy storage allows for a flatter production profile especially for coproduction units leading to further improvements in costs and resource utilization. One aspect not significantly studied in this work is the hydrological perspective. Some economic dispatch literature has accounted for air emissions through the preference of different fuel types [52]–[56]. By analogy, this work may be extended to account for the heterogeneity of water sources (e.g. ground water, ocean water, lakes and rivers).

Operations research in the energy water nexus is an area where there is great deal of potential for future development. As traditional power economic dispatch has evolved over the last few decades, the combined optimization of power and water can evolve similarly. Organic development that incorporate physical constraints like process ratio ramping, transmission losses, and start-ups are likely to appear. Similarly, initial developments on the incorporation of transmission constraints are reported [57].

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