The Synergistic Role of Renewable Energy Integration into the Unit Commitment of the Energy Water Nexus

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Abstract

In recent years, significant attention has been given to renewable energy integration within the context of global climate change. In the meantime, the energy-water nexus literature has recognized that the electricity & water infrastructure that enables the production, distribution, and consumption of these two precious commodities is intertwined. 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. Therefore, renewable energy integration has the potential to address both sustainability concerns. And yet, renewable energy integration studies have yet to methodologically consider an integrated energy-water infrastructure. Many of these works rely on a coupled unit commitment-economic dispatch simulation. Recently, a 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 development of the corresponding unit commitment problem. It demonstrates the optimization on several case studies inspired by Singapore & the Middle East. It concludes that renewable energy simultaneously reduces CO_2 emissions and water withdrawals. Furthermore, it shows how water storage can help alleviate binding co-production constraints, flatten production profiles and reduce production cost levels.

I. INTRODUCTION

A. Motivation

Renewable energy integration has been the subject of significant concern within the context of global climate change [1] and the need to curb CO_2 emissions. Consequently, many governments have enacted policies to directly support their technological integration into the electrical power grid [2]–[6]. Nevertheless, solar photovoltaics (PV) and wind power are considered variable energy resources in that they are non-dispatchable in the traditional sense [7] in that their output depends on external conditions and are not fully controllable by the grid operator. Furthermore, they are uncertain in that they present new forecasts errors; relatively unfamiliar to grid operators. These two challenges have motivated the need for renewable energy integration studies [8]–[12] that address the techno-economic performance of the power grid as a function of renewable energy penetration rates. Early works often focused on wind integration but more recently solar PV and its associated "duck curve" [13] has received new attention. While many technical solutions exist to mitigate these effects, grid-integrated energy storage is an often-proposed solution [14]–[16].

In the meantime, 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 indeed intertwined [17]. Large volumes of water are withdrawn and consumed from water sources for electricity generation processes while simultaneously the extraction, treatment and conveyance of municipal water and treatment of wastewater are dependent on significant amounts of electrical energy [18]–[26]. Table I summarizes many of these couplings [27], [28]. Of these, the water demands posed by the thermal-electric generation fleet and supply-side couplings posed by thermal desalination have received significant attention from policy and regulatory agencies [29]–[34].

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	Power Supply	**Power Demand**
Water Supply	Co-production: • Thermal Desalination • Hydroelectric	• Pumped Water • Water Distribution • Wastewater Recycling
Water Demand	Thermal-power generation facilities	Residential, Commercial, & Industrial Use of Electric Heating and Cooling of Water

TABLE I

SUPPLY AND DEMAND SIDE ELECTRICITY AND WATER GRID COUPLINGS.

While the two issues of renewable energy and the energy-water nexus may seem unrelated, their resolution is likely to be synergistic in that renewable energy technologies not only present low CO_2 emissions but often also low water-intensities as well [35]. Several recent reviews have been conducted of operational water withdrawal and consumption figures [21]–[26]. It shows the relatively low values associated with solar and wind technology relative to thermal-electric generation technologies. This has lead one study to conclude that in the case of drought-ridden California, a shift to water-efficient energy sources combined with the addition of dry cooling and coal gasification could reduce water withdrawals by as much as 80% [35]. Therefore, the development of methods to study renewable energy integration within the context of the energy-water nexus has the potential to enhance holistic environmental performance in regards to air emissions as well as water conservation.

Finally, this enhanced environmental performance must be considered in the context of grid reliability. In that regard, energy and water storage could provide additional grid flexibility which could help alleviate the stresses caused by the variable energy supply introduced by renewable energy integration. This could decrease costs by flattening the net-load curve and eliminating the need for expensive peak-demand power plants. Furthermore, such energy & water storage can help facilitate feasible dispatch during fast ramping scenarios. Finally, as energy & water storage will inevitably displace thermal-electric facilities there is the potential for even greater improvements in water efficiency and CO_2 emissions.

B. *Regional Relevance*

While the challenges of global climate change and the energy-water nexus are globally relevant, the synergistic energy-water effects of renewable energy integration are greatest in regions that simultaneously exhibit high solar/wind potential and water scarcity. Such regions are likely to simultaneously deploy renewable energy and desalination technologies. These specifically include the American West, Australia, Singapore, and the Middle East & North Africa (MENA) region [36]. Furthermore, several of these regions and most notably the Gulf Cooperating Council (GCC) have combined electricity-water utilities, and so the potential energy-water coordination is even greater [18], [19], [36].

C. *Relevant Literature*

In spite of this potential, renewable energy integration studies have yet to methodologically consider the integration of these energy resources into a coupled energy-water infrastructure. Several reviews have shown that such studies typically rely on a coupled unit commitment-economic dispatch simulation of the thermo-electric facilities in the power grid [8]–[12]. These works do not explicitly account for the water impacts of the electric power grid. In the meantime, several works consider the integration of hydro-electric [37]–[43] and pumped energy storage facilities [44]–[47] into the dispatch of electricity as a single product. Finally, co-optimization methods have been developed for the simultaneous dispatch of power and water by explicitly considering power generation, water production, and co-production facilities. Following their analogs in power systems engineering [48], [49], these co-optimizations have been presented as economic dispatch [27], look-ahead dispatch [28], unit-commitment [50], and optimal network flow [51] formulations. Together, these works lay the foundation for the study of renewable energy integration in the energy-water nexus.

D. *Contribution*

This paper builds upon this foundation to demonstrate the potential synergistic benefits of renewable energy integration in a co-optimized energy-water unit commitment problem. More specifically, it enhances the formulation first developed in [50] with the introduction of renewable energy generation, operating reserves, and storage. It demonstrates the optimization on several case studies inspired by Singapore & the Middle East. It concludes that renewable energy simultaneously reduces CO_2 emissions, water consumption, and production costs. Furthermore, it shows how water storage can help alleviate binding co-production constraints, flatten production profiles and reduce production cost levels.

E. *Paper Outline*

The remainder of this paper proceeds as follows. Section II provides a conceptual description of the energy-water nexus model. Section III presents the associated co-optimized energy-water unit commitment problem. Section IV describes the case studies considered in this paper. Section V discusses the results of these case studies. Finally, Section VI presents the conclusions from the case study and suggestions for future work.

II. BACKGROUND: CONCEPTUAL UNDERSTANDING OF THE ENERGY-WATER NEXUS MODEL

This section provides a conceptual background for the energy-water nexus unit commitment co-optimization problem developed in the following section. It is summarized by the graphical representation in Figure **??**. It is a subset of the recently-developed energy-water nexus reference architecture [18], [19], and consists of an integrated power and water utility that is interested in simultaneously serving an electrical power demand as well as a potable water demand. In the case of co-located but separate power and water utilities, the co-optimization model presented in Section III would demonstrate the potential *economies of scope* [52], [53] achieved by coordinated efforts in operations. As is common with power-only unit commitment formulations, the respective power and water grids are modeled as single nodes; leaving the inclusion of power and water network constraints for future work.

The total power and water demands, as well as the total renewable energy power injection are supplied directly to these single node-models of the energy and water grids. The demands are measured net of any power and water requirements of the supplying facilities and are ultimately delivered to the utility's power and water customers. In other words, they are the power and water flow minus any “parasitic use” from the five types of dispatchable facilities. 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 computational complexity similar to that found in traditional deregulated electrical energy markets. It is also important to note that demand response programs are neglected in this system model.

The utility dispatches and commits electrical power generation, electrical energy storage, water, water storage, and co-production facilities that may be independent or vertically integrated. The electric power generation plants are assumed to be dispatchable and thermo-electric unless stated otherwise. The water plants may be ground or surface pumping stations or reverse osmosis desalination plants. Each water and co-production facility is assumed to draw from its own independent water source. 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 co-production facilities produce both water and power. As mentioned in Table I, these may be hydro-electric or thermal desalination plants. While hydro-electric facilities present their operational challenges, with rare exception, they do not coincide with water-scarce regions. Instead, this work uses multi-stage flash (MSF) desalination plants for the case study [54], [55]. These plants are common in the Middle East. They couple a Rankine power generation cycle to water desalination at the condenser. The excess high-temperature low pressure steam heat salt water past its boiling point to produce pure steam which ultimately cools to deliver potable water. Because power generation is thermodynamically coupled to water desalination, co-production facilities have a range of production ratios within which they function. The ratio of power produced to water produced cannot fall outside a certain range. This creates the primary linkage in the energy-water nexus and necessitates co-optimization.

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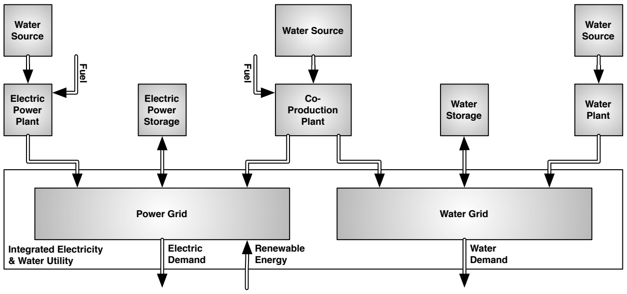

Fig. 1. Model for the Co-Dispatch of Power and Water Supply

III. Unit Commitment Model of the Energy-Water Nexus Combined Cogenerational Model for Energy and Water

This section presents the co-optimized energy-water unit commitment problem.

A. Objective Function

The production cost function C_G(t) is to be minimized with respect to the produced quantities of power and water over the discrete-time interval t = [1,. . . ,T] [50].

minimize:

$$\sum_{t=1}^{T} C_G(X_{pi}(t), X_{wj}(t), X_{ck}(t)) = \sum_{t=1}^{T}\Bigg[\sum_{i=1}^{n_p} C_{pi}(X_{pi}(t)) + \sum_{j=1}^{n_w} C_{wj}(X_{wj}(t)) + \sum_{k=1}^{n_c} C_{ck}(X_{ck}(t))\Bigg] + \Bigg[\sum_{i=1}^{n_p} C^s_{pi}(t) + \sum_{j=1}^{n_w} C^s_{wj}(t) + \sum_{k=1}^{n_c} C^s_{ck}(t)\Bigg] + \Bigg[\sum_{i=1}^{n_p} C^{sd}_{pi}(t) + \sum_{j=1}^{n_w} C^{sd}_{wj}(t) + \sum_{k=1}^{n_c} C^{sd}_{ck}(t)\Bigg] \tag{1}$$

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 cost functions C_{pi} , C_{wj} , C_{ck} are assumed to exhibit a quadratic structure in their respective production variables [50]. However, it is also possible to the cost to be linear, piecewise linear, and in certain cases with the form of higher polynomials as needed [48], [56]:

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

where the binary variables $U_{pi}(t), U_{wj}(t), U_{ck}(t)$ indicate whether a given facility is offline or online in time block t. The cost function coefficients are appropriately sized positive constant matrices based upon the heat rate characteristics of their respective production units.

The startup costs $C^s_{pi}(t), C^s_{wj}(t), C^s_{ck}(t)$ incurred in any time block t equal the constant startup costs $\mathcal{C}^s_{pi}, \mathcal{C}^s_{wj}, \mathcal{C}^s_{ck}$ which are plant parameters, if the plant is starting up in this time block. Otherwise the incurred startup cost is zero. This can be expressed as follows [50]:

$$\begin{aligned} C^s_{pi}(t) &= \mathfrak{C}^s_{pi} U^s_{pi}(t) \qquad \forall t, \forall i = 1 \ldots n_p \\ C^s_{wj}(t) &= \mathfrak{C}^s_{wj} U^s_{wj}(t) \qquad \forall t, \forall j = 1 \ldots n_w \\ C^s_{ck}(t) &= \mathfrak{C}^s_{ck} U^s_{ck}(t) \qquad \forall t, \forall k = 1 \ldots n_{cp} \end{aligned} \tag{3}$$

Similarly, the shutdown costs can be calculated [50]:

$$\begin{aligned} C^{sd}_{pi}(t) &= \mathfrak{C}^{sd}_{pi} U^{sd}_{pi}(t) \qquad \forall t, \forall i = 1 \ldots n_p \\ C^{sd}_{wj}(t) &= \mathfrak{C}^{sd}_{wj} U^{sd}_{wj}(t) \qquad \forall t, \forall j = 1 \ldots n_w \\ C^{sd}_{ck}(t) &= \mathfrak{C}^{sd}_{ck} U^{sd}_{ck}(t) \qquad \forall t, \forall k = 1 \ldots n_{cp} \end{aligned} \tag{4}$$

B. State Variable Constraints

The binary state variables are constrained by Equation 5 [50].

$$U_{pi}(t) = U_{pi}(t-1) + U_{pi}^{s}(t) - U_{pi}^{sd}(t) \quad \forall t > 1 \tag{5}$$

Where the binary variables U_{pi}^{s} and U_{pi}^{sd} equal one when the plant is turning on or off, respectively.

C. Capacity Constraints

The objective function is minimized subject to minimum and maximum power and water flow capacity constraints of each of the facilities [50].

$$\begin{aligned} u_i(t)P_i^{min} \le & X_{pi}(t) \le u_i(t)P_i^{max} \\ u_j(t)W_j^{min} \le & X_{wj}(t) \le u_j(t)W_j^{max} \\ \begin{bmatrix} u_k(t)P_k^{min} \\ u_k(t)W_k^{min} \end{bmatrix} \le & X_{ck}(t) \le \begin{bmatrix} u_k(t)P_k^{max} \\ u_k(t)W_k^{max} \end{bmatrix} \end{aligned} \tag{6}$$

As is typically found in the unit commitment problem, it is important to note that Eq. (6) limits the *flow rate* capacity of power and water for the different 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 7 govern the minimum and maximum capacity on the *stock* of energy and water stored [50].

$$\begin{aligned} \underline{StoreS}_u \le S_u(t) \le \overline{StoreS}_u \quad & \forall t, \forall u = 1 \ldots n_s \\ \underline{Store\sigma}_v \le \sigma_v(t) \le \overline{Store\sigma}_v \quad & \forall t, \forall v = 1 \ldots n_\sigma \end{aligned} \tag{7}$$

E. Power & Water Demand Constraints

Equation 8 shows the power and water demand constraint which includes terms from the two types of storage facilities and renewable energy sources.

$$D(t) = \sum_{i=1}^{n_p} X_{pi}(t) + \sum_{j=1}^{n_w} X_{wj}(t) + \sum_{k=1}^{n_c} X_{ck}(t) + \sum_{l=1}^{n_r} X_{rl}(t) + \sum_{u=1}^{n_s} X_{su}(t) + \sum_{v=1}^{n_\sigma} X_{\sigma v}(t) \quad \forall t = 1 \ldots T \tag{8}$$

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. Since the supply of renewable energy, $X_{rl}(t)$, is not assumed to be non-dispatchable, Equation 8 can be simplified as follows to create an equation for net demand:

$$\begin{aligned} D_{net}(t) =& D(t) - \sum_{l=1}^{n_r} X_{rl}(t) \\ D_{net}(t) =& \sum_{i=1}^{n_p} X_{pi}(t) + \sum_{j=1}^{n_w} X_{wj}(t) + \sum_{k=1}^{n_c} X_{ck}(t) + \sum_{u=1}^{n_s} X_{su}(t) + \sum_{v=1}^{n_\sigma} X_{\sigma v}(t) \quad \forall t = 1 \ldots T \end{aligned} \tag{9}$$

Thus, a unit commitment problem with renewable energy sources can simply be re-cast as a unit commitment problem without such resources and a different demand profile. The renewable resources likely affect the variance of the demand profile, but do not add a high degree of computational complexity to the optimization.

F. Co-Production Process Constraints

Equation 10 represents a process constraint for coproduction facilities [50].

$$r_k^{lower} \leq \frac{x_{cpk}}{x_{cwk}} \leq r_k^{upper} \quad \forall k = 1 \ldots n_{cp} \tag{10}$$

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 and allows individual facilities to optimize their own processes in response to price signals.

G. Ramping Constraints

Equation 11 represents the ramping constraints of the three types of production facilities. The storage facilities are assumed not to exhibit ramping constraints [50].

$$\begin{aligned} R_i^{min} \leq& \frac{X_{pi}(t) - X_{pi}(t-1)}{T} \leq R_i^{max} \\ Y_j^{min} \leq& \frac{X_{wj}(t) - X_{wj}(t-1)}{T} \leq Y_i^{max} \\ \begin{bmatrix} R_k^{min} \\ Y_k^{min} \end{bmatrix} \leq& \frac{X_{ck}(t) - X_{ck}(t-1)}{T} \leq \begin{bmatrix} R_k^{max} \\ Y_k^{max} \end{bmatrix} \end{aligned} \tag{11}$$

The ramping constraints serve to couple the facility outputs in successive time blocks and give preference to facilities that can ramp easily to meet demand variability.

H. Reserve Requirements

It is necessary to ensure adequate reserve capacity in the power system such that online facilities can increase or decrease production as required by variability of demand without contravening minimum or maximum production requirements. In this work, the up and down reserve requirements are assumed to be equal and time-independent [57]:

$$\sum_{i=1}^{N_P} u_i(t) P_i^{max} - \sum_{i=1}^{N_P} P_i(t) \geq P_{res} \tag{12}$$

$$\sum_{i=1}^{N_P} P_i(t) - \sum_{i=1}^{N_P} u_i(t) P_i^{min} \geq P_{res} \tag{13}$$

I. Storage Flow Constraints

Power and water flow constraints were applied to the storage system as shown in Equation 14. The up- and down-ramping rates were assumed to be the same for both power and water [50].

$$\begin{aligned} X_{su}^{min} \leq& X_{su}(t) \leq X_{su}^{max} \\ X_{\sigma v}^{min} \leq& X_{\sigma v}(t) \leq X_{\sigma v}^{max} \end{aligned} \tag{14}$$

J. Storage Continuity Relations

Equation 15 captures the power and water storage facility continuity relations as constraints [50].

$$\begin{aligned} S_u(t) &= S_u(t-1) - X_{su}(t) \qquad \forall t, \forall u = 1 \ldots n_s \\ \sigma_v(t) &= \sigma_v(t-1) - X_{\sigma v}(t) \qquad \forall t, \forall v = 1 \ldots n_\sigma \end{aligned} \tag{15}$$

Similar to the ramping constraints, these storage continuity relations couple the stocks of stored energy and water in successive time blocks.

K. Initial Conditions

Finally, the initial conditions of the two types of storage facilities are taken as constraints in Equation 16 [50].

$$\begin{aligned} S_u(t) &= 0 \quad \forall u = 1...n_s \\ \sigma_v(t) &= 0 \quad \forall v = 1...n_\sigma \end{aligned} \tag{16}$$

These may be adjusted over multiple days or seasons to reflect the need for medium-term and long term water management goals. Final conditions may be similarly applied if deemed necessary.

IV. CASE STUDY METHODOLOGY

The case study methodology seeks to investigate the role of renewable energy integration in concert with electrical energy and water storage facilities in an energy-water nexus unit commitment dispatch. The chosen test case was adapted from publicly available previous efforts focused on the corresponding economic dispatch and look-ahead dispatch problems [27], [28], [50], [51], [58], [59]. The test case is composed of four power plants, three co-production desalination facilities, and one reverse osmosis water plant. The scenario also includes three electrical energy and two water storage facilities. The test case also contains one solar plant, which serves as a stochastic power source that changes the net demand profile. The solar data was obtained from [60] and scaled to have a maximum value of 20% of the peak electrical demand. Table II shows the plant and cost data including power and water production capacity limits, ramping limits, and cost coefficients. Table III shows the electric power and water demand as well as the solar PV generation for 24 hours with one hour resolution. While the size of this system is relatively small, it serves to demonstrate the energy-water nexus unit commitment and its associated effects when solar PV and energy and water storage facilities have been integrated.

The optimization problem was numerically implemented in MATLAB and GAMS where the former was used for data processing and visualization and the latter was used for solving. Because the optimization problem may be classified as a mixed-integer quadratic constrained program, the CPLEX solver was chosen as an off-the-shelf solver. This solver has been tested on relatively large problems suggesting that this energy-water nexus unit commitment formulation can be applied to large scale industrial size problem. The code was executed on a Macbook Laptop with a 2.8 GHz Intel Core i7 and took up to 145 seconds to run depending on the case and its associated storage quantities.

The experimental design consists of four cases that vary storage quantities, storage charging rates, and the presence of renewable solar photovoltaic generation. The data for these test cases is summarized in Table IV.

Case 1.1: Singapore with Solar PV. This case is inspired by Singapore where limited land mass has constrained the total availability of water storage [61]–[63]. Therefore, the case maintains limited storage capacity but large charging and discharging abilities; especially in the case of water storage. Solar PV generation has been included to a level of 20% of the peak electrical demand.
Case 1.2: Singapore without Solar PV This case is identical to the prior but removes solar PV generation.
Case 2.1: Middle East with Solar PV The final case is inspired by the Middle East where the ability to build storage facilities is relatively unconstrained. Therefore, large storage capacities and discharge rates were allowed. Solar PV generation was included to a 20% of the peak electrical demand.
Case 2.2: Middle East without Solar PV. This case is identical to the prior but removes solar PV generation.

V. RESULTS

The optimization problem was solved for a 24-hour period using the data provided in the previous section. Figure **??** plots the electrical load and net-load curve data in Table III. The net load curve exhibits a large dip in the mid-afternoon hours followed by a sharp ramp in the early evening hours. This feature is often call the "duck curve" and has been raised as a challenge condition for power grid conditions. It creates a steep ramp which challenges many large power generation facilities with low ramping rates. This issue currently affects the state of California [13] and is likely to become more widespread as solar power becomes more prevalent in other energy markets.

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The "duck-curve" problem can be partially addressed through the addition of water and power storage facilities. These allow for faster ramping rates and provide cogeneration facilities with more flexibility in their demand ratios. The effect of such storage facilities can be seen by comparison in the four case studies presented below.

TABLE II
PLANT AND COST DATA

Name	Plant type	Max power	Min power	Max power ramp	Min power ramp	Max water	Min water	Max water ramp	Min water ramp
Power 1	Nuclear	800 MW	480 MW	100 MW/h	-100 MW/h		-	-	-
Power 2	Natural gas	400 MW	100 MW	200 MW/h	-100 MW/h		-	-	-
Power 3	Natural gas	400 MW	100 MW	200 MW/h	-100 MW/h		-	-	-
Power 4	Natural gas	400 MW	100 MW	200 MW/h	-100 MW/h		-	-	-
Cogen 1	Cogeneration	800 MW	200 MW	200 MW/h	-100 MW/h	200 m^3/h	50 m^3/h	100 m^3/h^2	-100 m^3/h^2
Cogen 2	Cogeneration	600 MW	150 MW	200 MW/h	-100 MW/h	150 m^3/h	37.5 m^3/h	50 m^3/h^2	-50 m^3/h^2
Cogen 3	Cogeneration	400 MW	100 MW	200 MW/h	-100 MW/h	100 m^3/h	25 m^3/h	50 m^3/h^2	-50 m^3/h^2
Water 1	Desalination	-	-	-	-	250 m^3/h	62.5 m^3/h	50 m^3/h^2	-50 m^3/h^2

Power Plant Cost Coefficients

A_p	B_p	C_p
3.013e-03	4.705e	2.319e+3
1.531e-2	9.008e+1	3.403e+3
1.531e-2	9.008e+1	3.403e+3
1.531e-2	9.008e+1	3.403e+3

Water Plant Cost Coefficients

A_w	B_w	C_w
1.2029e-1	1.879e+1	1.226e+4

Coproduction Plant Cost Coefficients

A_{c11}	A_{c12}	A_{c22}	B_{c1}	B_{c2}	C_c
9.390e-3	3.756e-02	3.756e-2	9.392	9.392	2.441e+4
1.252e-2	5.008e-02	5.008e-2	9.392	9.392	1.833e+4
1.878e-2	7.512e-02	7.512e-2	9.392	9.392	1.226e+4

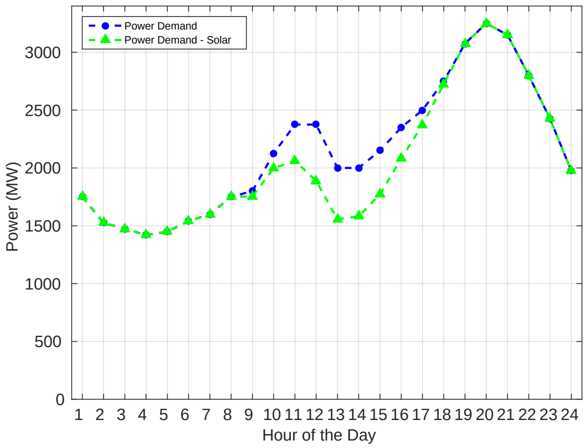

Fig. 2. Electrical Load & Net Load Curves

A. Singapore

1) Case 1.1: Singapore with Solar PV: 4in

The results for Case 2.1 are summarized in Figures **??**-**??**. Fig. **??** displays the power dispatch. As expected, the

TABLE III
POWER DEMAND, WATER DEMAND, SOLAR GENERATION DATA

Hour	Power Demand (MW)	Water Demand (m^3)	Solar Generation (MW)
1	1750	150	0
2	1525	130	0
3	1475	100	0
4	1420	150	0
5	1450	200	0
6	1540	250	0
7	1600	300	0
8	1750	350	0
9	1800	380	62.4
10	2125	400	169
11	2375	550	418.6
12	2375	500	650
13	2000	400	590.2
14	2000	300	559
15	2150	400	504.4
16	2350	500	358.8
17	2500	600	169
18	2750	500	33.8
19	3075	550	0
20	3250	400	0
21	3150	400	0
22	2800	300	0
23	2425	250	0
24	1975	150	0

TABLE IV
STORAGE CAPACITY AND CHARGING RATES

Cases	$\overline{GenS}$ (MWh)	$\overline{Gen\sigma}$ (m^3)	$\overline{StoreS}$ (MW)	$\overline{Store\sigma}$ (m^3/hr)
Singapore	50	63.5	40	100
	125	125	60	100
	135	–	100	–
Middle East	50	125	40	100
	125	250	60	100
	135	–	100	–

solar power generation appears during the day time from Hour 9 to Hour 18. Meanwhile, the limited role of energy storage is signified by the difference between the dashed blue and green lines. Nevertheless, the largest differences appear in House 13-14 and 20-21 to flatten the “duck curve”. In Hour 1, Power Plants 2 and 3 are brought online for one hour to satisfy the demand and required ramping in subsequent hours even though the other plants have enough capacity when Hour 1 is considered alone. Cogeneration Plant 2 is brought online in Hour 7 to increase power and water production while simultaneously allowing it to ramp up in the hours preceding the peak load in Hours 19-21. Finally, Power Plants 3 and 4 serve as peaking units during those hours.

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Figure **??** shows the water dispatch for the associated case. As water is significantly easier to store than electricity, the case shows a larger difference between the dashed blue and green lines. The water storage serves to clip the peaks and fill the troughs in water demand in Hours 2-4, 11-12, and 17-19. Again, Cogeneration Plant 2 is brought online in Hour 7 to meet the higher water demand levels throughout the rest of the day. Otherwise, the dispatch is relatively stable over the course of the day.

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Figure **??** shows the coproduction ratios for the associated case. As mentioned previously, these ratios provide

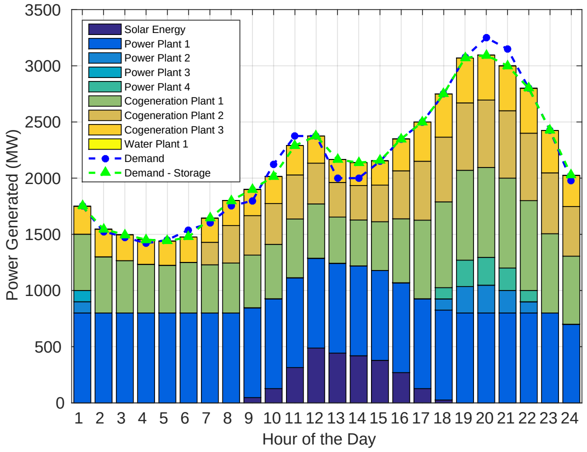

Fig. 3. Electric Power Dispatch for Case 1.1: Singapore with Solar PV

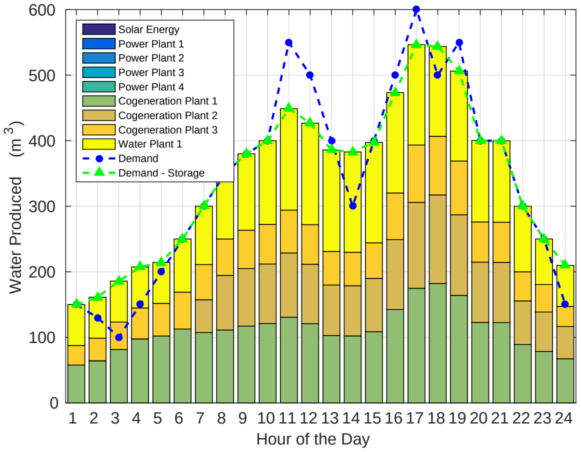

Fig. 4. Water Dispatch for Case 1.1: Singapore with Solar PV

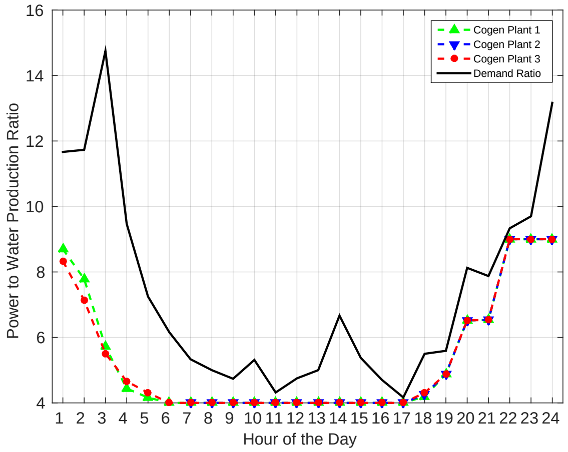

Fig. 5. Coproduction Ratios for Case 1.1: Singapore with Solar PV

the primary coupling between the water and electric power infrastructures. As the power-to-water demand ratio changes over the course of the day, coproduction units must also change their production ratios. The degree to which they much do so alleviated by single-production facilities in either infrastructure. Storage facilities further alleviate this constraint. In this case, the coproduction ratios generally follow the shape of the demand ratio but to a less exaggerated degree. The water plant in combination with the peaks clipped by the power and water storage systems provides this alleviation. Consequently, the coproduction ratios begin near their maximum value of 9, falling to their minimum by Hour 6. In Hour 17, they begin to increase reaching their maximum value again by Hour 22.

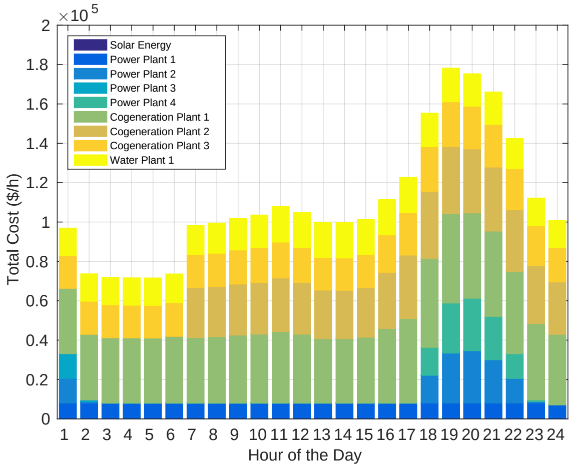

Fig. 6. Costs for Case 1.1: Singapore with Solar PV

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Figure **??** shows the costs for the associated case. They mirror the production profiles fairly closely. The costs during Hours 2-6 and 7-15 are relatively stable because the number of plants in operation stays constants. The large cost spike in Hours 16-22 occurs because of the additional plants brought online for the peak in power demand.

2) Case 1.2: Singapore without Solar PV: In the interests of brevity, this case is discussed in Section V-C as part of the cross-case comparison.

B. Middle East

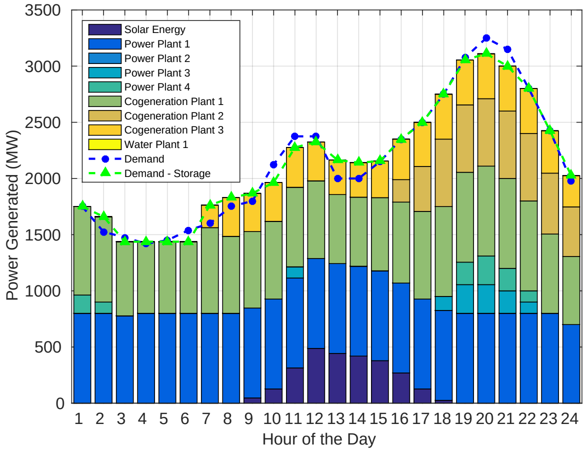

Fig. 7. Electric Power Dispatch for Case 2.1: Middle East with Solar PV

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The results for Case 2.1 are summarized in Figures **??**-**??**. Fig. **??** displays the power dispatch. The solar power generation and electrical energy storage play a similar role as in Singapore Case 1.1. In Hours 1-2, and 11 Power

Plant 3 is brought online to meet ramp over those hours. Similarly, Power Plants 3 and 4 address the sharp ramps and peak demand experienced in Hours 18-22. While either of these plants have enough capacity to fulfill this role, the two plants are dispatched to meet the required ramps. The primary difference in the electric power dispatch between the two cases is that Cogeneration Plant 2 does not begin until Hour 16 where in the prior case it began production in Hour 7. The difference can be attributed to the significant difference in the two cases' water production profiles.

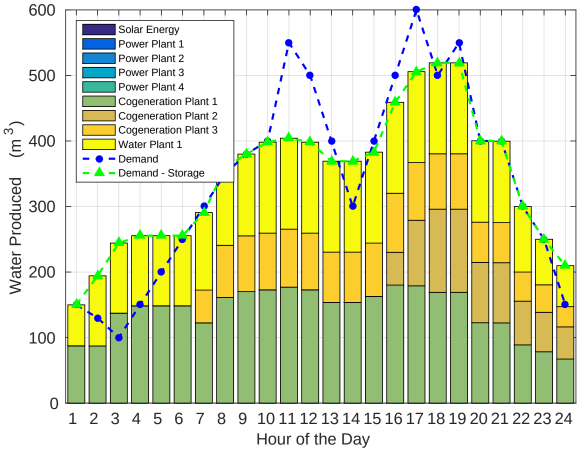

Fig. 8. Water Dispatch for Case 2.1: Middle East with Solar PV

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Figure **??** shows the water dispatch for the associated case. Here, the high water storage capabilities allow for a more aggressive flattening of the demand curve and give cogeneration plants more flexibility in their production ratio. This phenomenon can be seen in Fig. **??**. Water is stored during early, low-demand hours,creating a plateu in production not seen in raw demand, and is used to more aggressively offset the sharp peaks in demand. This decreases cost by preventing additional plants from coming online and creates a smoother production profile than the Singapore case, with a higher base production rate but smaller peaks and less drastic variations. Notably, the ramping in demand from hours 3-6 is replaced by the aforementioned production plateau, unlike in the Singapore case. These changes explain the delayed appearance of Cogeneration Plant 2 in Hour 16.

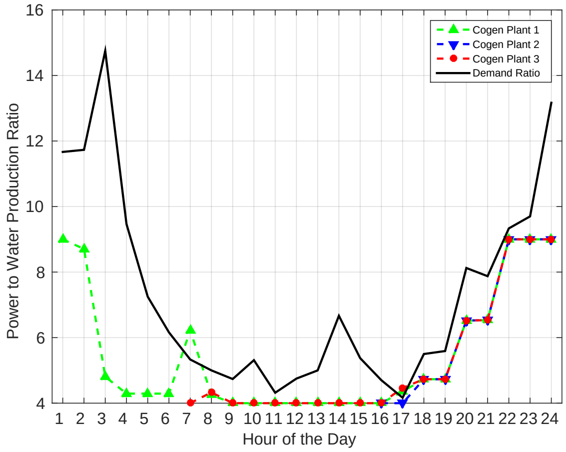

Fig. 9. Coproduction Ratios for Case 2.1: Middle East with Solar PV

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Figure **??** shows the coproduction ratios for the associated case. They are similar to those shown in the Singapore case. The ratios follow the demand ratio in a similar manner, with two notable differences. One, there is only one

TABLE V

CROSS CASE COMPARISON OF COST, CO_2 EMISSIONS & WATER WITHDRAWAL BY THERMO-ELECTRIC FACILITIES

Case	Cost (M$)	CO_2 (metric tons)	Water Withdrawal (m^3)
Case 1.1: Singapore with Solar PV	2.592	16,070	3,674,000
Case 1.2: Singapore without Solar PV	2.702	18,020	3,873,000
Case 2.1: Middle East with Solar PV	2.444	16,090	3,673,000
Case 2.2: Middle East without Solar PV	2.608	18,030	3,872,000

cogeneration plant running for the first 6 hours, and in hours 4-6 its production ratio stays slightly above the minimum, unlike in the Singapore case. Second, there is a spike in Cogeneration Plant 1's ratio at Hour 7, which is not seen in the demand ratio. This is due to the addition of Cogeneration Plant 2 to deal with ramping in the following hours. This plant produces additional water which, without the subsequent ramping, would be unnecessary in Hour 7. Therefore, Cogeneration Plant 1 must reduce its water output to compensate for the additional water, increasing its cogeneration ratio.

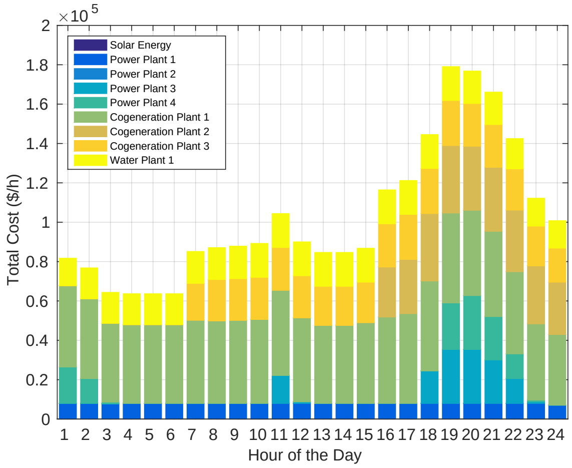

Fig. 10. Costs for Case 2.1: Middle East with Solar PV

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Figure **??** shows the costs for the associated case. They mirror the production profiles fairly closely and are not too dissimilar from the Singapore case. There is a cost spike in Hour 11 to account for the ramping capabilities of Power Plant 3. Otherwise, the cost spike in Hours 16-22 is attributed peak demand and high ramp conditions.

C. Cross Case Comparison of Cost, CO_2 Emissions & Water Usage

Returning to the original premise of the paper, a holistic performance comparison can be made across the four cases. The results of which can be found in Table V. CO_2 coefficients from [64] and water coefficients from [65] were used to compare costs, CO_2 emissions and water withdrawal results.

Despite the exaggerated net-load ramps caused by solar PV integration, their integration improves the holistic performance in both Cases 1.2 and 2.2. Solar PV has zero operating cost and consequently displaces generation from more expensive facilities. Because they have low CO_2 emission and water withdrawal factors, a cost-optimal market solution also serves to improve performance with respect to these criteria as well. Furthermore, the integration of additional water storage in the Middle East Case 2.2 relative to the Singapore Case 1.2 improves cost performance. The performance with respect to CO_2 and water withdrawal remains approximately the same. This shows that storage actions taken in the water infrastructure can serve to improve the electric power infrastructure when the two are coupled together in an energy-water nexus.

These results suggest an interplay between the two infrastructures which obeys the following pattern: cogeneration plants couple energy and water production, causing production constraints due to limited generation ratios. Solar power reduces CO_2 emissions but exacerbates the evening ramp in power demand; creating issues for power plants with limited ramping capabilities, especially nuclear plants. Energy and water storage present a promising solution to both of these problems, as they allow for flattening of the demand curves and cogeneration ratios, reducing costs significantly.

VI. Conclusions and Future Work

Traditionally, electric power and water infrastructure have been thought of as separate uncoupled systems. However, the presence of cogeneration facilities couples their respective supply sides and the presence of thermo-electric facilities intensifies their impacts on the aqueous environment. There are two ways to handle this situation. One possibility is to try to reduce the coupling between the two products. Desalination plants based upon reverse osmosis technology do require significant electrical input, but they avoid coupling power generation with water production as in thermal desalination plants. Renewable energy integration further reduces the impact on the aqueous environment. However, this approach generally is only applicable to new plant installations and not to already well established infrastructure. Another option is to better understand the coupling between these two resources and use well established algorithms to optimize their production costs.

Consequently, this work has sought to highlight the synergistic role of renewable energy integration in the unit commitment of the energy-water nexus. The developed case studies showed that the low operating cost of solar PV integration displaces thermo-electric generation. This cost-optimal solution also serves to reduce CO_2 emissions as well as water withdrawal. Meanwhile, the incorporation of storage into the energy-water nexus system helped alleviate binding constraints in both cases and therefore acts directly at the margin for maximal cost-efficiency. Most notably, greater storage capacity was seen to alleviate the power-to-water ratio constraints of the cogeneration plants in the both cases.

While the formulated unit commitment problem can be implemented in existing integrated electricity and water authorities, greatest economic benefit will be realized through the development of integrated electricity and water markets. Such markets would provide the incentive for independent water and power producers to continuously innovate to provide lower costs to the benefit of consumers. Future work will further explore these incentives particularly as they relate to the energy-water nexus in the Middle East.

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