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AN INTEGRATED ENERGY AND WATER MARKET FOR THE SUPPLY SIDE OF THE ENERGY-WATER NEXUS IN THE ENGINEERED INFRASTRUCTURE

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ABSTRACT

The cogeneration of electric power and water in cogeneration desalination plants introduces coupling between the supply sides of the power and water grids. Due to this coupling, electricity and water require co-optimization. In an environment in which electricity supply is determined by deregulated wholesale markets, this need for co-optimization suggests a need for integrated electricity and water markets. Recently, a simultaneous co-optimization method has been contributed for the economic dispatch of networks that include water, power and co-production facilities in such an integrated market. This paper builds upon this foundation with the introduction of the corresponding unit commitment problem. Furthemore, it investigates the impact of electrical energy and water storage as a technology that can help alleviate binding constraints and lead to flatter production and reduced cost levels for the unit commitment problem.

1 INTRODUCTION

The energy-water nexus is a multifaceted problem of growing global importance. In the ever increasing number of regions that employ desalination as part of their water supply portfolio, the energy-intensity of desalination technologies is often discussed as a key sustainability concern [1]. Another key, but less often discussed, facet is the coupling of the supply sides of electricity and water grids created by the cogeneration of water and power in cogeneration facilities. For a fixed design, these facilities have a limited range of possible ratios of generated electric power to produced water at any given time. As storage capabilities for both power and water are limited, the former by technology and the latter by cost, this limited range of ratios essentially couples the two grids.

Deregulation of the electric power industry and the subsequent introduction of electricity markets have been credited with accruing several efficiency and economic benefits to electric power systems in many parts of the world. In electricity markets, bids submitted by independent power producers are fairly assessed by market clearing mechanisms on different timescales and are either dispatched in real time or scheduled to be online over a future time period. Cogeneration plants are currently concentrated in parts of the world that have made strides towards the deregulation of their power sectors but that have not set up electricity markets. Such countries include the countries that make up the Gulf Cooperative Council. In regions that do have electricty markets, cogeneration plants make up a small percentage of the water and power supply portfolios. As the percentage contribution of cogeneration plants grows in regions that do have electricity markets, due to physical water scarcity exacerbated by climate change, and as the regions that already rely on cogeneration set up markets, the question of how best to operate cogeneration plants in wholesale electricity markets arises. Price signals for both power and water must be sent to cogeneration plant op-

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erators in order for them to determine in which proportions the two products are to be produced. An integrated energy-water market could simultaneously co-optimize supply of both water and electric power while accounting for the physical constraints of cogeneration.

Such an integrated market would have two critical clearing mechanisms, similar in function and potentially homonymous to equivalents in pure electricity markets. The first, economic dispatch, would determine the optimal output of a number of electricity generation facilities, water treatment plants, and cogeneration plants to meet the water and power demands, at the lowest possible cost, subject to transmission and operational constraints. A model for the joint economic dispatch of both power and water in such a market has been presented in previous work [2, 3]. The economic dispatch problem assumes that all facilities considered are online and ready to produce. The second mechanism, unit commitment, would be run to determine which production facilities are scheduled to be online over the duration of a future time period, and which can thus be included in the economic dispatch. In this work, a model for this unit commitment in integrated energy-water markets is presented.

2 BACKGROUND

In regions such as the GCC that have independent power and water producers but that have not yet set up wholesale electricity markets, Power and Water Purchase Agreements (PWPAs) stipulate, in advance, the quantities of power and water to be bought by the grids from these producers at a fixed price. The agreements typcially also specify a fixed fuel cost. This model, though attractive to investors, does not provide any incentive for producers to compete on efficiency and to continuously innovate to deliver the lowest possible economic and environmental costs. Fully liberalized power and water markets would provide this incentive and thus should be pursued.

Although the need to manage water as an economic good in order to achieve efficiencies and equitable use has long been recognized [4], the concept of water markets both for water resource management and municipal water supply has not achieved intellectual consensus or widespread adoption. One barrier is the perception that water is essential for life, and thus, below a certain level of demand, is price inelastic making it a poor candidate for deregulation and market allocation [5]. While this point is cogent the evidence of non-zero price elasticities of water [6] suggests that many water users are consuming volumes of water that are significantly above the bare minimum required for survival. Furthemore, modern life is equally dependent on electricity, but this has not hampered consensus on the development of electricity markets.

The integrated management of dual product infrastructures is not without precedent. Facilities that cogenerate power and heat demonstrate high efficiencies by using heat as a valued product for nearby industrial sectors such as food processing, chemical production, and district heating [7–9]. The resulting efficiency gains bring about cost savings, reduced air pollution and greenhouse gas emissions, increased power reliability and quality, reduced grid congestion and avoided distribution losses [10]. Many policy-makers, particularly in Northern Europe, have supported dual product facilities through regulatory development [11]. The technical and economic rationalization of a cogeneration solution often depends on the challenging conditions of having a consistently available, dedicated and co-located heat consumer [12] with whom, often contentiously negotiated [13, 14] long-term contracts are signed [15]. Naturally, some have argued for a more dynamic treatment [16] and to that effect, a power-heat economic dispatch approach has been applied within the literature. Typically, it creates a single objective function for co-generation plants that is dependent on the amount of power and heat produced. Constraints are then added to set up limits for both power and heat capacities. These limits usually define a feasible region in which the cogeneration plant can operate with respect to power and heating steam produced [17–21].

In regards to the co-optimization of power and water supply, research efforts have previously focused on one particular plant and its associated process flow diagram hence not providing an extensible optimization formulation. Some such efforts focus on optimized planning and design [22–24] while other efforts find methods of cost allocation [25]. One author directly addresses the economic dispatch of a single specific facility composed of a number of sub-units but neither generalizes the formulation nor applies it to all the water and production units in the water and power grids [26].

Recently however, a number of power-water grid co-optimization programs have been developed [2, 3, 27–29]. These efforts have focussed on the economic dispatch of power, water and cogeneration plants in which all plants are assumed to be ready to produce. In Section 3 a formulation for unit commitment of power, water and cogeneration plants is presented. The unit commitment model, like the previously developed economic dispatch models [2, 3, 27–29] is developed with the aim of supporting discussion of the potential for integrated energy and water markets. It, however, can be directly implemented in the integrated water and electricity authorities that already exist in many countries in the GCC.

3 MODELING METHODOLOGY

This section describes the modeling methodology for the formulation of an optimization program for the unit commitment of both power and water. Subsection 3.1 describes the system model. The remaining subsections develop the model which extends the joint economic dispatch model previously presented in [2] to include binary unit commitment variables and startup costs. 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.

3.1 Conceptual Model

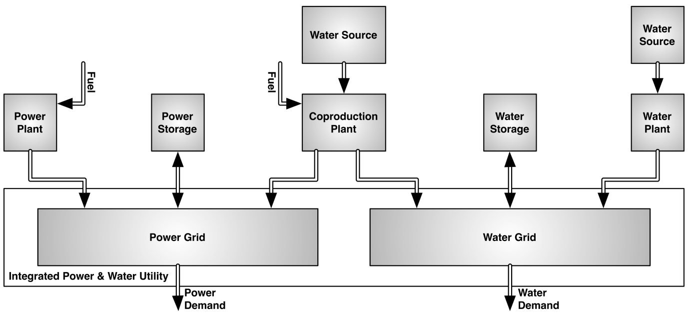

FIGURE 1. Model for the Co-Dispatch of Power and Water Supply

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 and 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 and commits power, electrical energy storage, water, water storage, and co-production facilities that may be independent or vertically integrated. The power plants and co-production facilities require fuel. 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. 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 of the supplying facilities and are ultimately delivered to the utility's power and water customers.

3.2 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].

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

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.

$$\begin{aligned} C_{pi} &= X_{pi}^T A_{pi} X_{pi} + B_{pi} X_{pi} + U_{pi} \mathscr{K}_{pi} \\ C_{wj} &= X_{wj}^T A_{wj} X_{wj} + B_{wj} X_{wj} + U_{wj} \mathscr{K}_{wj} \\ C_{ck} &= X_{ck}^T A_{ck} X_{ck} + B_{ck} X_{ck} + U_{ck} \mathscr{K}_{ck} \end{aligned} \quad (2)$$

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 given time block t are equal to the constant startup costs $\mathscr{C}^s_{pi}, \mathscr{C}^s_{wj}, \mathscr{C}^s_{ck}$ which are plant parameters, if the plant is indeed starting up in this time block. Otherwise the incurred startup cost is zero. This can be expressed as follows:

$$\begin{aligned} C^s_{pi}(t) &\geq \mathscr{C}^s_{pi}(U_{pi}(t) - U_{pi}(t-1)) \forall t, \forall i = 1 \ldots n_p \\ C^s_{wj}(t) &\geq \mathscr{C}^s_{wj}(U_{wj}(t) - U_{wj}(t-1)) \forall t, \forall j = 1 \ldots n_w \\ C^s_{ck}(t) &\geq \mathscr{C}^s_{ck}(U_{ck}(t) - U_{ck}(t-1)) \forall t, \forall k = 1 \ldots n_{cp} \end{aligned} \quad (3)$$

3.3 Capacity Constraints

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

$$\begin{aligned} minGenP_i * U_{pi} \leq X_{pi} \leq maxGenP_i * U_{pi} \quad & \forall i = 1 \ldots n_p \\ minGenW_i * U_{wj} \leq X_{wj} \leq maxGenW_j * U_{wj} \quad & \forall j = 1 \ldots n_w \\ minGenC_k * U_{ck} \leq X_{ck} \leq maxGenC_k * U_{ck} \quad & \forall k = 1 \ldots n_c \\ minGenS_u \leq X_{su} \leq maxGenS_u \quad & \forall u = 1 \ldots n_s \\ minGen\sigma_v \leq X_{\sigma v} \leq maxGen\sigma_v \quad & \forall v = 1 \ldots n_\sigma \end{aligned} \quad (4)$$

As is typically found in the unit commitment problem, it is important to note that Equation 4 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.

3.4 Storage Limit Constraints

In contrast, the second group of constraints found in Equation 5 govern the minimum and maximum capacity on the *stock* of energy and water stored.

$$\begin{aligned} minStoreS_u \leq S_u(t) \leq maxStoreS_u \quad \forall t, \forall u = 1 \ldots n_s \\ minStore\sigma_v \leq \sigma_v(t) \leq maxStore\sigma_v \quad \forall t, \forall v = 1 \ldots n_\sigma \end{aligned} \tag{5}$$

3.5 Power & Water Demand Constraints

Equation 6 shows the power and water demand constraint that includes the terms from the two types of storage facilities.

$$\begin{aligned} &\forall t = 1 \ldots T \; D(t) = \\ &\sum_{i=1}^{n_p} X_{pi}(t) + \sum_{j=1}^{n_w} X_{wj}(t) + \sum_{k=1}^{n_c} X_{ck}(t) + \sum_{u=1}^{n_s} X_{su}(t) + \sum_{v=1}^{n_\sigma} X_{\sigma v}(t) \end{aligned} \tag{6}$$

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.

3.6 Co-Production Process Constraints

Equation 7 represents a process constraint for coproduction facilities.

$$r_k^{lower} \leq \frac{x_{cpk}}{x_{cwk}} \leq r_k^{upper} \quad \forall k = 1 \ldots n_{cp} \tag{7}$$

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.

3.7 Ramping Constraints

Equation 8 represents the ramping constraints of the three types of production facilities.

$$\begin{aligned} &\forall i = 1 \ldots n_p \\ &\begin{bmatrix} -maxDRRP_i \\ 0 \end{bmatrix} \leq X_{pi}(t) - X_{pi}(t-1) \leq \begin{bmatrix} maxURRP_i \\ 0 \end{bmatrix} \\ &\forall j = 1 \ldots n_w \\ &\begin{bmatrix} 0 \\ -maxDRRW_j \end{bmatrix} \leq X_{wj}(t) - X_{wj}(t-1) \leq \begin{bmatrix} 0 \\ maxURRW_j \end{bmatrix} \\ &\forall j = 1 \ldots n_c \\ &\begin{bmatrix} -maxDRRCP_k \\ -maxDRRCW_k \end{bmatrix} \leq X_{ck}(t) - X_{ck}(t-1) \leq \begin{bmatrix} maxURRCP_k \\ maxURRCW_k \end{bmatrix} \end{aligned} \tag{8}$$

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.

3.8 Storage Continuity Relations

Equation 9 captures the power and water storage facility continuity relations as constraints.

$$\begin{aligned} S_u(t) = S_u(t-1) - X_{su}(t) \quad \forall t, \forall u = 1 \ldots n_s \\ \sigma_v(t) = \sigma_v(t-1) - X_{\sigma v}(t) \quad \forall t, \forall v = 1 \ldots n_\sigma \end{aligned} \tag{9}$$

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

3.9 Initial Conditions

Finally, the initial conditions of the two types of storage facilities are taken as constraints in Equation 10.

$$\begin{aligned} S_u(t) = 0 \quad \forall u = 1 \ldots n_s \\ \sigma_v(t) = 0 \quad \forall v = 1 \ldots n_\sigma \end{aligned} \tag{10}$$

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

4 SIMULATION METHODOLOGY

The optimization program in the previous section was demonstrated on a hypothetical test case adapted from previous efforts focussed on the corresponding economic dispatch problem [2, 3, 27–29]. This data is selected for two reasons: 1) The timing of power and water demand peaks and troughs is typical in the GCC and, 2) the range of the power and water demands

TABLE 1. Plant and Cost Data

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)	Startup Cost ($)
Power	i_1	500	0	100	0	200	100	0	0	500
Power	i_2	400	0	80	0	200	100	0	0	400
Power	i_3	400	0	80	0	200	100	0	0	200
Power	i_4	350	0	70	0	200	100	0	0	400
Coproducts	k_1	800	200	160	30	200	100	100	100	500
Coproducts	k_2	600	150	120	23	200	100	50	50	500
Coproducts	k_3	400	100	80	15	200	100	50	50	400
Water	j_1	0	250	0	0	0	0	50	50	200

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

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 Tab. 1. Table 2 shows 24 hours of power and water demand data used for the simulation. 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 Tab. 3. 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 [30–32]. Therefore, the case maintains limited storage capacity but large charging and discharging abilities; especially in the case of water storage. 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.

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 languages were used together; the former for data handling and visualization and the latter for optimization. The in-built DICOPT solver was used. The code was executed on a desktop computer with a 2.4 GHz

TABLE 2. Power & Water Demand Data [2, 3]

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

Intel Xeon processor in approximately 30 seconds for each of the test cases.

5 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.

5.1 Base Case - Limited Storage, Limited Charging Capabilities

Figures 2 and 3 show the power and water generation profiles respectively, over the 24 hours for the base case. The optimization successfully completed in spite of a nearly 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 in real life unit commitment.

TABLE 3. Storage Capacity and Charging Rates

	maxGenS units(MWh)	**maxGenσ** units(m3)	**maxStoreS** units (MW)	**maxStoreσ** units (m3/hr)
Base Case	500.00 1250.00 1350.00	250.00 500.00	200.00 300.00 400.00	50.00 50.00
Singapore Case	500.00 1250.00 1350.00	250.00 500.00	400.00 600.00 800.00	100.00 100.00
Middle East Case	800.00 1500.00 1800.00	400.00 800.00	400.00 600.00 800.00	100.00 100.00

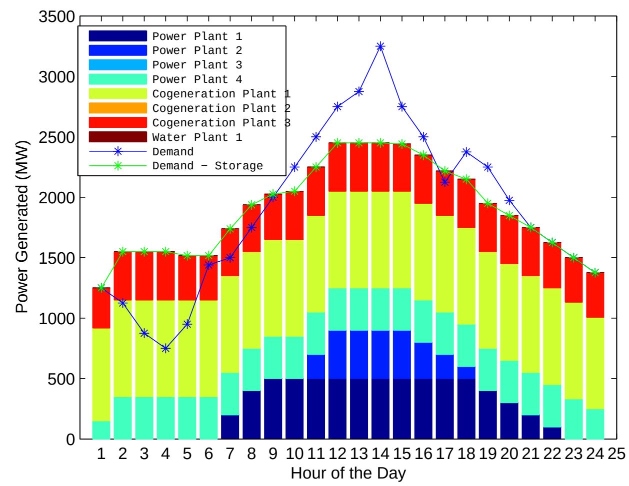

FIGURE 2. Base Case,Power Generation and Demand Profile Over 24 Hour Period

From the figures it is seen that cogeneration plants 1 and 3 and power plant 2 are selected as the units of "first-choice" and are operated at or close to their full capacity for the 24 hour time period for both electricity and water supply. Cogeneration plant 3 appears to be selected in place of cogeneration plant 2, inspite of the fact that it has higher cost-coefficients because of its slightly lower start-up costs. In the power system, these plants are complemented by power plant 4 as the final baseload plant.

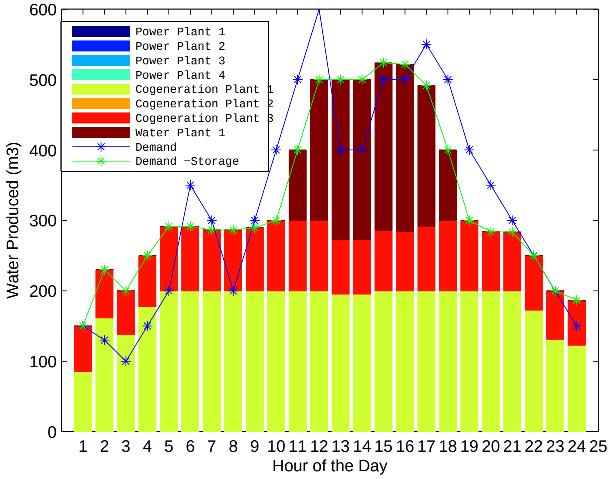

FIGURE 3. Base Case, Water Production Over 24 Hour Period

The single product water plant and the power plants 1 and 2 are essentially being used as peaking plants; coming into operation only to meet periods of high demand. The difference between the blue and green lines represents the contribution of the energy and water storage units to satisfying demand in any given time block. This contribution is fairly modest in this case, particularly for water production as storage capabilities are limited both with regards to capacity and discharge rate.

Figure 4 shows the contributions to total cost in each time block. The base case total costs amount to $8,677 which is used for comparison in the next two cases.

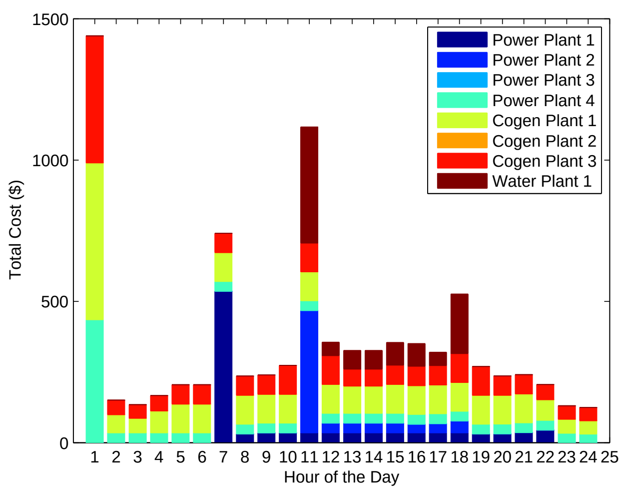

FIGURE 4. Base Case, Total Production Cost over 24 Hour Period.

5.2 Singapore Inspired Case - Limited Storage, Large Charging Capabilities

Singapore's water management challenges are well known [31, 32]. 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.

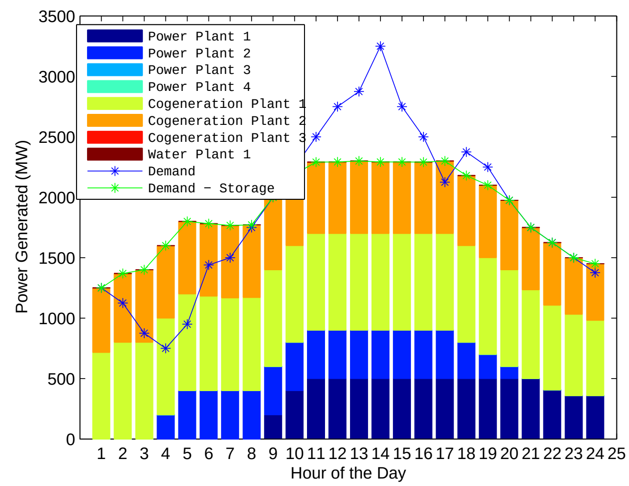

FIGURE 5. Singapore Inspired Case, Power Generation and Demand Profile Over 24 Hour Period

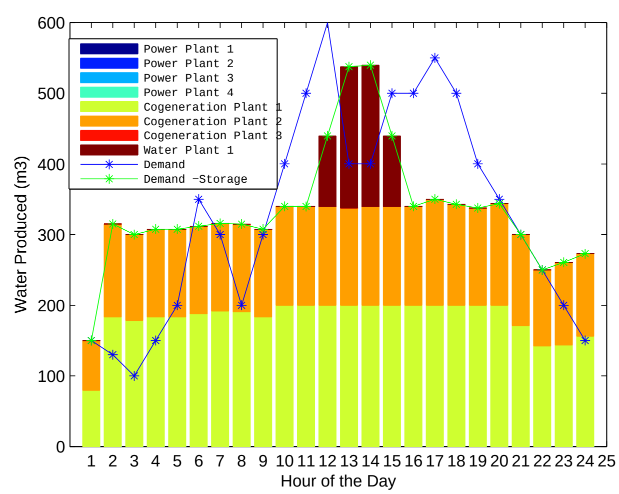

FIGURE 6. Singapore Inspired Case, Water Production Over 24 Hour Period

Figures 5 and 6 show the power and water production profile over 24 hours. In contrast to the previous section, the two large cogeneration plants act as the units of first choice in this case. The large charging and discharging abilities enable better use of storage as evidenced by the much flatter water production profile in Figure 6. The role of the large charging rates for the water storage in particular can further be observed from the difference between the blue and green lines in Figure 6. The water storage facilities are now seen to saturate during the morning hours resulting in complete utilization (Table 4). The total costs amount to \$7,522, a 13.3 % reduction in comparison to the base case.

TABLE 4. Peak Electricity and Water Storage Comparison

	Peak Electricity Storage (MWh)	Utilization (%)	Peak Water Storage (m^3)	Utilization (%)
Base Case	2996	96	406	54
Singapore Case	3100	100	750	100
Middle East Case	4100	100	899	75

5.3 Middle East Inspired Case - Large Storage, Large Charging Capabilities

The Middle East, and especially countries within the Gulf Cooperation Council, have well known water scarcity challenges [33]. 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 [34] which introduce new dynamics to the power grid as variable energy resources [35]. Therefore, energy and water storage technologies present themselves as key enabling technologies for the successful management of the energy-water nexus.

To that effect, Figures 7 and 8 show the total power and water production over the next 24 hours. With the increase of both water and electricity storage capacity, the observations made in the previous case are even more pronounced. The water production, Figure 8, is very strongly flattened over the course of the day and resultantly, the pure water plant, previously selected as a peaking plant because it has a zero minimum production requirement (Table 1), is not selected in this case. Similarly energy production, Figure 7, is also strongly flattened with all plants operating at, or close to, full capacity for the time that they are online. There is a very pronounced contribution from storage in the peak demand period between hours 9 and 16. While the electricity storage capacity is fully utilized the water storage capacity

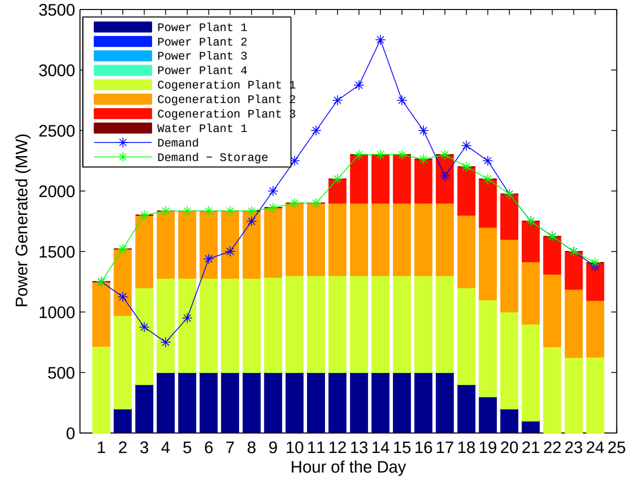

FIGURE 7. Middle East Inspired Case, Power Generation Profile Over 24 Hour Period

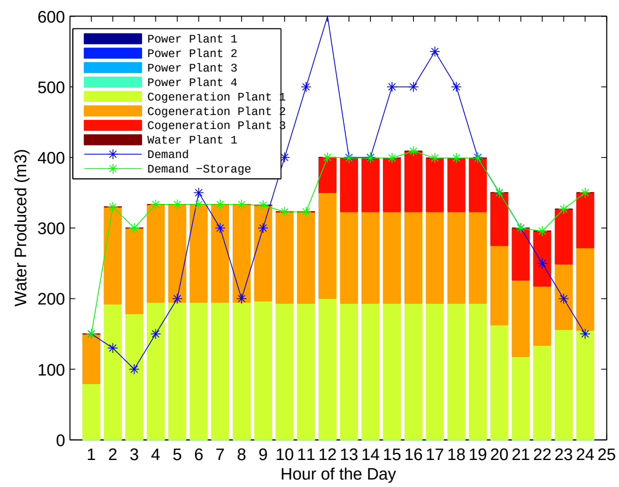

FIGURE 8. Middle East Inspired Case, Water Production Over 24 Hour Period

is in excess of the requirement (Table 4). In total, the production costs amount to \$ 6,983; a 7.2 % reduction over the previous case and a 19.5 % reduction over the base case.

An additional benefit of the increased storage is illustrated in Figure 9 which shows that in spite of large fluctuations in the power to water demand ratios over the course of the 24 hour period, the cogeneration plants are able to maintain fairly constant power to water production ratios.

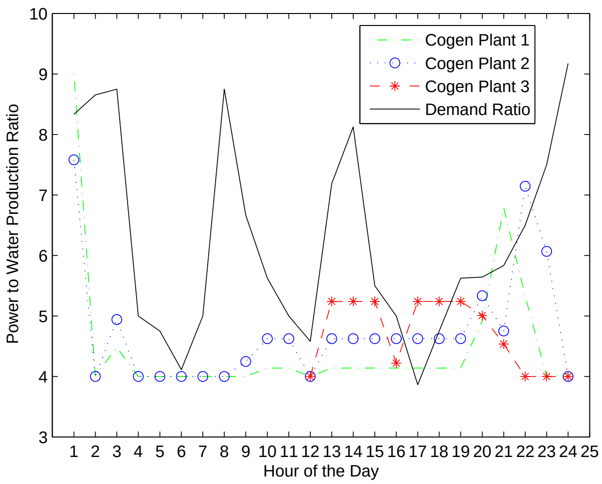

FIGURE 9. Cogeneration Plant Power to Water Ratios

6 Conclusions and Future Work

This work has presented a formulation for the joint unit commitment of electric power, water and cogeneration plants. It builds upon previous work [2, 3, 36] that presented the corresponding economic dispatch problem. The formulation was implemented and solved using MATLAB and GAMS.

Traditionally water distribution and power distribtution networks have been thought of as separate uncoupled infrastructure systems, however in the presence of cogeneration facilities this is not the case. There are two ways to handle this situation. One possible option is to try to reduce 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. However, this generally is only applicable to new plant installations but not to retrofitting scenarios. The other option is to better understand the coupling between these two resources and use well established algorithms to optimize their production. The simultaneous co-optimization of power and water networks presented here aims to contribute to this latter effort. It enables the realization of cost and efficiency benefits across the two infrastructure systems.

The presented work has also demonstrated the effect of different levels of electricity and water storage on the joint unit commitment problem through three case studies. The incorporation of storage into the energy-water nexus system helped alleviate binding constraints in all three cases and therefore acts directly at the margin for maximal cost-efficiency. Most notably, greater storage capacity or charging capability, was seen to alleviate the power-to-water ratio constraints of the cogeneration plants in the second and third cases. The second case was inspired by the water management challenges found in Singapore. Here, it was found that when only limited storage capacity is available, it is critical to increase the storage charging capabilities to encourage their full utilization. This resulted in a 13.3% cost reduction over the base case. The third case was inspired by the water management challenges found in the Middle 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 further reduce costs. In this hypothetical case, costs were reduced another 7.2%.

While the formulated unit commitment problem, like the referenced economic dispatch problems, can be implemented in existing integrated electricity and water authorities, greatest economic benefit will only 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 explore more detailed economic justification for integrated electricity and water markets.

NOMENCLATURE

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_{ck} Cost function for k^{th} coproduction plant
C_G Production cost function
C_{pi} Cost function for i^{th} power generation plant
C_{wj} Cost function for j^{th} water production plant
$C^s_{ck}(t)$ Startup cost incurred by k^{th} coproduction plant in time block t
C^s_{pi} Startup cost incurred by i^{th} power generation plant in time block t
C^s_{wj} Startup cost incurred by j^{th} water production plant in time block t
$\mathscr{C}^s_{ck}$ Startup cost for k^{th} coproduction plant
$\mathscr{C}^s_{pi}$ Startup cost for i^{th} power generation plant
$\mathscr{C}^s_{wj}$ Startup cost for j^{th} water production plant
D_p Electrical power demand
D_w Water demand
$\mathscr{K}_{ck}$ Constant prod. cost function coeff. of k^{th} power plant
$\mathscr{K}_{pi}$ Constant prod. cost function coeff. of i^{th} power plant
$\mathscr{K}_{wj}$ Constant prod. cost function coeff. of j^{th} water plant
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
n_σ Number of water storage 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
U_{ck} Binary unit commitment status variable for the k^{th} power plant
U_{pi} Binary unit commitment status variable for the i^{th} power plant
U_{wj} Binary unit commitment status variable for the j^{th} water plant
x_{pi} Power generated at the i^{th} power plant
x_{wj} Water produced at the j^{th} water plant
x_{cpk} Power generated at the k^{th} coproduction plant
x_{cwk} Water produced at k^{th} coproduction plant
x_{su} Power discharged by u^{th} electric energy storage plant
$x_{\sigma v}$ Water released by v^{th} water storage plant
σ_v Water level of the v^{th} water storage plant
minGenP_i Min. capacity limit of the i^{th} power plant
minGenW_j Min. capacity limit of the j^{th} water plant
minGenC_k Min. capacity limit of the k^{th} coproduction plant
minGenS_u Min. capacity limit of the u^{th} energy storage plant
$\text{minGen}_{\sigma v}$ Min. capacity limit of the v^{th} water storage plant
maxGenP_i Max. capacity limit of the i^{th} power plant
maxGenW_j Max. capacity limit of the j^{th} water plant
maxGenC_k Max. capacity limit of the k^{th} coproduction plant
maxGenS_u Max. capacity limit of the u^{th} energy storage plant
$\text{maxGen}_{\sigma v}$ Max. capacity limit of the v^{th} water storage plant
maxDRRP_i Max. down ramp of the i^{th} power plant
maxDRRW_j Max. down ramp of the j^{th} water plant
maxDRRCP_k Max. power down ramp of k^{th} coproduction plant
maxDRRCW_k Max. water down ramp of k^{th} coproduction plant
maxURRP_i Max. up ramp of the i^{th} power plant
maxURRW_j Max. up ramp of the j^{th} water plant
maxURRCP_k Max. power up ramp of the k^{th} coproduction plant
maxURRCW_k Max. water up ramp of the k^{th} coproduction plant
minStoreS_u Min. storage limit of the u^{th} energy storage plant
$\text{minStore}\sigma_v$ Min. storage limit of the v^{th} water storage plant
maxStoreS_u Max. storage limit of the u^{th} energy storage plant
$\text{maxStore}\sigma_v$ Max. storage limit of the v^{th} water storage plant

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