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The Impact of Storage Facilities on the Simultaneous Economic Dispatch of Power and Water Networks Limited by Ramping Constraints.

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ABSTRACT

Recently, the production and consumption of energy and water resources and their potential coupling in what is often called the energy-water nexus has gained attention as an issue of global concern[1, 2]. Ultimately, a significant amount of water is required to produce energy and vice versa [2, 3]; motivating the need for co-optimization based approaches for the two resources. Recently, one such simultaneous co-optimization method has been contributed for the economic dispatch of networks that include water, power and co-production facilities [4]. That study showed that capacity and process constraints often limit total production cost. This paper seeks to add plant ramping behavior as potentially binding constraints and investigate the impact of water and storage facilities as a technology that can help alleviate binding constraints and lead to more levelized production and cost levels. The paper builds upon the optimization program provided in previous work [4] to develop two optimization programs with and without storage facilities and compares their respective results. Storage facilities are shown to reduce total operating costs and lead to more levelized daily production suggesting that they have an important role to play in the optimization of the energy-water nexus.

1. INTRODUCTION

Recently, the production and consumption of energy and water resources and their potential coupling in what is often called the energy-water nexus has gained attention as an issue of global concern[1, 5]. 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 [6]. Similarly, energy management has become an important concern for utilities that deliver water for residential, industrial and irrigational purposes[3]. Such coupling also exists purely on the supply side; the steam balance found in desalination plants effectively couples the thermal heat by-product of power generation to the production of potable water [7-10]. This last type of supply side coupling is particularly important in hot and arid climates like the gulf region where there is both a heavy reliance on desalination technology due the scarcity of potable ground water as well as on climate-controlled buildings due to elevated ambient temperatures. Fundamentally, water and energy resources are valuable commodities that require co-optimization especially when demand for their consumption continues to grow. For these reasons, this paper specifically seeks to address energy-water supply side couplings in the energy-water nexus.

A recent paper [4] contributed an optimization program for the simultaneous economic dispatch of systems that consist of power generation, co-production, and potable water production plants. 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. Nevertheless, recent discussion in the smart (power) grid space [11] have motivated the need to consider the flexibility or ramping capabilities of power plants. Therefore, this paper specifically addresses ramping constraints and investigates the role of both water and energy storage as a means for their partial alleviation.

Energy storage is commonly seen to bring multiple positive effects to power grid dispatch[12, 13]. Daily load curves and the associated hourly electricity prices typically reach their minima in the early morning hours and their maxima in the afternoon. Hence, an energy storage utilization strategy in which power is stored at low periods and used during peak periods provides the potential for "peak-shaving" capability in which both power generation and costs are more levelized over the course of the day. Furthermore, energy storage is seen as a grid stabilizing technology in the case of variable energy resources such as demand side management and renewable energy. Similar concepts are seen to hold for water production and distribution. Here, for the first time, the impacts of both water and energy storage are studied simultaneously.

The remainder of the paper develops in six sections. Section 2 highlights aspects of the background literature to power-water co-optimization and storage. The dual-product co-optimization literature is reviewed and the current literature on storage is examined. The paper then presents the problem formulation for the co-optimization of power and water incorporating ramping and storage in Section 3 and then proceeds to explain the simulation methodology in Section 4. Section 5 presents the results for a system with eight plants under two different operating scenarios: with and without storage. The paper concludes in Section 6.

2. BACKGROUND

This section briefly explains the relevant existing literature in two subsections. First, previous work in power-water co-optimization is reviewed, followed by a discussion of the incorporation of energy storage into power system dispatch.

2.1 Co-optimization of power and water

Optimization research has been conducted on cogeneration water and power facilities. Generally speaking, this research has focused on the optimization and proper operation of one specific plant and hence do not provide an extensible and general optimization formulation for multiple plant optimization. More dual-product multi-plant optimization programs have been conducted in northern European countries where co-produced steam is seen as a potential valuable by-product of power generation[14, 15]. Heat, in the form of steam, can be used for heating purposes in industrial as well as district applications leading to numerous quantifiable benefits including: gains in energy efficiency, power reliability and quality and reductions in costs, air pollution, greenhouse emissions, and grid congestion [16]. These works typically define a single objective function for cogeneration plants that is a function of the power and heat produced subject to demand and capacity constraints.[14, 15, 17]

Analogously, and most recently, one work co-optimizes the total operating costs of power plants, pure water plants and cogeneration plants subject to demand, capacity and process constraints[4]. This paper seeks to build upon the results of this work with the inclusion of the increasingly important flexibility or ramping characteristics of the production facilities as well as the impact of energy and water storage facilities.

2.2 Storage facilities for power and water

Increasing attention has been devoted to storage facilities within dispatch algorithms of power grids. Fundamentally speaking, energy storage facilities couple the normally independent optimization time blocks as the storage state of a subsequent time block depends on the prior state by the amount of power charged or discharged. As such, dispatch formulations with storage lend themselves to a unit commitment formulation[18, 19]. The work in this paper uses a "centralized look-ahead" economic dispatch which closely resembles the real-time market operations of North American independent system operators. These formulations have been customized for battery[20, 21] and pumped hydro[22, 23] storage. The last of these is particularly interesting in the context of the energy-water nexus as it presents a new technology by which the two resources are coupled. Finally, these works differ in their treatment of the objective function with some formulations, especially those addressing pumped hydro storage , include a specific operating cost to charge and discharge while others [24] add no additional terms.

3. CO-OPTIMIZATION OF POWER AND WATER: Optimization FORMULATION

Provided the background of the previous section, the formulation of the power-water co-optimization is as follows. Minimize the production cost objective function $C_G(t)$ with respect to the quantities,

- x_{pi} -- the power generated at the i[th] power plant
- x_{wj} – the water produced at the j[th] water plant
- x_{cpk} -- the power generated at the k[th] coproduction plant
- x_{cwk} -- the water produced at the k[th] coproduction plant
- x_{su} -- the power discharged by the u[th] power storage facility
- $x_{\sigma v}$ -- the water released by the v[th] water storage facility

over the discrete-time interval t=[1,…,T]. These terms are organized within the following notation: $X_p=[x_p,0]^T$, $X_w=[0,x_w]^T$, $X_c=[x_{cp}, x_{cw}]^T$, $X_s=[x_s,0]^T$, $X_\sigma=[0,x_\sigma]^T$ such that the objective function becomes formally:

$$\sum_{t=1}^{T} C_G(X_{pi}(t), X_{wj}(t), X_{ck}(t)) = \sum_{t=1}^{T}\left(\sum_{i=1}^{n_p} C_{pi}\left(X_{pi}(t)\right) + \sum_{j=1}^{n_w} C_{wj}\left(X_{wj}(t)\right) + \sum_{k=1}^{n_c} C_{ck}\left(X_{ck}(t)\right)\right) \quad (1)$$

and is subjected to power and water capacity (2), energy and water storage capacity (3), demand (4), process (5), and ramping constraints (6) as well as storage continuity relations (7) and initial conditions(8).

$$\begin{array}{lll} MinGenP_i \le X_{pi} \le MaxGenP_i & & i = 1\ldots n_p \\ MinGenW_j \le X_{wj} \le MaxGenW_j & & j = 1\ldots n_w \\ MinGenC_k \le X_{ck} \le MaxGenC_k & \forall & k = 1\ldots n_c \\ MinGenS_u \le X_{su} \le MaxGenS_u & & u = 1\ldots n_s \\ MinGen\sigma_v \le X_{\sigma v} \le MaxGen\sigma_v & & v = 1\ldots n_\sigma \end{array} \quad (2)$$

$$\begin{array}{ll} MinStorageS_u \le S_u(t) \le MaxStorageS_u & \forall t, \forall \; i = 1\ldots n_s \\ MinStorage\sigma_v \le \sigma_v(t) \le MaxStorage\sigma_v & \qquad j = 1\ldots n_\sigma \end{array} \quad (3)$$

$$\sum_{i=1}^{n_p} X_{pi}(t) + \sum_{j=1}^{n_w} X_{wj}(t) + \sum_{k=1}^{n_c} X_{ck}(t) + \sum_{u=1}^{n_s} X_{su}(t) + \sum_{v=1}^{n_\sigma} X_{\sigma v}(t) = D(t) \quad \forall \quad t = 1\ldots T \quad (4)$$

$$r_k^{lower} \le \frac{x_{cpk}}{x_{cwk}} \le r_k^{upper} \quad \forall k = 1\ldots n_c \quad (5)$$

$$\begin{array}{ll} \begin{bmatrix} \text{-maxDRRP}_i \\ 0 \end{bmatrix} \le X_{pi}(t) - X_{pi}(t\text{-}1) \le \begin{bmatrix} \text{maxURRP}_i \\ 0 \end{bmatrix} & i = 1\ldots n_p \\ \begin{bmatrix} 0 \\ \text{-maxDRRW}_j \end{bmatrix} \le X_{wj}(t) - Y_{wj}(t\text{-}1) \le \begin{bmatrix} 0 \\ \text{maxURRW}_j \end{bmatrix} & \forall \; j = 1\ldots n_w \\ \begin{bmatrix} \text{-maxDRRCP}_k \\ \text{-maxDRRCW}_k \end{bmatrix} \le X_{ck}(t) - X_{ck}(t\text{-}1) \le \begin{bmatrix} \text{maxURRCP}_k \\ \text{maxURRCW}_k \end{bmatrix} & k = 1\ldots n_c \end{array} \quad (6)$$

$S_u(t) = S_u(t-1) - X_{su}(t)$ $\sigma_v(t) = \sigma_v(t-1) - X_{\sigma v}(t)$ $\quad \forall t, \forall \; u = 1 \ldots n_s, \; v = 1 \ldots n_\sigma$	(7)
$S_u(t=1) = 0$ $\sigma_v(t=1) = 0$ $\quad \forall \; u = 1 \ldots n_s, \; v = 1 \ldots n_\sigma$	(8)

where:

- C_{pi} – the cost function for the i^{th} power generation facility
- C_{wj} – the cost function for the j^{th} water production facility.
- C_{ck} – the cost function for the k^{th} coproduction facility.
- n_p – the number of power generation facilities.
- n_w – the number of water production facilities.
- n_c – the number of coproduction facilities.
- n_s – the number of energy storage facilities.
- n_σ – the number of water storage facilities.
- $MinGenP_i$ – minimum power generation capacity limit of i^{th} plant
- $MaxGenP_i$ – maximum power generation capacity limit of i^{th} plant
- $MinGenW_j$ – minimum water production capacity limit of j^{th} plant
- $MaxGenW_j$ – maximum water production capacity limit of j^{th} plant
- $MinGenC_k$ – minimum power & water capacity limit of k^{th} plant
- $MaxGenC_k$ – maximum power & water capacity limit of k^{th} plant
- $MinGenS_u$ – minimum power discharge of the u^{th} energy storage facility
- $MaxGenS_u$ – maximum power discharge of the u^{th} energy storage facility
- $MinGen\sigma_v$ – minimum water flow limit of the v^{th} water storage facility
- $MaxGen\sigma_v$ – maximum water flow limit of the v^{th} water storage facility
- $MinStorageS_u$ – minimum energy storage capacity limit of the u^{th} energy storage facility
- $MaxStorageS_u$ – maximum energy storage capacity limit of the u^{th} energy storage facility
- $MinStorage\sigma_v$ – minimum water storage capacity limit of the v^{th} water storage facility
- $MaxStorage\sigma_v$ – maximum water storage capacity limit of the v^{th} water storage facility
- $D(t) = [D_p(t), D_w(t)]$ – the demand for power and water respective at the t^{th} time step.
- r_k^{lower} – the lower power to water ratio process limit of the k^{th} coproduction facility.
- r_k^{upper} – the upper power to water ratio process limit of the k^{th} coproduction facility.
- $maxDRRP_i$ – the maximum down ramp rate for the i^{th} power generation facility.
- $maxURRP_i$ – the maximum up ramp rate for the i^{th} power generation facility.
- $maxDRRW_j$ – the maximum down ramp rate for the j^{th} water production facility.
- $maxURRW_j$ – the maximum up ramp rate for the j^{th} water production facility.
- $maxDRRCP_k$ – the maximum down ramp rate for the k^{th} coproduction facility.
- $maxURRCP_k$ – the maximum up ramp rate for the k^{th} coproduction facility.
- $maxDRRCW_k$ – the maximum down ramp rate for the k^{th} coproduction facility.
- $maxURRCW_k$ – the maximum up ramp rate for the k^{th} coproduction facility.
- S_u – the energy storage level of the uth energy storage facility
- σ_v – the water storage level of the vth water storage facility.

and the three component cost functions C_{pi}, C_{wj}, C_{ck} are assumed to exhibit a quadratic structure with respect to their associated production variables. The cost function coefficients are appropriately sized positive constant matrices based upon the heat rate characteristics of their respective production units as described in [4]. The heat rate for different types of plants are well discussed in the literature[25].

4. SIMULATION METHODOLOGY

The optimization program provided above was demonstrated on a hypothetical system composed of three coals plants, a natural gas plant, three cogenerators and one pure water plant. The data for heat rates, demand profile, process constraint ratios and maximum and minimum capacity was taken from [4]. This optimization introduces storage facilities and ramping constraints to the above mentioned problem. The ramping constraints are mentioned below. In addition, a total of five storage facilities was introduced, three for power storage and two for water. Each of these has a maximum storage capacity. In addition, there is a limit to how much power can be charged or discharged in one time period.

The implementation was programmed in a combination of MATLAB and GAMS languages on a HP Laptop with an Intel Core i5 CPU2.27 GHz processor. The CONOPT solver was used to execute the optimization. In total, the code for the hypothetical system above completed within 5 seconds.

5. RESULTS

The results of the optimization program in Section 3 as applied to the hypothetical system described in Section 4 are now presented in eight Figures. Figures 1, and 2 show the generation levels of power without and with storage respectively. Figures 3, and 4 show the generation levels of water without and with storage respectively. Figures 5 and 6 show the energy storage and water storage profile over the time period. Figures 7 and 8 show the cost profile for the case without storage and the one with storage respectively.

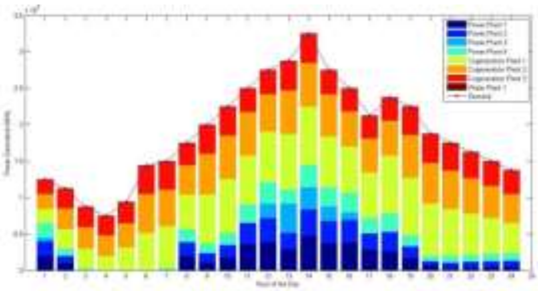

Figure 1. Power generation and demand profile over 24 hour period

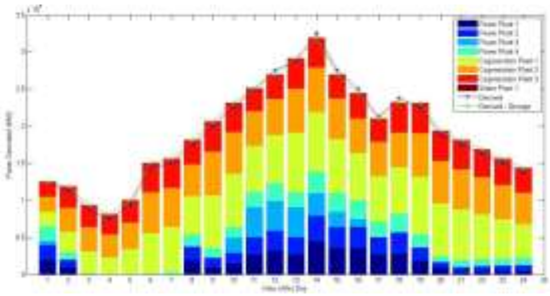

Figure 2. Power generation and demand profile over 24 hour period with storage

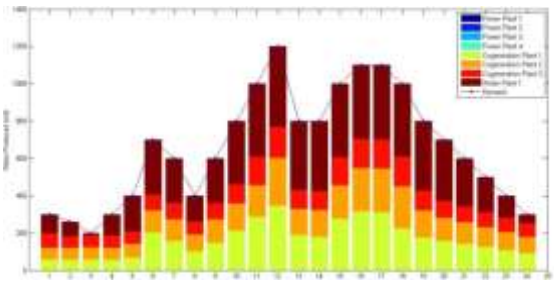

Figure 3. Water production and demand profile over 24 hour period.

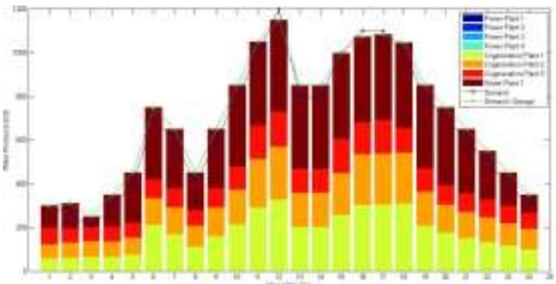

Figure 4. Water production and demand profile over 24 hour period with storage and ramping

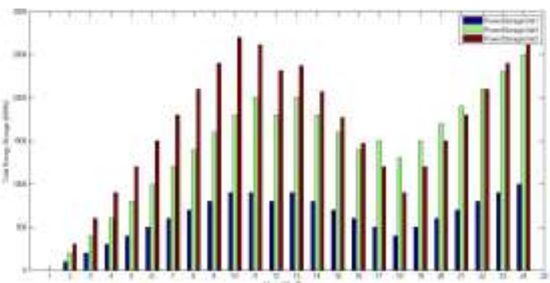

Figure 5 Energy storage profile over 24 hour period

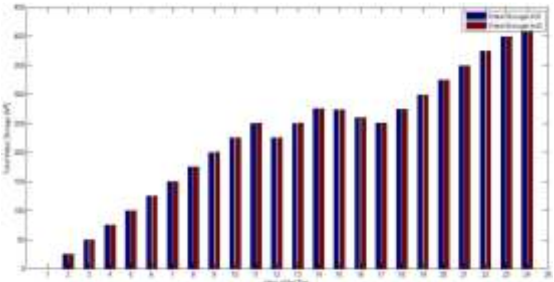

Figure 6 Water Storage profile over 24 hour period

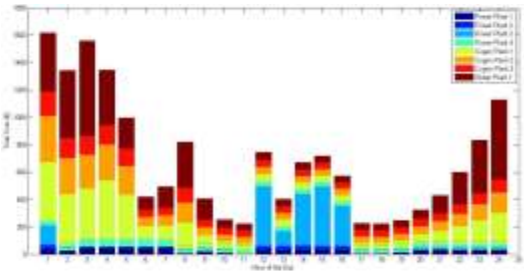

Figure 7 cost incurred by different units over 24 hour period

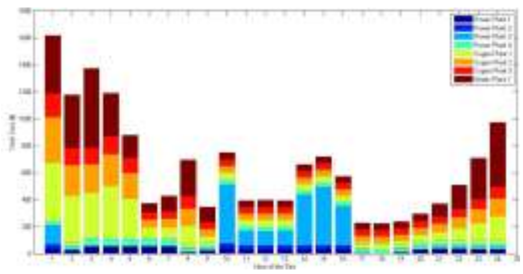

Figure 8 Cost incurred by different units over 24 hour period with storage

Figure 1 and Figure 2 show an optimal result in which the total power generated in each hour matches the power demand profile exactly in both cases. 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. Nevertheless, the two figures do show differences in how the demand is met. In the first case, when no storage capacity is available, the production facilities are forced to meet the demand exactly in each time period. In contrast, the second case demonstrates a more levelized power generation profile. Energy storage facilities charge in the morning hours and discharge during peak periods. Interestingly, in the presence of coproduction facilities, power storage facilities provide an additional benefit than simply peak load shaving. Rather, in time periods in which the demand ratio of power to water is particularly elevated, the energy storage facilities can serve to complement the already strained process-limited co-production facilities.

Figures 3 and 4 demonstrate similar behavior in the water domain, and, as expected, the presence of storage leads to a more levelized production of water while still meeting the demand. As in the power domain, the water storage facilities have the potential to alleviate the coproduction facilities when the demanded ratio of power to water is particularly low.

Figures 5 and 6 indicate the total energy and water storage in each time period respectively beginning from the previously mentioned zero initial conditions. Here, morning storage behavior and peak discharging behavior becomes apparent. Interestingly, the optimal solution did not cause the end-of-day storage levels to return to the zero initial storage conditions. In mathematical principle, this solution does not pose any difficulties. However, in practice, it implies that two days with similar profiles would 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.

Figured 7 and 8 indicate the operation cost of the entire system for each time period without and with storage. The total operation cost values were found to be 1.657e4 and 1.505e4 dollars respectively over the 24 hour span. As a first observation, in both figures, the total costs seem to be higher during periods of low demand. This atypical result originates from the fact that the heat rate 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. This strongly quadratic cost curve data is particularly noticeable in the coproduction facilities than in the single-product facilities; causing the coproduction facilities to become units of “first-choice”. It must be noted that the process constraints regarding power to water ratio for the cogenerator plants also influence their being chosen first. A similar result was observed in [4]. The power and water plants are essentially being used as peaking plants, coming into operation to meet periods of high demand.

Despite these similarities, the two cases do differ. The total costs in the second case are lower due to the “peak-shaving” characteristic. Essentially, the storage facilities, which were modeled to have no impact on the objective function, provide cost relief from the single-product facilities which are being used during peak periods in the very steep regions of their respective cost curves. This reduction in cost is noticeable but not dramatic given the relative quantity of storage capacity to power and water production. Furthermore, the results suggest that storage facilities can have a much greater cost and production impact on fleets of facilities with less pronounced cost curves.

6. CONCLUSIONS

This paper has improved upon a simultaneous co-optimization program for the economic dispatch of water and power by adding storage facilities and modeling the impacts of ramping constraints in all types of plants. The introduction of ramping constraints reflects more realistic scenarios in which power and water demand can change sharply from one time period to the next. The results show that storage facilities can have significant benefit in the peak shaving sense in both the power and water domains on both physical production as well as total operating costs. This benefit would be more pronounced not just with greater storage capacity but also if the marginal power generation and water production units were operating in more flat regions of their respective cost curves. Most interestingly, power 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; thus showing the tremendous interconnected nature of these two valuable and essential resources.

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