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

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ABSTRACT

In regions that utilize thermal desalination as part of their water supply portfolio, the cogeneration of water and power in cogeneration desalination plants couples the supply sides of the electricity and water grids. For a fixed plant design, there is a limited range of ratios of generated electric power to produced water at any given time. 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. In this market, independent power producers, independent water producers and independent cogeneration plants would submit bids to satisfy demand over a time horizon to a clearing mechanism, indicating relevant physical constraints. The mechanism would then optimize supply of both electricity and water over the time horizon of interest. Recently, a simultaneous co-optimization method has been contributed for the economic dispatch of networks that include water, power and cogeneration facilities in such an integrated market. This paper builds upon this foundation with the introduction of the corresponding 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 (GCC). In regions that do have electricity 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 operators 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 (PWPA) stipulate, in advance, the quantities of power and water to be bought by the grids from these producers at a fixed price. The agreements typically 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. Furthermore, 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 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 $t = [1,\ldots,T]$.

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

Here, the individual production quantities are organized into two-vectors to address the two products simultaneously. $X_{pi} = [x_{pi,0}]$, $X_{wj} = [0, x_{wj}]$, $X_{ck} = [1, x_{cpk}, x_{cwk}]$, $X_{su} = [x_{su}, 0]^T$, $X_{sv} = [0, x_{sv}]^T$.

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

$$
C_{pi} = X_{pi}^T A_{pi} X_{pi} + B_{pi} X_{pi} + U_{pi} \mathcal{K}_{pi}
C_{wj} = X_{wj}^T A_{wj} X_{wj} + B_{wj} X_{wj} + U_{wj} \mathcal{K}_{wj}
C_{ck} = X_{ck}^T A_{ck} X_{ck} + B_{ck} X_{ck} + U_{ck} \mathcal{K}_{ck}
$$

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 $C_{pi}^s(t), C_{wj}^s(t), C_{ck}^s(t)$ incurred in any given time block $t$ are equal to the constant startup costs $\mathcal{C}_{pi}^s, \mathcal{C}_{wj}^s, \mathcal{C}_{ck}^s$ 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:

$$
C_{pi}^s(t) \geq \mathcal{C}_{pi}^s(U_{pi}(t) - U_{pi}(t-1)) \forall t, \forall i = 1\ldots n_p
C_{wj}^s(t) \geq \mathcal{C}_{wj}^s(U_{wj}(t) - U_{wj}(t-1)) \forall t, \forall j = 1\ldots n_w
C_{ck}^s(t) \geq \mathcal{C}_{ck}^s(U_{ck}(t) - U_{ck}(t-1)) \forall t, \forall k = 1\ldots n_c
$$

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.

$$
\min GenP_i \ast U_{pi} \leq X_{pi} \leq \max GenP_i \ast U_{pi} \forall i = 1\ldots n_p
\min GenW_j \ast U_{wj} \leq X_{wj} \leq \max GenW_j \ast U_{wj} \forall j = 1\ldots n_w
\min GenC_k \ast U_{ck} \leq X_{ck} \leq \max GenC_k \ast U_{ck} \forall k = 1\ldots n_c
\min GenS_u \leq X_{su} \leq \max GenS_u \forall u = 1\ldots n_s
\min GenS_v \leq X_{sv} \leq \max GenS_v \forall v = 1\ldots n_s
$$
As is typically found in the unit commitment problem, it is important to note that Eqn. 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 Eqn. 5 govern the minimum and maximum capacity on the stock of energy and water stored.

\[
\text{minStore}_{S_u} \leq S_u(t) \leq \text{maxStore}_{S_u} \quad \forall t, \forall u = 1 \ldots n_s
\]
\[
\text{minStore}_{\sigma_v} \leq \sigma_v(t) \leq \text{maxStore}_{\sigma_v} \quad \forall t, \forall v = 1 \ldots n_\sigma
\]  

\[ (5) \]

### 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.

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

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.

\[ (6) \]

### 3.6 Co-Production Process Constraints

Equation 7 represents a process constraint for coproduction facilities.

\[
r_k^{\text{lower}} \leq \frac{X_{cpk}}{x_{cwk}} \leq r_k^{\text{upper}} \quad \forall k = 1 \ldots n_{cp}
\]

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.

\[ (7) \]

### 3.7 Ramping Constraints

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

\[
\forall i = 1 \ldots n_p
\]
\[
\left[ -\text{maxRRR}_{pi}, 0 \right] \leq X_{pi}(t) - X_{pi}(t-1) \leq \left[ \text{maxURR}_{pi}, 0 \right]
\]

\[
\forall j = 1 \ldots n_w
\]
\[
\left[ -\text{maxRRW}_{wj}, 0 \right] \leq X_{wj}(t) - X_{wj}(t-1) \leq \left[ \text{maxURW}_{wj}, 0 \right]
\]

\[
\forall j = 1 \ldots n_c
\]
\[
\left[ -\text{maxRRCP}_k, \text{maxURCP}_k \right] \leq X_{ck}(t) - X_{ck}(t-1) \leq \left[ \text{maxURCP}_k, \text{maxURCP}_k \right]
\]

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.

\[
S_u(t) = S_u(t-1) - X_{su}(t) \quad \forall t, \forall u = 1 \ldots n_s
\]
\[
\sigma_v(t) = \sigma_v(t-1) - X_{\sigma v}(t) \quad \forall t, \forall v = 1 \ldots n_\sigma
\]

\[ (9) \]

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 Eqn. 10.

\[
S_u(t) = 0 \quad \forall u = 1 \ldots n_s
\]
\[
\sigma_v(t) = 0 \quad \forall v = 1 \ldots n_\sigma
\]

\[ (10) \]

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

<table>
<thead>
<tr>
<th>Plant Type</th>
<th>Index</th>
<th>Max Power Capacity (MW)</th>
<th>Max Water Capacity (m³/hr)</th>
<th>Min Power Capacity (MW)</th>
<th>Min Water Capacity (m³/hr)</th>
<th>Max Power Up Ramp Rate (MW/hr)</th>
<th>Max Power Down Ramp Rate (MW/hr)</th>
<th>Minimum Water Up Ramp Rate (m³/hr²)</th>
<th>Minimum Water Down Ramp Rate (m³/hr²)</th>
<th>Startup Cost ($)</th>
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<td>200</td>
<td>100</td>
<td>0</td>
<td>0</td>
<td>500</td>
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<tr>
<td>Power</td>
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<td>0</td>
<td>80</td>
<td>0</td>
<td>200</td>
<td>100</td>
<td>0</td>
<td>0</td>
<td>400</td>
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<tr>
<td>Power</td>
<td>i₃</td>
<td>400</td>
<td>0</td>
<td>80</td>
<td>0</td>
<td>200</td>
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<td>0</td>
<td>0</td>
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<tr>
<td>Power</td>
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<td>Coproducts</td>
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Power Plant Cost Coefficients

<table>
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<tr>
<th>Aₚ</th>
<th>Bₚ</th>
<th>Cₚ</th>
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<tbody>
<tr>
<td>2.069e-4</td>
<td>-1.483e-1</td>
<td>5.711e+1</td>
</tr>
<tr>
<td>3.232e-4</td>
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<td>5.711e+1</td>
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Water Plant Cost Coefficients

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<tr>
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</table>

Coproduct Plant Cost Coefficients

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<th>Aₑ₁₂</th>
<th>Aₑ₂₂</th>
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<th>Bₑ₂</th>
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<td>4.433e-4</td>
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<td>-8.851</td>
<td>7.374e+2</td>
</tr>
</tbody>
</table>

is exaggerated to demonstrate the convergence capability of the selected optimization engine. The hypothetical test case is composed of 4 power plants, 3 co-production desalination facilities, and 1 reverse osmosis water plant. The associated plant and cost data is summarized in Table 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. The storage capacities and charging/discharging rates are as indicated in Table 3.

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 Intel Xeon processor in approximately 30 seconds for the test case.

5 RESULTS

This section presents the results for the test case. Figures 2 and 3 show the power and water generation profiles respectively, over the 24 hour period. 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.

From the figures it is seen that cogeneration plants 1 and 3 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. 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 in Fig. 2 and Fig. 3 represents the contribution of the energy and water storage units to satisfying demand in any given time block. The contribution of storage to satisfying peak demand is seen to be fairly modest in this case, particularly for water production as storage capabilities are limited both with regards to capacity and discharge rate. The power and water storage profiles are shown in Fig. 4 and Fig. 5 respectively.

Figure 7 shows the contributions to total cost in each time block. The total costs amount to $8,677 for the 24-hour period.

### Table 2. Power & Water Demand Data [2, 3]

<table>
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<tr>
<th>Hour</th>
<th>Power Demand (MW)</th>
<th>Water Demand (m³)</th>
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<tr>
<td>1</td>
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<td>2</td>
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<td>24</td>
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### Table 3. Storage Capacity and Charging Rates

<table>
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<th></th>
<th>maxGenS units(MWh)</th>
<th>maxGenσ units(m³)</th>
<th>maxStoreS units(MW)</th>
<th>maxStoreσ units(m³/hr)</th>
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<td>300.00</td>
<td>50.00</td>
</tr>
<tr>
<td></td>
<td>1350.00</td>
<td>400.00</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
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, 30] that presented the corresponding economic dispatch problem. The formulation was implemented and solved using MATLAB and GAMS.

Traditionally water distribution and power distribution 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.

While the formulated unit commitment problem, like the referenced economic dispatch problems, can be implemented in ex-
isting 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  
$C_{pi}$ Cost function for $i^{th}$ power generation plant  
$C_{wj}$ Cost function for $j^{th}$ water production plant  
$C_{ck}(t)$ Startup cost incurred by $k^{th}$ coproduction plant in time block $t$  
$C_{pi}(t)$ Startup cost incurred by $i^{th}$ power generation plant in time block $t$  
$C_{wj}(t)$ Startup cost incurred by $j^{th}$ water production plant in time block $t$  
$g_{ck}$ Startup cost for $k^{th}$ coproduction plant  
$g_{pi}$ Startup cost for $i^{th}$ power generation plant  
$g_{wj}$ Startup cost for $j^{th}$ water production plant  
$D_p$ Electrical power demand  
$D_w$ Water demand  
$\lambda_{ck}$ Constant prod. cost function coeff. of $k^{th}$ power plant  
$\lambda_{pi}$ Constant prod. cost function coeff. of $i^{th}$ power plant  
$\lambda_{wj}$ Constant prod. cost function coeff. of $j^{th}$ water plant  
$n_c$ Number of coproduction plants  
$n_p$ Number of power generation plants  
$n_e$ Number of electrical energy storage plants  
$n_w$ Number of water production plants  
$n_{\sigma}$ Number of water storage plants  
$r_{lower}$ Lower bound of $k^{th}$ coproduction ratio  
$r_{upper}$ 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 $k^{th}$ cogeneration 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  
$X_{pi}$ Decision vector for the $i^{th}$ power plant  
$x_{wj}$ Water produced at the $j^{th}$ water plant  
$X_{wj}$ Production vector for the $j^{th}$ water plant  
$x_{\sigma i}$ Water released by $i^{th}$ water storage plant  
$x_{\sigma j}$ Decision vector for the $j^{th}$ water energy storage plant  
$\sigma_i$ Water level of the $i^{th}$ water storage plant  
$\min GenP_i$ Min. capacity limit of the $i^{th}$ power plant  
$\min GenW_j$ Min. capacity limit of the $j^{th}$ water plant  
$\min GenC_k$ Min. capacity limit of the $k^{th}$ coproduction plant  
$\min GenS_u$ Min. capacity limit of the $u^{th}$ energy storage plant  
$\min Gen_{\sigma v}$ Min. capacity limit of the $v^{th}$ water storage plant  
$\max GenP_i$ Max. capacity limit of the $i^{th}$ power plant  
$\max GenW_j$ Max. capacity limit of the $j^{th}$ water plant  
$\max GenC_k$ Max. capacity limit of the $k^{th}$ coproduction plant  
$\max GenS_u$ Max. capacity limit of the $u^{th}$ energy storage plant  
$\max Gen_{\sigma v}$ Max. capacity limit of the $v^{th}$ water storage plant  
$\max DR RR P_i$ Max. down ramp of the $i^{th}$ power plant  
$\max DR RR W_j$ Max. down ramp of the $j^{th}$ water plant  
$\max DR RR C_k$ Max. power down ramp of the $k^{th}$ coproduction plant  
$\max DR RC W_k$ Max. water down ramp of the $k^{th}$ coproduction plant  
$\max U R R P_i$ Max. up ramp of the $i^{th}$ power plant  
$\max U R R W_j$ Max. up ramp of the $j^{th}$ water plant  
$\max U R R C_k$ Max. power up ramp of the $k^{th}$ coproduction plant  
$\max U R R C W_k$ Max. water up ramp of the $k^{th}$ coproduction plant  
$\min Store S_u$ Min. storage limit of the $u^{th}$ energy storage plant  
$\min Store_{\sigma v}$ Min. storage limit of the $v^{th}$ water storage plant  
$\max Store S_u$ Max. storage limit of the $u^{th}$ energy storage plant  
$\max Store_{\sigma v}$ Max. storage limit of the $v^{th}$ water storage plant  

**REFERENCES**


