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Optimal Network Flow for the Supply Side of the Energy-Water Nexus

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***Abstract*—Clean energy and water are two essential resources that any society must securely deliver. Their usage raises sustainability issues and questions of nations' resilience in face of global changes and mega-trends such as population growth, global climate change, and economic growth. Recently, attention has been paid to the infrastructure systems for water distribution and power transmission and the coupling between them in what is commonly known as the energy-water nexus. Although numerous policy and regulatory agencies have addressed the subject, rarely is it holistically addressed in terms of an integrated engineering system for its management, planning, and regulation as an interdisciplinary concern. This work specifically addresses the supply side of this integrated engineering system framework. It takes as its subject the real-time optimal flows in power and water networks. Significant background literature is brought to bear on this topic including the emerging co-dispatch of power and water and the more well established optimizations for power and water networks individually. The work presents a mathematical optimization program for the co-dispatch of the two commodities for three types of plants: power generation plants, co-production facilities and water production plants. Production costs are minimized subject to capacity, demand and transmission constraints and demonstrated on an illustrative example of modest size. On a practical basis, the program can be applied directly in middle eastern countries where water and power distribution are typically under the responsibility of a single utility. Furthermore, the program provides a systematic method of achieving optimal results and can serve as a basis for set-points upon which individual plants can implement their optimal control. In so doing, it makes a supply-side contribution to the ongoing grand-challenge of improving the sustainability of the energy-water nexus.**

I. Introduction

Clean energy and water are two essential resources that any society must securely deliver [1] in order to develop sustainably; i.e. meet its economic, social and environmental goals. In the case of energy, the overuse of conventional resources has led to their rapid depletion [2]. Moreover, the associated emission of carbon, nitrogen, and sulphur oxides has caused environmental issues such as global climate change, smog, and acid rain respectively [3]. Consequently, research into clean renewable energy resources and energy efficiency methods has increased. Similarly, potable water is another vital resource for survival and development. Increased water use has grown substantially in recent years; tracking strongly with energy use and economic development and leading to depleted water tables in many geographic regions [4]. Hence, there is an important need to optimize both energy and water resources. Therefore, the co-optimization of water production and power generation has gained a new found importance [5] in light of quickly depleting global energy resources [6] , increased concern about national security [7] , and the need for sustainable economic growth [2].

Traditionally water distribution and power transmission networks are thought of as separate uncoupled infrastructure systems. However, in reality, they are very much coupled in what is commonly known as the energy-water nexus [8]. As shown in Table I, the energy and water systems may be viewed as two interlinked value chains. The greatest attention has been given to the cross-interactions of energy supply to water demand or vice versa. Many empirical methods have attempted to quantitatively assess the water consumption requirements of thermal power generation facilities [9]. Similarly, research is underway to improve technologies that would diminish this impact [10]. Another cross-coupling is the electrical pumping energy required to produce and dispatch potable water [11]. As the subject of this paper, co-production facilities like hydroelectric and thermal desalination plants [5] couple the respective supply sides of energy and water [12]. Finally, the residential, commercial, and industrial use of electric heating and cooling for water consumption presents a major coupling on the demand side of both systems [13].

Although the energy-water nexus has recently caught the attention of numerous policy and regulatory agencies [9] , is it holistically addressed in terms of an integrated engineering system framework for its management, planning and regulation as an interdisciplinary concern. Recent research into smart (power) grid activities implicitly require a rebalancing of power generation technology portfolio [14]. Similarly, smart (water) grid activities implicitly require a rebalancing of the water supply technologies be they desalination, groundwater pumping or water recycling [15] . Paradigmatically, as well as technologically, there is a great potential for convergence of these work streams. Recently, the energy-water nexus has been

TABLE I. SUPPLY & DEMAND SIDE ENERGY-WATER NEXUS COUPLINGS

	Power Supply	Power Demand
Water Supply	Co-generation: • Thermal Desalination • Hydroelectric	• Pumped Water • Water Distribution • Wastewater Recycling
Water Demand	Thermal-Power Generation Facilities	Residential, Commercial, & Industrial Use of Electric Heating & Cooling of Water

modeled as an integrated engineering system [16] and initial work for holistic quantified planning is reported [17].

This work specifically addresses the supply side of this integrated engineering system framework in recognition of the coupling role that cogeneration facilities play. Technologically, cogeneration provides many advantages; the first being the more efficient use of fuel, and the second being the production of more than one useful product. In northern European countries, co-production can be used to provide power and heat, while in Middle Eastern nations, co-production of power and water is common because of the shortage of fresh water resources. Since both these resources need to be dispatched through a distribution network and co-production plants produce both power and water, there are significant advantages to optimizing both simultaneously [5], [18].

This paper takes as its subject optimal network flows for the supply side of the energy-water. Previous work on the subject by the authors has investigated the couplings within the simultaneous dispatch of power and waterciteSanthosh2012d. It considered the plants' physical characteristics as well as the process constraints that limit the relative quantities of power and water. Additional work has also investigated the role of ramping rates and storage facilities in the simultaneous dispatch. These contributions, however, treated the energy-water nexus supply side as a single node neglecting the power and water distribution networks that they feed. This paper specifically builds upon previous work to address this network behavior within the mathematical program.

The remainder of the paper develops in six sections. Section II describes the background literature relevant to power-water co-optimization. Section III presents the the mathematical program including the power and water network constraints. The simulation methodology is explained in Section IV. Section V presents the results for a hypothetical example system of modest size. The paper concludes in Section VI.

II. BACKGROUND LITERATURE

This section highlights aspects of the background literature for power-water co-optimization in three steps. First, the literature on power and water co-optimization are reviewed. Next, optimal power flow is introduced as a prerequisite single product optimization. Optimal water flow is then similarly described.

A. Co-optimization of Power and Water

The operations research literature on cogeneration power and water facilities has evolved over the years from single plant optimization to full scale multi-plant research. For example, some work has focused on the optimized planning and design rather than operation [19] . Still others find methods of cost allocation [20]. Finally, 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 all the water and production units in water and power grid [21]. These works do not provide an extensible and general optimization applicable to dual-product multi-plant markets.

Dual-product multi-plant optimization programs have also been developed. The first experience was that of northern European countries where an economic dispatch approach has been applied to power and heat. A single objective function for cogeneration plants based on power and heat is formed and then optimized subject to power and heat production capacity [22] . More recently, an economic dispatch approach for power and water has been developed that considers demand, process, and capacity constraints [23], [24]. Another version of this work considered ramping rates and the introduction of power and water storage facilities [25].

B. DC Optimal Power Flow

Optimal power flow methods evolved due to the limitations built into the assumption of economic dispatch. Economic Dispatch seeks to minimize the cost of generation assuming that the entire generation and distribution occurs at one node. This, however, creates many issues when it comes to its practical application in electrical power systems. Efficient power system operation does not just require the respect of aggregate supply-demand and capacity limits, but also must consider constraints emerging from the transmission network. Such an approach can be used to assure thermal and/or stability based line flow limits and voltage stability. Furthermore, incorporation of the transmission network can be used to limit line losses [26]. Recent work, on the subject has sought the optimized operation of flexible AC transmissions system (FACTS) devices [27], [28]. Therefore, over recent decades, there has been a consistent, detailed and diverse effort to integrate topology into the economic dispatch [29] [30] [31] [32]–[34].

For the purposes of this paper, the simplest and most commonly presented OPF formulations suffice. The AC OPF problem is described as [35]:

$$min\ C_pi(x_pi) = \sum_{n=1}^{n_{pp}} C_{pi}(x_{pi}) \tag{1}$$

subject to:

$$\begin{aligned} p_{yz} - D_{py} &= v_y \sum_{y=1}^{m_p} v_y \left[G_{yz}\cos(\theta_{yz}) + B_{yz}\sin(\theta_{yz})\right] \\ q_{yz} - D_{qy} &= v_y \sum_{y=1}^{m_p} v_y \left[(G_{yz}\sin(\theta_{yz}) - B_{yz}\cos(\theta_{yz})\right] \end{aligned} \tag{2}$$

$$\begin{aligned} \text{MinGenPP} \quad &\leq \quad X_p \quad \leq \quad \text{MaxGenPP} \\ \text{MinGenWP} \quad &\leq \quad X_w \quad \leq \quad \text{MaxGenWP} \end{aligned} \tag{3}$$

$$V^{min} \leq v_y \leq V^{max} \tag{4}$$

$$\begin{aligned} p_{yz}^{min} &\leq v_y z_y (G_{yz} \cos\theta_{yz} + B_{yz} \sin\theta yz) - G_{yz} v_y^2 \leq p_{yz}^{max} \\ q_{yz}^{min} &\leq v_y z_y (G_{yz} \sin\theta_{yz} - B_{yz} \cos\theta yz) + B_{yz} v_y^2 \leq q_{yz}^{max} \end{aligned} \tag{5}$$

$$\delta_1 = 0 \tag{6}$$

where Equation 1 is the cost function, Equation 2 gives the power flow equations, Equation 3 captures the generator active and reactive power limits, Equation 4 limits the bus voltages, and Equation 5 describes the line flow limits. h and k refer to bus indices. G_{yz}, B_{yz} θ_{yz} are the conductance, the susceptance and the voltage angle difference between buses y and z. $X_p i$ and $D_p w$ are the active power injections of the generators and loads while Q_G and Q_L are the reactive power injections. v_y is the bus voltage vector. Equation 6 sets the slack bus to zero.

The AC OPF formulation is not straightforwardly tractable and is often replaced by the linearized DC OPF problem. Three approximations are made to that effect [36]:

1) $v_y = 1$pu $\forall y$. Node voltages are set to unity per unit.
2) $G_y z = 0$. Lines are assumed to be lossless.
3) $\sin(\theta_{yz})$=θ_{yz}, $\cos(\theta_{yz}) = 1$. Trigonometric terms have small angles.

C. Optimal Water Flow

Despite being similar in many ways, water flow has not been explored to the same extent. However, there are some papers that deal with optimization for both design and optimization purposes [37]–[39]. When considering water flow networks, one needs ensure continuity: that the total flow entering a node is equal to the sum of the demand at that point and the outflow. Additionally, the pressure (head) loss between nodes needs to be included.

These constraints are formulated as shown below:

$$\sum_{t=1}^{m_w} Q_{tu} + D_{wt} = 0 \tag{7}$$

$$H_t - H_u = R_{tu} Q_t |Q_u|^{n-1} \tag{8}$$

where Q_{tu} is the water flow in between nodes t and u, m_w is the total number of pipes, D_{wt} is water demand at the t^th node, H_t is t^{th} nodal head, R_{tu} is the resistance coefficient in the pipe connecting t and u and n is flow exponent in the head loss equation. The flow exponent depends on the selection of head loss relationship. In the Darcy-Weisbach relationship, n=2, whereas in Hazen-Williams relationship n=1.852. The Darcy-Weisbach equation is generally speaking more accurate, but the Hazen-Williams equation can also provide useable values for head loss with much less intensive calculation needed [40], [41].

III. Problem Formulation

An optimal network flow for the supply side of the energy-water nexus can be viewed as the combination of the three types of literature reviewed in the Background section. The problem formulation builds upon the previous work on simultaneous co-dispatch of power and water while introducing the constraints from optimal power flow and optimal water flow.

Prior to proceeding a summary of the utilized nomenclature is provided in Table II.

TABLE II. Summary of Nomenclature for the Optimal Flow of Supply Side of the Energy-Water Nexus

	Power Domain	Water Domain
Power Plant		
Index	i	—
Number	n_{pp}	—
Product	x_{pi}	—
Minimum Capacity Limit	MinGenPP	—
Maximum Capacity Limit	MaxGenPP	—
Incidence Matrix	I_{piy}	—
Cost Function	$C_{pi}(x_{pi})$	—
Water Plant		
Index	—	j
Number	—	n_{wp}
Product	—	x_{wj}
Minimum Capacity Limit	—	MinGenWP
Maximum Capacity Limit	—	MaxGenWP
Incidence Matrix	—	I_{wjt}
Cost Function	—	$C_{wj}(x_{wj})$
Cogeneration Plant		
Index	k	k
Number	n_{cp}	n_{cp}
Product	x_{cpk}	x_{cwk}
Minimum Capacity Limit	MinGenCPP	MinGenCPW
Maximum Capacity Limit	MaxGenCPP	MaxGenCPW
Incidence Matrix	I_{cky}	I_{ckt}
Cost Function	$C_{ck}(x_{ckp}, x_{ckw})$	$C_{ck}(x_{ckp}, x_{ckw})$
Distribution Network		
Bus Node Indices	y, z	t, u
Number	m_p	m_w
Demand	D_{py}	D_{wt}
Electric Admittance	B_{yz}	—
Electric Conductance	G_{yz}	—
Hydraulic Resistance	—	R_{tu}
Voltage	v_y	—
Voltage Angle	δ_y	—
Pressure	—	H_t
Flow	$B_{yz}(\delta_y - \delta_z)$	F_{tu}
Minimum Flow	MinPFlow$_{yz}$	MinWFlow$_{tu}$
Maximum Flow	MaxPFlow$_{yz}$	MaxWFlow$_{tu}$

The primal problem is then formally described as:

$$min\ C_G(x_{pi}, x_{wj}, x_{ck}) = \sum_{i=1}^{n_{pp}} C_{pi}(x_{pi}) + \sum_{j=1}^{n_{wp}} C_{wj}(x_{wj}) + \sum_{k=1}^{n_{cp}} C_{ck}(x_{ckp}, x_{ckw}) \tag{9}$$

where $C_{pi}(x_{pi}), C_{wj}(x_{wj}), C_{ck}(x_{ckp}, x_{ckw})$ are the cost functions for i^{th} power generation plant, the j^{th} water production facility, and the k^{th} cogeneration facility respectively. The cost functions may take any one of a number of functional forms. In the scope of this work, they are taken as quadratic in their respective decision variables.

$$\begin{aligned} C_{pi}(x_{pi}) &= a_{2i} x_{pi}^2 + a_{1i} x_{pi} + a_{oi} \\ C_{wj}(x_{wj}) &= a_{2j} x_{wj}^2 + a_{1j} x_{wj} + a_{oj} \\ C_{ck}(x_{ckp}, x_{ckw}) &= a_{11k} x_{ckp}^2 + a_{22k} x_{ckw}^2 + a_{12k} x_{ckp} x_{ckw} \\ &\quad + a_{1k} x_{ckp} + a_{2k} x_{ckw} + a_{ok} \end{aligned} \tag{10}$$

The objective function is subjected to active power flow constraint in Equation 2 with the DC power flow approximations.

It also specifically adds a term for the cogeneration facilities.

$$\begin{aligned} &\forall y = \{1 \dots m_p\} \\ &0 = D_{py} - \sum_{k=1}^{n_{cp}} I_{cky} x_{cpk} - \sum_{i=1}^{n_{pp}} I_{piy} x_{pi} + \sum_{y=1}^{m_p} B_{yz}(\delta_y - \delta_z) \end{aligned} \tag{11}$$

Similarly, the water balance constraint in Equation 7 adds another term for the cogeneration facilities.

$$\begin{aligned} &\forall t = \{1 \dots m_w\} \\ &0 = D_{wt} - \sum_{k=1}^{n_{cp}} I_{ckt} x_{cwk} - \sum_{j=1}^{n_{wp}} I_{wjt} x_{wj} + \sum_{t=1}^{m_w} F_{tu} \end{aligned} \tag{12}$$

The pressure loss equation is taken from Equation 8 assuming the Darcy-Weisbach relationship.

$$H_t - H_u = R_{tu} Q_{tu}^2 \tag{13}$$

The power and water generation limits are then gathered together for all three types of production facilities.

$$\begin{array}{ccccc} \text{MinGenPP} & \leq & X_p & \leq & \text{MaxGenPP} \\ \text{MinGenWP} & \leq & X_w & \leq & \text{MaxGenWP} \\ \text{MinGenCPP} & \leq & X_{cpp} & \leq & \text{MaxGenCPP} \\ \text{MinGenCPW} & \leq & X_{cpw} & \leq & \text{MaxGenCPW} \end{array} \tag{14}$$

The power and water flow limits are then gathered $\forall y, z = \{1 \dots m_p\}$: and $\forall t, u = \{1 \dots m_w\}$.

$$\begin{array}{ccccc} \text{MinPFlow}_{yz} & \leq & B_{yz}(\delta_y - \delta_z) & \leq & \text{MaxPFlow}_{yz} \\ \text{MinWFlow}_{tu} & \leq & Q_{tu} & \leq & \text{MaxWFlow}_{tu} \end{array} \tag{15}$$

Finally, the slack bus constraint of zero voltage is taken from Equation 6.

IV. Simulation Methodology

The optimization program provided above was carried out on a hypothetical system composed of four power plants, one cogenerator and one pure water plant. The power network admittance data was taken from the standard IEEE 14 bus system as shown in 1 and has five generators. The four power plants are located at buses 1 ,2 ,3 ,6 while the cogeneration facility is located at bus 8.

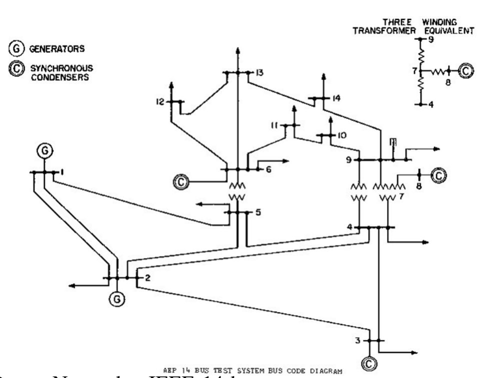

Fig. 1. Power Network - IEEE 14 bus system

The water network system consists of eight nodes as shown in 2 and includes a water plant at node 1 and a cogeneration facility at node 2.

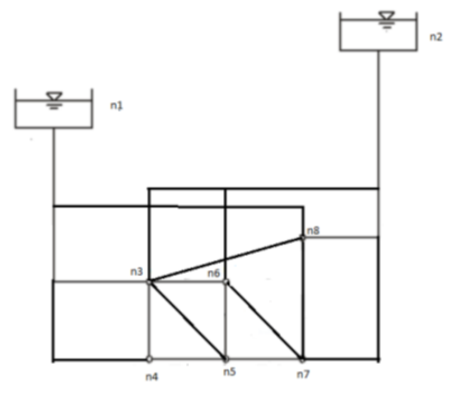

Fig. 2. Water Network - 8 node system

The interested reader is referred to X for the complete set of input data.

The optimization was conducted in GAMS Optimization software on a HP Laptop with an Intel Core i5 CPU 2.27 GHz processor. The CONOPT solver was used to execute the optimization. In total, the code for the hypothetical system above completed within 15 seconds.

V. Results

Figures 3 shows the power generation levels where power plants 1 and 2 are acting like base load plants, while plants 3 and 4 are acting like peaking units. As has been previously discussed [5], [9], [11], the cogeneration facilities are particularly constrained and maintain relatively steady power generation rates. The water dispatch is shown in Figure 4. Here, the limited number of water facilities has caused both the water and cogeneration facility to meet the demand. Finally, Figure 5 shows the total costs incurred over the 24 hour period.

The optimization runs correctly and gives an optimal solution. Beyond the dispatch itself, the optimization program does run up against all of various constraints over the course of the day. Line 1-2 in the power network is habitually constrained over the course of the day. This suggests the need for a transmission capacity upgrade. In the meantime, the water network showed much more balanced behavior. Ten different lines showed constrained behavior particularly in the midday hour when the aggregate water demand was at its highest. In all, these results suggest that the expansion of the simultaneous co-dispatch of power and water from a single node model to a network model is not just effective in meeting meeting supply-demand balance but also is effective in assuring the safety constraints imposed by the line flow limits.

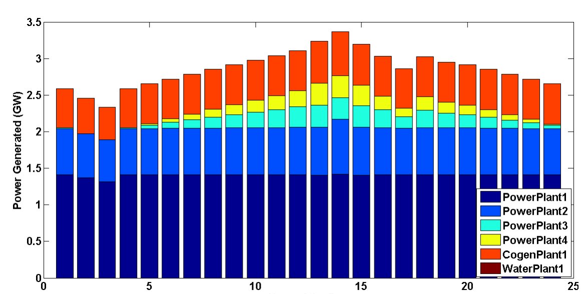

Fig. 3. Power Generation Profile over 24 hours

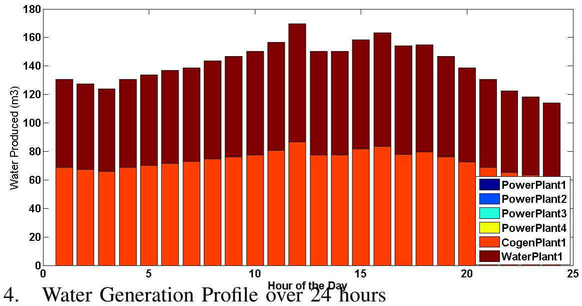

Fig. 4. Water Generation Profile over 24 hours

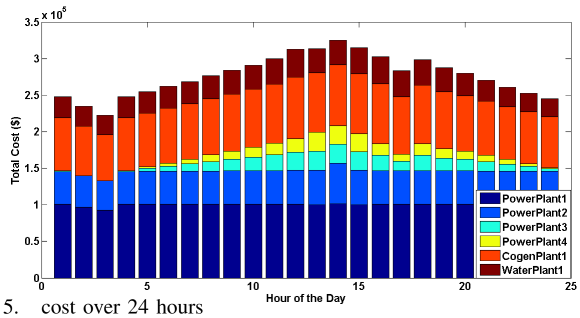

Fig. 5. cost over 24 hours

VI. Conclusions

Thus it can be seen that the economic dispatch of power and water can be expanded by taking into consideration the power and water networks flows. This does lead to a more complex optimization with more severe constraints and therefore finding the feasible region and optimal solution are more difficult in some cases. However, the optimization does run successfully for a complex hypothetical system that consists of a standard IEEE system and realistic water network. Furthermore, the results suggest that the that the expansion of the simultaneous co-dispatch of power and water from a single node model to a network model is not just effective in meeting meeting supply-demand balance but also is effective in assuring the safety constraints imposed by the line flow limits. In such a way, it expands the operations management of the supply side of the energy-water nexus as a single integrated engineering systems.

References

[1] A. R. Hoffman, "The Connection: Water and Energy Security," *Energy Security*. [Online]. Available: http://www.iags.org/n0813043.htm

[2] S. M. N. Islam, M. Munasinghe, and M. Clarke, "Making long-term economic growth more sustainable: evaluating the costs and benefits," *Ecological Economics*, vol. 47, no. 2Äì3, pp. 149–166, 2003. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0921800903001629

[3] J. Glasson, R. Therivel, and A. Chadwick, *Introduction to environmental impact assessment*, 3rd ed. London ; New York: Routledge, 2005. [Online]. Available: http://www.loc.gov/catdir/enhancements/fy0701/2006297949-d.html

[4] United Nations, "Managing Water under Uncertainty and Risk," Paris, France, Tech. Rep., 2012.

[5] A. M. El-Nashar, "Cogeneration for power and desalination - State of the art review," *Desalination*, vol. 134, no. 1-3, pp. 7–28, 2001. [Online]. Available: http://dx.doi.org/10.1016/S0011-9164(01)00111-4

[6] F. Akdeniz, A. Caglar, and D. Gullu, "Recent energy investigations on fossil and alternative nonfossil resources in Turkey," *Energy Conversion and Management*, vol. 43, no. 4, pp. 575–589, 2002. [Online]. Available: http://dx.doi.org/10.1016/S0196-8904(01)00036-X

[7] J. J. Bogardi, D. Dudgeon, R. Lawford, E. Flinkerbusch, A. Meyn, C. Pahl-Wostl, K. Vielhauer, and C. Vrsmarty, "Water security for a planet under pressure: interconnected challenges of a changing world call for sustainable solutions," *Current Opinion in Environmental Sustainability*, vol. 4, no. 1, pp. 35–43, 2012. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S1877343511001369

[8] G. Olssonn, *Water and Energy: Threats and Opportunities*. London: IWA Publishing, 2012.

[9] J. Macknick et al, "A Review of Operational Water Consumption and Withdrawal Factors for Electricity Generating Technologies," *National Renewable Energy Laboratory*, 2011.

[10] R. Pate, M. Hightower, C. Cameron, and W. Einfeld, "Overview of Energy-Water Interdependencies and the Emerging Energy Demands on Water Resources," Albuquerque, New Mexico, Tech. Rep., 2007.

[11] B. Griffiths-Sattenspiel, W. Wilson, and B. Griffiths-sattenspiel & Wilson, W., "The Carbon Footprint of Water," Portland, Oregon, Tech. Rep., 2009. [Online]. Available: http://www.rivernetwork.org/sites/default/files/TheCarbonFootprintofWater-RiverNetwork-2009.pdf

[12] A. Cipollina, G. Micale, and L. Rizzuti, *Seawater desalination : conventional and renewable energy processes*. Berlin ; London: Springer, 2009.

[13] G. M. Thirwell C.A. Madramootoo , I.W. Heathcote, "Energy- Water Nexus: Energy Use in the Municipal, Industrial, and Agricultural Water Sectors," Washington, D.C., 2007.

[14] J. G. Kassakian, R. Schmalensee, G. Desgroseilliers, T. D. Heidel, K. Afridi, A. M. Farid, J. M. Grochow, W. W. Hogan, H. D. Jacoby, J. L. Kirtley, H. G. Michaels, I. Pérez-Arriaga, D. J. Perreault, N. L. Rose, G. L. Wilson, N. Abudaldah, M. Chen, P. E. Donohoo, S. J. Gunter, P. J. Kwok, V. A. Sakhrani, J. Wang, A. Whitaker, X. L. Yap, and R. Y. Zhang, "The Future of the Electricity Grid: An Interdisciplinary MIT Study," MIT, Cambridge, MA, Tech. Rep., 2011. [Online]. Available: http://web.mit.edu/mitei/research/studies/documents/electric-grid-2011/Electric_Grid_Full_Report.pdf

[15] T. M. Walski and Haestad Methods Inc., *Advanced water distribution modeling and management*. Exton, PA: Bentley Institute Press, 2007.

[16] W. N. Lubega and A. M. Farid, "A Meta-System Architecture for the Energy-Water Nexus," in *8th Annual IEEE Systems of Systems Conference*, Maui, Hawaii, USA, 2013, pp. 1–6.

[17] W. Lubega and A. M. Farid, "An engineering systems model for the quantitative analysis of the energy-water nexus," in *Complex Systems Design & Management*, Paris, France, 2013.

[18] M. J. Safi and A. Korchani, "Cogeneration applied to water desalination: Simulation of different technologies," *Desalination*, vol. 125, no. 1–3, pp. 223–229, 1999. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0011916499001423

[19] E.-N. Ali M, "Optimal design of a cogeneration plant for power and desalination taking equipment reliability into consideration," *Desalination*, vol. 229, no. 1–3, pp. 21–32, 2008. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0011916408002695

[20] ——, "Cost allocation in a cogeneration plant for the production of power and desalted water — comparison of the exergy cost accounting method with the WEA method," *Desalination*, vol. 122, no. 1, pp. 15–34, 1999. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0011916499000247

[21] A. M. El-nashar and M. S. Khan, "Economic scheduling of the UAN cogeneration plant: A preliminary optimization study," *Desalination*, vol. 85, no. 1, pp. 93–127, 1991. [Online]. Available: http://www.sciencedirect.com/science/article/pii/001191649185149O

[22] C. Algie and W. Kit Po, "A test system for combined heat and power economic dispatch problems," in *Electric Utility Deregulation, Restructuring and Power Technologies, 2004. (DRPT 2004). Proceedings of the 2004 IEEE International Conference on*, vol. 1, Hong Kong, 2004, pp. 96–101 Vol.1.

[23] A. Santhosh, A. M. Farid, A. Adegbege, and K. Youcef-Toumi, "Simultaneous Co-optimization for the Economic Dispatch of Power and Water Networks," in *The 9th IET International Conference on Advances in Power System Control, Operation and Management*, Hong Kong, China, 2012, pp. 1–6.

[24] A. Santhosh, A. M. Farid, and K. Youcef-Toumi, "Real-Time Economic

Dispatch for the Supply Side of the Energy-Water Nexus," *Applied Energy(submitted)*, p. 10, 2013.

[25] ——, "The Impact of Storage Facilities on the Simultaneous Economic Dispatch of Power and Water Networks Limited by Ramping Rates," in *IEEE International Conference on Industrial Technology*, Cape Town, South Africa, 2013, pp. 1–6.

[26] U. Leeton, D. Uthitsunthorn, U. Kwannetr, N. Sinsuphun, and T. Kulworawanichpong, "Power loss minimization using optimal power flow based on particle swarm optimization," in *Electrical Engineering/Electronics Computer Telecommunications and Information Technology (ECTI-CON), 2010 International Conference on*, 2010, pp. 440–444.

[27] N. G. Hingorani and L. Gyugyi, *Understanding FACTS : concepts and technology of flexible AC transmission systems*. New York: IEEE Press, 2000. [Online]. Available: http://ieeexplore.ieee.org/xpl/bkabstractplus.jsp?bkn=5264253

[28] X.-P. Zhang, C. Rehtanz, B. Pal, and Books24x7 Inc., "Flexible AC transmission systems modelling and control," Berlin, 2012.

[29] Z. Qiu, G. Deconinck, and R. Belmans, "A literature survey of Optimal Power Flow problems in the electricity market context," in *Power Systems Conference and Exposition, 2009. PSCE '09. IEEE/PES*, ser. 2009 IEEE/PES Power Systems Conference and Exposition, PSCE 2009. Department of Electrical Engineering, KUL: IEEE Computer Society, 2009, pp. 1–6. [Online]. Available: http://dx.doi.org/10.1109/PSCE.2009.4840099

[30] M. A.-R. Abdel-Moamen and N. P. Padhy, "Optimal Power Flow Incorporating FACTS Devices - Bibliography and Survey BT - 2003 IEEE PES Transmission and Distribution Conference, September 7, 2003 - September 12, 2003," ser. Proceedings of the IEEE Power Engineering Society Transmission and Distribution Conference, vol. 2. Department of Electrical Engineering, Indian Institute of Technology, Roorkee - 247667, India: Institute of Electrical and Electronics Engineers Inc., 2003, pp. 669–676. [Online]. Available: http://dx.doi.org/10.1109/TDC.2003.1335357

[31] G. R. M. da Costa, C. E. U. Costa, and A. M. de Souza, "Comparative studies of optimization methods for the optimal power flow problem," *Electric Power Systems Research*, vol. 56, no. 3, pp. 249–254, 2000. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0378779600001140

[32] M. Huneault and F. D. Galiana, "A survey of the optimal power flow literature," pp. 762–770, 1991.

[33] J. A. Momoh, M. E. El-Hawary, and R. Adapa, "A review of selected optimal power flow literature to 1993. II. Newton, linear programming and interior point methods," pp. 105–111, 1999.

[34] J. A. Momoh, R. Adapa, and M. E. El-Hawary, "A review of selected optimal power flow literature to 1993. I. Nonlinear and quadratic programming approaches," pp. 96–104, 1999.

[35] F. Milano, *Power System*, 1st ed. New York: Springer-Verlag Berlin Heidelberg, 2010. [Online]. Available: http://www.uclm.es/area/gsee/web/Federico/psat.htm

[36] P. Schavemaker and L. Van der Sluis, *Electrical Power System Essential*, 2009.

[37] B. Coulbeck, "Dynamic simulation of water distribution systems," in *Simulation of Systems '79. Proceedings of the 9th IMACS Congress, 24-28 Sept. 1979*. Amsterdam, Netherlands: North-Holland, 1980, pp. 545–551.

[38] E. Ramirez-Llanos and N. Quijano, "Analysis and control for the water distribution problem BT - 2010 49th IEEE Conference on Decision and Control, CDC 2010, December 15, 2010 - December 17, 2010," ser. Proceedings of the IEEE Conference on Decision and Control. Departamento de Ingenieria Electrica y Electronica, Universidad de Los Andes, Bogota, Colombia: Institute of Electrical and Electronics Engineers Inc., 2010, pp. 4030–4035. [Online]. Available: http://dx.doi.org/10.1109/CDC.2010.5717629

[39] E. Salomons, "WaterIng - Water Distribution System Design and Analysis," *EPANET*, pp. 1–10, 2010.

[40] "Chapter 1 Hydraulics and Head Loss Equations Basic Equations," pp. 1–20, 1984. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0167564808701497

[41] T. Haktanr and M. Ardçloğlu, "Numerical modeling of Darcy–Weisbach friction factor and branching pipes problem," *Advances in Engineering Software*, vol. 35, no. 12, pp. 773–779, Dec. 2004. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0965997804001358