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Abstract

Electric power is required to produce, treat, distribute, and recycle water while water is required to generate and consume electricity. Naturally, this energy-water nexus is most evident in multi-utilities that provide electricity and water but still exists when the nexus has distinct organizations as owners and operators. Therefore, the sustainability question that arises from energy-water trade-offs and synergies is very much tied to the potential for economies of scope. Furthermore, in the Middle East and North Africa (MENA) region, multi-utilities are not only common, but also the nexus is particularly exacerbated by the high energy intensity of the water supply due to limited fresh water resources. The goal of this paper is to identify and motivate several opportunities for enhanced integrated operations management and planning in the energy-water nexus in multi-utilities in the MENA. It proceeds in four parts. First, an exposition of the energy-water nexus especially as it applies to the MENA is given. This discussion focuses on the electric power system, the potable water distribution system, and thirdly, the wastewater distribution system. Second, the paper shifts to opportunities in integrated operations management highlighted by an energy-water nexus supply- side economic dispatch illustration. Thirdly, the discussion shifts to planning opportunities for the energy-water nexus for the sustainable development of water and energy resources. A concluding section summarizes the policy implications of the identified opportunities.

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1. Introduction

The supply and demand of water and electricity are closely linked and as a consequence should be managed jointly. This *energy-water nexus*, which couples the critical systems upon which human civilization depends, has existed since the first implementations of the electricity, water and wastewater systems (Olssonn, 2012; USDOE, 2014).

Definition 1. Energy-Water Nexus (Lubega and Farid, 2013a, 2013b, 2014a; Farid and Lubega, 2013; Santhosh et al., 2013b, 2013c): a system-of-systems composed of one infrastructure system with the artifacts necessary to describe a full energy value chain and another infrastructure system with the artifacts necessary to describe a full water value chain.

The coupling, however, is becoming increasingly strained due to a number of global mega-trends (United Nations Education Scientific and Cultural Organization, 2012): 1) Growth in total demand for both electricity and water driven by population growth, 2) Growth in per capita demand for both electricity and water driven by economic growth, 3) Distortion of availability of fresh water due to climate change, and 4) Multiple drivers for more electricity-intensive water and more water-intensive electricity such as enhanced water treatment standards, water-consuming flue gas management processes at thermal power plants (Zhai et al., 2011) and aging infrastructure which incurs greater losses (Lee Willis, 2012; Baur, 2006). These trends raise concerns over the robustness of the electricity and water systems today and their sustainability over the coming decades. There is a risk that if the nexus is not optimally managed, then scarcity in either water or energy will create aggravated shortages in both.

In the MENA region, this nexus is particularly exacerbated. As shown in Figure 1, per capita demand for electricity has steadily increased in most MENA countries. Those countries that have seen recent per capita reductions (e.g. Kuwait, UAE, and Bahrain) are three of the four most electricity intensive countries in the region. Meanwhile, Figure 2 shows that all MENA regions are unsustainably consuming water and drawing down their total renewable water resources per capita. These trends are further exacerbated by the high energy intensity of the water due to the limited freshwater resources and the hot and arid climate. As shown in Table 1, *energy-expensive* groundwater and desalination contribute 65% and 5% of the total water supply in the MENA respectively (FAO, 2012). Four out of the six Gulf Cooperation Council (GCC) countries (Saudi Arabia, UAE, Kuwait, Qatar) are among the ten countries with the highest desalination capacity, representing between them nearly 40% of global desalination capacity (Mezher et al., 2011).

Despite this exacerbated relationship, the norm in electricity and water utilities is for siloed operations associated with the discipline of each product. This paper, instead, discusses several opportunities for enhanced integration of operations and planning of the energy-water nexus from a multi-utility perspective. While not all MENA regions have electricity-water multi-utilities, their presence does present new opportunities for integrated operations within a single organization. Furthermore, the successful implementation of these approaches in multi-utilities motivates greater coordination and collaboration between single commodity utilities. As the energy-water nexus is a multi-faceted challenge, this work advances several complementary points of potential action rather a single one. Section 2 provides a discussion of the main coupling points that create the energy-water nexus; with particular emphasis on the issues that are salient in the Middle East and North Africa. In Section 3, the opportunities for improved, holistic management in the operations timescale are considered. In Section 4, integrated planning considerations and approaches are discussed. Section 5 completes the work with several conclusions and policy implications.

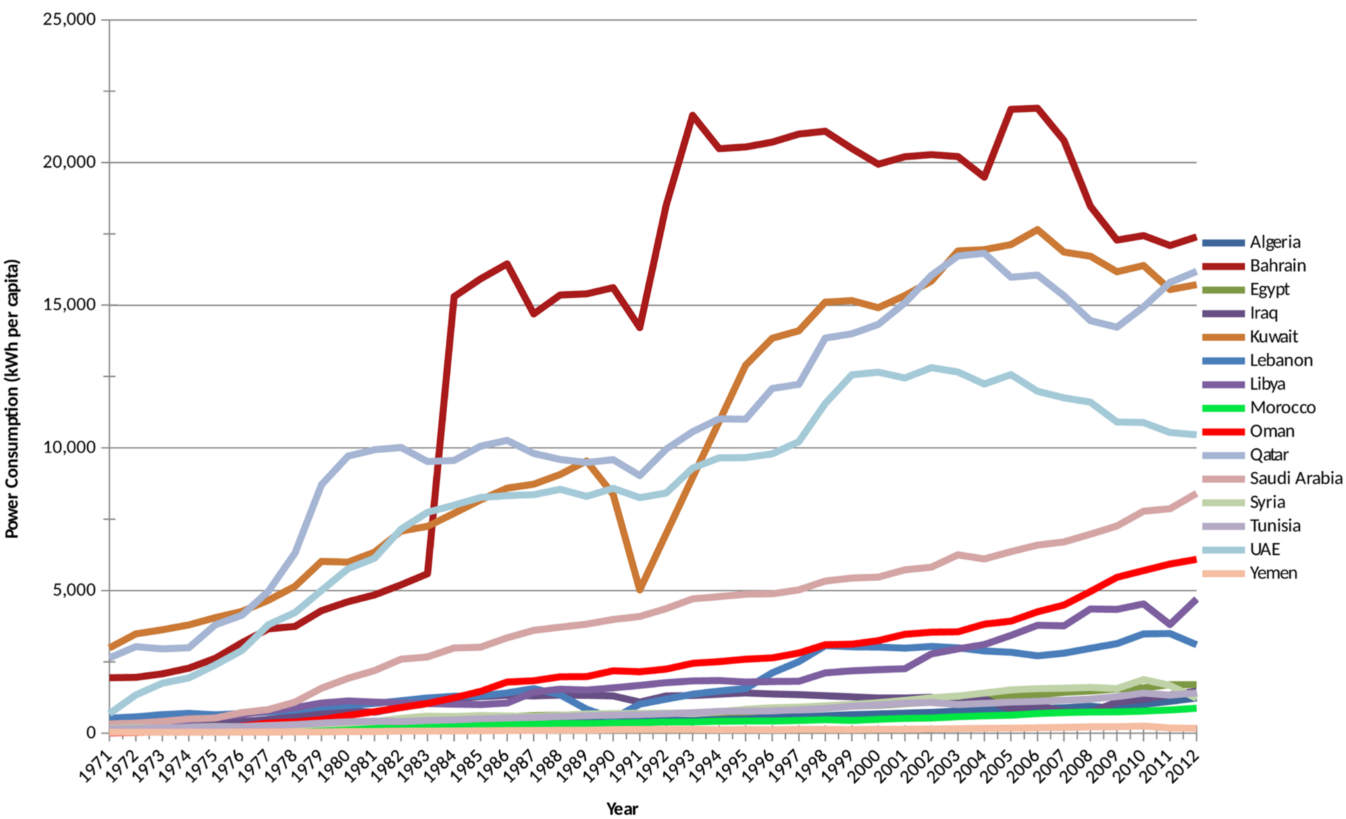

Figure 1

Historical electric power consumption consumption per capita in the mena region (The World Bank, 2014).

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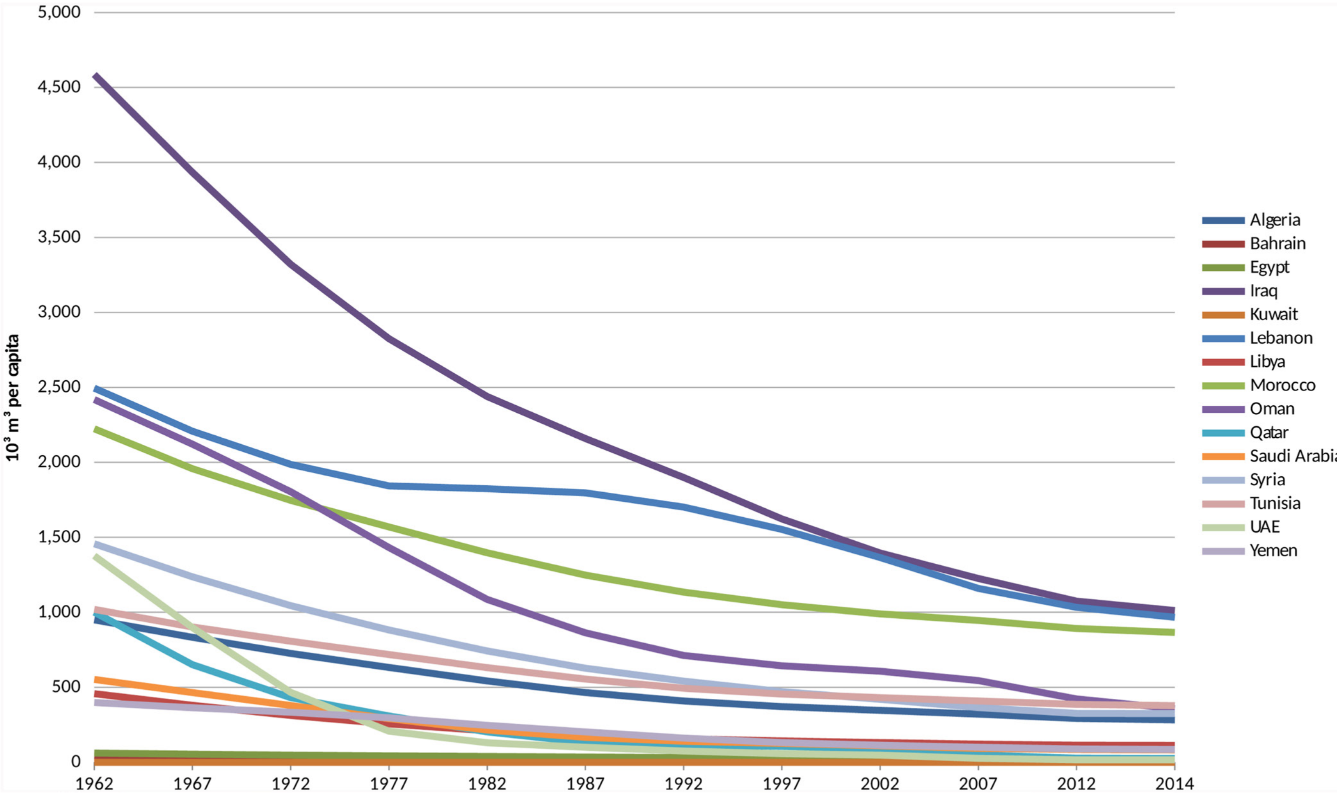

Figure 2

Total internal renewable water resources per capita (FAO, 2012).

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Table 1. Individual country water withdrawals by source in million m^3/*year* (FAO, 2012)[a]

Country	Year	Surface Water	Ground Water	Desalinated Water	Recycled Wastewater
Algeria	2012	4800	3000	615	324
Bahrain	2003	0	239	102	61.9
Egypt	2000, 2002	–[b]	7043	100	1900
Iraq	1999, 2000	–[b]	–[b]	7.4	425
Kuwait	2002	0	415	420	152
Lebanon	2001, 2005–06	396	700	47.3	56
Libya	1999, 2000	0	4308	18	40
Morocco	2010–11	8251	2322	7	166
Oman	2003, 2006	0	1186	109	37
Qatar	2005	0	217	180	75[a]
Saudia Arabia	2006	1100	21540	1033	167[a]
Syria	2005	–[b]	–[b]	–[b]	75
Tunisia	2010–12	1151	2066	19.7	226
UAE	2005–06	0	2800	950	289
Yemen	1999, 2000	987	2397	10	46
Total (%)		**16695 (24%)**	**45533 (65%)**	**3618 (5%)**	**4040 (6%)**

[a]Interpolated from nearest years
[b]Not available

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2. The energy-water nexus in the MENA

In this section, the processes that realise the energy-water nexus are introduced generally but with particular emphasis on those that are of importance to the MENA. This discussion proceeds in three parts. First, the use of water for electricity generation is discussed. Second, the various points of coupling that exist between electricity and municipal water supply systems are highlighted. Finally, the use of electricity by the waste-water management system is discussed.

2.1 Water use for electricity generation

In many parts of the world, the water withdrawal requirements of thermal power plants are of major concern (Macknick et al., 2012; Rogers et al., 2013). For example, in the United States, these withdrawals account for 45% (Pate et al., 2007) of all fresh water withdrawals. This reliance on thermo-electric generation, by far the most dominant generation technology, on copious water withdrawals makes electrical power systems vulnerable to water shortages. This has been the case in France in 2003 (United Nations Education Scientific and Cultural Organization, 2012) and in various locations in the United States over the last decade (US Department of Energy, 2013). Power plants have been forced to draw down output during heat waves; creating electricity shortages at times that demand was spiking due to increased air conditioning use. Such disturbances are likely to become more frequent in certain areas with the effects of climate change. Furthermore, in these same areas, over the long term, even relatively low water consumption levels become a sustainability concern with erratic precipitation.

Electric power generation in the MENA region is complex and depends highly on local geography. The default option in most MENA nations is coastal installation. In this case, thermo-electric power generation facilities use abundantly available sea water and thus are not vulnerable to water scarcity. However, the major concern in this case is the environmental impact of water discharged by once-through cooling plants, often referred to as *thermal pollution*. The power plant effluent, which is at elevated temperatures, can cause localized temperature increases and thus adversely affect the habitat of fish and other marine life (Miara et al., 2013; Madden et al., 2013). Furthermore, once-through cooling water systems still require significant quantities of polymers, and oxidizing biocides as treatment agents to prevent corrosion, scaling and biofouling (Integrated Pollution Prevention and Control (IPPC), 2001). All of these effects must be systematically assessed within the context of a power generation facility's environmental impact assessment.

Certain MENA countries, namely Morocco, Algeria, Tunisia, Egypt, Syria, and Iraq have fresh surface water resources in the form of rivers. With the exception of the Nile River, all of these originate from local mountain ranges which are often snow-capped in Winter. Morocco, Egypt, and Syria have all chosen to site at least one thermo-electric facility on these rivers (Gupta and Shankar, 2016). In the remaining cases, however, the dominant technology choice across the region is hydro-electric generation (Gupta and Shankar, 2016). Hydro-electric facilities have several environmental benefits; most notably their lack of carbon emissions. However, from an energy-water nexus perspective, they are one of its primary couplings (Lubega and Farid, 2014a; Olssonn, 2012). Furthermore, the construction of a dam at a hydro-electric facility often creates reservoirs which in dry and arid climates are susceptible to high evaporation rates (Siddiqi and Anadon, 2011). Additionally, the change in downstream water flow often impacts soil fertility and long term agricultural capacity (White, 1988).

Finally, in order to alleviate densely populated coastal areas and river banks, many MENA countries are developing towns and cities more inland. Some of these are old oasis settlements (e.g. Liwa & Al Ain in the UAE), while others are new "satellite" cites (e.g. Madinat Nasr, October 6th City in Egypt). These new developments often rely on ground water and water supply chains. From an energy-water nexus perspective, (Brayton-Cycle) gas turbines are appropriately chosen to meet electricity demand without placing additional water stress on the area.

2.2 Couplings between electricity and municipal water systems

A useful taxonomy for considering the various processes that couple the engineered electricity and municipal water infrastructure systems is provided in Table 2. The *supply side* is taken to be all processes that are under the purview of the respective grid operators. The *demand side* is taken to be processes that grid operators do not typically control. This taxonomy clarifies demand and supply side opportunities for improved management of this coupled infrastructure. There does not exist any direct coupling between the demand side for municipal water and the supply side for electricity because grid water is not used for power plant processes. The other three couplings, however, merit discussion.

Table 2. Supply & demand side electricity and water grid couplings

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

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2.2.1 Power supply - municipal water supply

The supply side coupling of these two infrastructure systems takes the form of *cogeneration* facilities; be they hydro-electric power plants or thermal desalination plants. Hydro-electric facilities serve electricity and water for municipal demand and irrigation. They can also consume water by evaporation from their reservoirs. However, because these reservoirs serve multiple uses, it is difficult to quantify the water losses due to power generation alone.

Thermal desalination facilities which generate electricity and desalinate water are a distinguishing feature of the energy-water nexus in the MENA region. Multistage Flash (MSF) desalination, the dominant desalination technology in the region, is a thermal process in which sea water is passed through a series of stages with successively lower pressures causing pure water to *flash* out of solution. Large scale MSF desalination is typically integrated with thermal generation in cogeneration plants with the desalination process deriving its requisite thermal energy from steam extracted at the exit of a back pressure turbine at the appropriate pressure and temperature (Cipollina et al., 2009; Sommariva, 2010).

Determination of the specific energy requirement of the desalination process, in this case, is complicated by the need to apportion the primary energy consumed between the electricity and water generation processes. In addition, for comparison purposes, it is impossible to compare heat, which is of low energy grade, with electric power. The solution commonly employed (Sommariva, 2010) is to express the energy associated with the steam input to the desalination plant in terms of an equivalent loss of electric power that would otherwise have been generated by the steam. With this approach the specific energy requirement of MSF desalination has been estimated to be between 10 and 20 $kW\,h/m^3$ (Sommariva, 2010).

2.2.2 Power demand - municipal water supply

The coupling between power demand and municipal water supply in the region takes the form of three processes:

(i) **Water Treatment**: Groundwater treatment plants, which represent the largest portion of the water supply portfolio require significantly more electric power for their operations than surface water treatment plants. The bulk of the electrical energy is used for pumping, to which over 98 percent of the energy consumption in typical plants has been attributed (Goldstein and Smith, 2002b). Specific energy requirements have been estimated (United Nations Education Scientific and Cultural Organization, 2012) to be, on average, 0.16 $kW\,h/m^3$. However the exact amount of electrical energy required is, of course, dependent on the depths of individual wells. A first order estimate (Siddiqi and Anadon, 2011) utilizing average well depths and an assumed pump efficiency attributes 5% of all electricity consumption in Saudi Arabia to groundwater pumping.

(ii) **Membrane Desalination**: Reverse Osmosis (RO), the dominant membrane desalination technology, is a process in which seawater is forced across a semi-permeable membrane that holds back dissolved salts. Electrical energy is utilized in RO plants for pumping to generate the significant hydraulic pressure required to overcome the natural osmotic pressure which would cause filtered fresh water to flow back across the membranes. The specific electric energy requirement for RO varies with the salinity of the seawater but is typically in the range of 3 to 5 kWh/m^3 (Isaka, 2012; Sommariva, 2010).

(iii) **Water Distribution**: Treated and desalinated water is distributed to end users with the aid of pumps within the distribution system. The amount of electrical energy required depends on the conveyance distances, the system topology, and the volume of water being transported. Another significant contributor to the energy footprint of water distribution systems is pipe leakages. Country level data for the MENA is not readily available, however, double-digit percentage losses are common in water distribution systems (California Department of Water Resources, 2014) and it has been estimated that globally, approximately 32 billion cubic meters of treated water leaks out of water distribution systems every year (Kingdom et al., 2006).

2.2.3 Power demand - municipal water demand

Electrical energy is utilized in conditioning water for end use applications such as heating, cooling, pressurizing or purifying. In some cases, this energy consumption is greater than the consumption in supply and distribution. In California, for instance, it has been estimated that 5% of all consumed electrical energy is used for water supply while 14% is used for activities involving or related to domestic water use such as heating water and washing clothes (US Department of Energy, 2005). While, to our knowledge, there are no published equivalent studies for MENA countries, it is reasonable to anticipate similarly significant amounts given the similarly hot & arid climates. Energy intensities for various categories of domestic and commercial water uses have been estimated (Griffiths-Sattenspiel and Wilson, 2009) and range from zero to as much as 50 $kW\,h/m^3$. A recent study at the relatively sustainable Masdar City, UAE, found 2.6–4$kW\,h/m^3$ (Siddiqi and Weck, 2013). This demand-side coupling creates the potential for integrated demand-side management in the operations timescale which will be of ever-increasing importance with high penetrations of renewable energy resources and associated emerging smart grid paradigms. Furthermore, the demand side coupling means that end-use devices and processes that minimize water consumption can conserve energy; both upstream in supply and conveyance, as well as downstream at the point-of-use.

2.3 Electricity use for wastewater management

Wastewater is typically conveyed by gravity-flow sewers with wastewater treatment plants being built at low elevations, traditionally close to the water bodies into which effluent is to be discharged. The wastewater system, however, does require electric power for treatment. Various types of electric motor-driven equipment including pumps, blowers and centrifuges are used in wastewater treatment operations. In addition to the standard processes of filtration and biological decomposition, a wide range of processes with different energy requirements such as chemical precipitation, ion exchange, reverse osmosis and distillation (Tchobanoglous et al., 2004) are variously employed in different wastewater treatment plants to eliminate specific residual constituents as required by local environmental discharge regulations and reuse quality requirements. Attempts to quantify the per-unit energy requirements for wastewater treatment have typically classified treatment plants into four representative categories: Trickling Filter, Activated Sludge, Advanced Treatment and Advanced Treatment with Nitrification. The per-unit energy requirements for these categories have been estimated by survey (Goldstein and Smith, 2002b) and are contrasted with the energy requirements of water treatment options in Table 3.

Wastewater recycling presents a tremendous opportunity for reducing the energy and carbon footprints of water supply in the MENA. Comparison of the specific energy requirements of wastewater treatment and desalination processes (Table 3) shows that even advanced wastewater treatment processes consume an order of magnitude less energy than desalination. MENA countries have among the highest per capita water consumption rates in the world and thus have a lot of collectable wastewater that can be recycled. Table 4 provides estimates (FAO, 2012) of industrial and municipal water demands in the UAE. If the sum of these is compared with the contribution of recycled wastewater to the supply portfolio in the MENA (Table 1), the percentage of collectable wastewater that is directly recycled can be determined and is also shown in Table 4. While it is clear that significant efforts have been made to recycle wastewater in the MENA, particularly in the UAE and Qatar, the percentages show that there is still room for more reuse throughout the region.

Table 3. Comparison of energy requirements of wastewater treatment and water treatment technologies (Goldstein and Smith, 2002b)

Treatment type	Energy Intensity (*kWh/m*^{3})
Trickling filter	0.25
Activated sludge	0.34
Advanced	0.4
Advanced with Nitrification	0.5
Surface Water Treatment	0.06
Ground Water Treatment	0.16
Reverse Osmosis	3–5
Multistage Flash Desalination	10–20

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Table 4. Industrial and municipal water demands in million *m*^{3}*/year* (FAO, 2012)

Country	Year	Industrial Demand	Municipal Demand	Total	% Recycled
Algeria	2012	415	3020	3435	9.4
Bahrain	2003	20	178	198	31.2
Egypt	2000, 2002	4000	5300	9300	20.4
Iraq	1999, 2000	9700	4300	1400	3
Kuwait	2002	21	401	421	36.1
Lebanon	2001, 2005–06	150	380	530	10.6
Libya	1999, 2000	132	610	742	5.4
Morocco	2010–11	212	1063	1275	13
Oman	2003, 2006	19	134	153	24.2
Qatar	2005	8	174	182	41.2
Saudia Arabia	2006	710	2130	2840	5.9
Syria	2005	615	1475	2090	3.6
Tunisia	2010–12	165	496	661	34.2
UAE	2005–06	69	617	686	42.1
Yemen	1999, 2000	68	272	340	13.5

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There are a number of water recycling options for the region. The most prominent wastewater reuse categories are agricultural irrigation, landscape irrigation, groundwater recharge and industrial processes (Tchobanoglous et al., 2004). Groundwater recharge has an energy benefit, in that it prevents the depletion of aquifers close to the surface and thus the need to extract water from deeper ones. While public sentiment may prohibit blending of recycled wastewater into the potable water supply, industrial consumers are likely to choose recycled water if there is a financial benefit and the water can be demonstrated to be suitable for their applications. The integration of recycled wastewater into the industrial water supply system has been implemented aggressively in Singapore under the *NEWater* scheme (United Nations Education Scientific and Cultural Organization, 2012) which supplies water, that in addition to conventional biological treatment and filtration processes, has been purified with ultraviolet, micro-filtration and reverse osmosis technologies making it suitable for industrial applications requiring water of high purity. It has been shown (Siddiqi and Anadon, 2011) that in several MENA countries, recycled wastewater has the potential to meet nearly all industrial water demand. Careful classification of the quality requirements for different categories of reuse opens up tremendous water recycling opportunities.

3. Integrated energy-water operations

This section argues that the energy-water nexus would benefit significantly from integrated energy-water market operation rather than addressing each product individually. The argument proceeds in four parts. First, the need and opportunity for integrated energy-water operations is presented. Second, deregulation of the power and water supply systems in the context of the MENA is discussed in relation to the identified need and opportunity. Third, a sample integrated electricity-water dispatch is presented as an optimization program. Finally, the potential for incorporating demand side management into the integrated operations paradigm is discussed.

3.1 The need for integrated energy-water operations in the MENA region

The need for integrated energy and water infrastructure operations in the MENA arises from the supply side coupling created by power and water co-production facilities. Similarly, the integrated operational management of dual products is not without precedent in other parts of the world. For example, in Northern European countries, 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 (Kiameh, 2012; Tsai and Hsien, 2007; Ziebik and Gladysz, 2012). 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 (Rosen, 2009). To that effect, combined power-heat economic dispatch approaches have been developed within the literature. Typically, they create 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 heat produced (Algie and Wong, 2004; Piperagkas et al., 2011; Tao et al., 1996; Linkevics and Sauhats, 2005; Rifaat, 1998).

In regards to the co-optimization of power and water, it has generally focused on one particular plant and its associated process flow diagram. Hence, it does not provide an extensible optimization formulation. For example, some focus on optimized planning and design rather than operations (El-Nashar, 2008; Cardona and Piacentino, 2004; Shakib et al., 2012). Still others find methods of cost allocation (El-Nashar, 1999). 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 to all the water and production units in the water and power grids (El-Nashar and Sarfraz Khan, 1991). Recent work (Santhosh et al., 2012, 2013a, 2013b, 2013c, 2014; Lubega et al., 2014), however, has developed parametrized models for the optimization of multiple co-generation plants in conjunction with pure power and water plants with no assumptions of cost splitting. Such models treat all three plant-types equally. Ultimately, this work may serve as the basis for setpoint determination for single-plant optimization formulations.

3.2 IPPs, IWPs, and IWPPs in the MENA

Electric power sector liberalization has been widely prescribed for improvements in power system efficiency (Gutman and Wilcox, 2009). Many have argued that the unbundling of vertically integrated utilities and the creation of competitive wholesale markets stimulates innovation and thus increases reliability and efficiency while reducing end-user tariffs. Even where there are no wholesale markets, Independent Power Producers (IPPs) relieve governments and centralized utilities of upfront financing allowing them to channel available funds to other development projects. In the case of the MENA, where the water and electricity supply are so coupled, there is the potential for the unbundling of both power and water to form Independent Water

Producers (IWPs) (e.g reverse osmosis desalination facilities) and Independent Water and Power Producers (IWPPs) (e.g thermal power plants with multi-stage flash desalination units).

Following initial forays in the 1990s, the number of IPPs and IWPPs has grown significantly in the MENA region. In 1996, the Al-Manah Power Plant in Oman, became the first Independent Power Producer (IPP) in the region (Sarraf et al., 2010). In 2002, the first Integrated Water and Power Producer (IWPP), Taweelah A2, was opened in Abu Dhabi (Sarraf et al., 2010). Currently, there are over two dozen IPPs and IWPPs in operation in the the six countries that make up the Gulf Cooperation Council with a total installed capacity of 20 GW. This accounts for 23% of the GCC's 94 GW of installed power capacity (Sarraf et al., 2010). By 2016, existing expansion plans will see the contribution of independent power producers increase to 35% of the market and a doubling of installed capacity in absolute terms (Sarraf et al., 2010).

Unlike in other regions in the world, the regulatory model of privatization currently employed throughout the region is advance purchase contracts. They stipulate the quantity of power (and water) to be purchased, a fixed per unit cost, and a fixed fuel cost. The government identifies capacity expansion needs, solicits bids for new power and cogeneration plants and awards tenders based on the levelized costs of electricity and water. The successful bidders then finance, construct and operate the plants. There is no competitive market pool and all produced electricity and water is sold to a single government controlled entity through Power and Water Purchase Agreements that typically run for 20 to 25 years. The agreements provide for a capacity payment designed to cover fixed costs and an energy payment that covers operations and maintenance costs. Fuel costs are often guaranteed by the government. In this set up, the single buyer absorbs both the fuel and demand risks (Sarraf et al., 2010). This model, though attractive to investors, has a number of disadvantages (Sarraf et al., 2010): 1) It reduces the incentive for the independent producers to continuously improve efficiency, 2) Power purchase commitments made in growth periods may lead to an overubandance of capacity in the future if there is an economic downturn, 3) Average energy costs decline as the use of a unit increases, and thus bids based on levelized costs favor IPPs that are committed to running at full capacity. This base load plant bias may, over time, result in an unbalanced system that isn't as responsive as it could be to daily and seasonal demand fluctuations, and 4) The baseload bias forces existing government-owned plants to operate in mid-load territory where they are typically less efficient.

A disciplined and staged transition to liberalized electric power markets would help eliminate these disadvantages. However, in light of the coupling that cogeneration plants introduce to the supply sides of power and water grids, an integrated energy-water market could simultaneously co-optimize supply of both water and electric power while accounting for the physical constraints of cogeneration. In this market, IPPs, IWPs and IWPPs would submit bids to satisfy demand over a time horizon to a clearing mechanism, indicating relevant physical constraints. The mechanism would then optimize supply over the time horizon of interest. As in power systems, multiple time horizon markets would likely be required in a final implementation.

Development of integrated energy-water markets could readily proceed from the status quo in MENA countries. Integrated dispatch mechanisms could be introduced within the context of the existing regulated water and electricity authorities all across the region, with the transition to integrated competitive wholesale markets taking place as IPPs, IWPs, and IWPPs come to dominate the supply portfolio and with development of appropriate market infrastructure. The illustration of the market clearing mechanism in Section 3.3 can be used to clarify the integrated energy-water markets concept.

3.3 A supply-side power-water economic dispatch example

A number of power-water co-optimization programs have been recently developed (Santhosh et al., 2012, 2013a, 2013b, 2013c, 2014). The first and simplest was first proposed in (Santhosh et al., 2012) is as follows. Minimize the production cost objective function C_G with respect to the quantity of power generated by the i^{th} power plant x_{pi}, water produced by the j^{th} water plant x_{wj}, power generated by the k^{th} co-generator plant x_{cpk} and water produced by the k^{th} cogeneration plant x_{cwk}. The following notation is introduced:

$$X_{pi} = [x_{pi,} 0]^T$$

$$X_{wj} = [0, x_{wj}]^T$$

$$X_{ck} = [x_{cpk,} x_{cwk}]^T$$

$$D = [D_{p,} D_w]^T$$

The objective function can be written as:

$$\min\ C_G\left(X_{pi}, X_{wj}, X_{ck}\right) = \sum_{i=1}^{n_{pp}} C_{pi}\left(X_{pi}\right) + \sum_{j=1}^{n_{wp}} C_{wj}\left(X_{wj}\right) + \sum_{k=1}^{n_{cp}} C_{wj}(X_{ck}) \quad (1)$$

It includes a sum of the cost curves of all of the power, cogeneration, and water plants to introduce the concept of economies of scope across the two commodities. This objective is minimized subject to the capacity, demand and process constraints in Equations 2, 3, and 4 respectively.

$$\begin{aligned} &MinGenPP_i \le X_{pi} \le MaxGenPP_i\ i\ =\ 1 \ldots n_{pp} \\ &MinGenWP_i \le X_{wj} \le MaxGenWP_j\ j\ =\ 1 \ldots n_{wp} \\ &MinGenCP_k \le X_{ck} \le MaxGenCP_k\ k\ =\ 1 \ldots n_{cp} \end{aligned} \quad (2)$$

$$\sum_{i=1}^{n_{pp}} X_{pi}\ +\ \sum_{j=1}^{n_{wp}} X_{wj}\ +\ \sum_{k=1}^{n_{cp}} X_{ck}\ =\ D \quad (3)$$

$$r_k^{lower} \le \frac{x_{cpk}}{x_{cwk}} \le r_k^{upper}\ \forall k\ =\ 1..n_{cp} \quad (4)$$

where C_{pi}, C_{wj}, C_{ck} are the scalar cost functions for the i^{th} power production facility, the j^{th} water production facility and the k^{th} co-production facility. Additionally, n_p, n_w, n_c are the numbers of power, water and co-production facilities respectively. r_k^{upper} and r_k^{lower} are upper and lower bounds on the power-water production ratio for the cogeneration plants. 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. *D* represents the power and water product demand vector. Finally, *MinGenPP*, *MinGenWP*, *MinGenCP*, *MaxGenPP*, *MaxGenWP* and *MaxGenCP* are the minimum and maximum power and water capacity limits for power, water, and co-production facilities respectively.

Enhancements to this simple dispatch example have considered the impacts of various levels of storage capacity on overall operating cost (Santhosh et al., 2014), as well as the introduction of water and electricity network constraints (Santhosh et al., 2013a).

3.4 Integrated demand side management

The dispatch presented in the previous section can be further enhanced by incorporating water pumping and storage as flexible electrical demands. The ease with which water can be stored, in comparison to electricity, makes pumping, either at water treatment plants or with distribution system pumps, a valuable demand-side resource for the power grid. The pumping energy in water distribution systems typically accounts for 3–5% (United Nations Education Scientific and Cultural Organization, 2012) of electric power consumption in a given region depending on its geographical topology. Considering that independent system operators typically maintain 15% operating reserves (PJM-ISO, 2013), smart operation of water distribution systems have the potential for a significantly stabilizing impact.

The demand-side coupling discussed in Section 2.2.3 presents further opportunities. Direct load control programs in the United States have, for example, already targeted residential water heaters (Kassakian et al., 2011) as demand-side levers whereby the duty cycle of the residential water heater is tuned to provide an ancillary regulation service. Along the same lines, researchers have developed control algorithms to intelligently control swimming pool pumps so as to provide a demand-side management service (Meyn et al., 2013). Similarly and perhaps particularly germane to the MENA region, district cooling systems (Looney and Oney, 2007) which employ chilled water as a working fluid can leverage the thermal capacitance of the water to provide an electrical load displacement function. Ultimately, the adoption of demand side management strategies can also serve to incentivize MENA residents away from the long trend of extensive water and power subsidies. Such efforts would promote water and energy conservation, reduce government spending on these resources, and diminish the demand side coupling in the energy water nexus.

Active demand side management can also be applied to wastewater treatment when the plants are operated with batch rather than continuous processes (Simon et al., 2006). In some cases, such processes improve the quality of the end-product water while simultaneously allowing the scheduling of the process outside the peak. This possibility is particularly promising as the industry trends to distributed water treatment (Konig et al., 2015), thus allowing a more granular and more geographically distributed demand side control of the power grid. Finally, as wastewater treatment generates methane, plants can harvest this gas for power generation by a co-located gas turbine (City of San Diego, 2014; AMERESCO, 2014). Depending on the amount of methane produced and whether the plant is operating batch or continuous treatment processes, such an application can effectively install distributed, fast-ramping and highly available peak load capacity that could directly contribute to the reliability and resilience of the smart grid as a whole.

Leveraging demand-side opportunities, however, presents various challenges. In liberalized electric power sectors these include increased operational complexity, lack of appropriate market structures and difficulty in fairly apportioning the costs and benefits of demand side management programs to the market actors (Strbac, 2008). In the case of dual-product demand side management programs, there would likely be even greater challenges that would have to be managed through appropriate policy. Furthermore, whereas the electric power sector shows a strong trend towards liberalization around the world, municipal water and wastewater infrastructure is typically publicly managed, thus integrated operations would have to be coordinated through carefully-designed public-private partnerships.

4. Integrated energy-water planning

Moving on from opportunities in the operations time scale, this section considers integrated energy-water planning opportunities. The argument proceeds in three parts. First, some of the challenges to integrated energy-water nexus modeling are discussed. Next, some recent efforts to develop engineering systems models for integrated energy-water nexus planning are described. Finally, the opportunities for integrated energy-water nexus planning are identified.

4.1 Challenges to integrated energy-water nexus modeling

It is important to recognize that the electricity, water and wastewater infrastructure systems fall under the classification of engineering systems which De Weck et al. define as: *"A class of systems characterized by a high degree of technical complexity, social intricacy, and elaborate processes aimed at fulfilling important functions in society."* (De Weck et al., 2011). In other words, addressing the technical complexity alone is often insufficient to bring about effective and measurable holistic change. Rather, methods from the necessary engineering disciplines must be seamlessly intertwined with the economic and social context in which these infrastructure systems operate. For this reason, the challenges can be viewed as both technical as well as socioeconomic.

From a technical perspective, the main challenge behind the energy-water nexus is that engineers are typically trained within disciplines (e.g. mechanical, electrical, chemical, civil) rather than broad-scoped problem areas such as the energy-water nexus. This often leads to *silo* thinking that generates piece-meal technical solutions that are restricted by the boundaries, competences, and methods of the respective engineering field. Nevertheless, if many of the traditional methods from multiple disciplines can be combined into a single analytical framework that addresses the full scope of the technical problem, then new, effective solutions can be developed that target the main technical barriers at the heart of the problem. Such an approach would also require an integrated technical modeling framework that draws upon engineering knowledge from electrical, mechanical and civil/water engineering. Furthermore, as seen from various studies, it is important to note that the challenges presented by the energy-water nexus are location specific. The mix of available water sources, electricity generation options, local effects of climate change, and societal requirements together determine the sustainability and robustness concerns associated with the nexus.

That enough technical disciplines can be combined into a single technical analytical framework is no guarantee that the technical solutions that it recommends will be implemented. Recalling the social intricacy of engineering systems, effective and measurable holistic change requires facilitating the decision-making processes that adopt the recommended technical solutions. Here, it is critical to demonstrate the partiality of typical decision-making methods for technical solutions. For example, rarely do cost-benefit analyses and ROI calculations consider that a renewable energy project has demonstrable impacts on water availability. Even if the true benefits and impacts of technical solutions were to be demonstrated in a single decision-making process, it does not necessarily mean that there exists a decision-making entity with sufficient jurisdiction for its implementation. Therefore, any technical solution must recognize the context of decision-making is one in which multiple stakeholders must be brought to the table for coordinated decision-making on shared benefits and costs.

In many cases in the MENA region, however, the energy-water nexus is effectively contained within the scope of oversight of integrated electricity and water multi-utilities and hence can be viewed as a "directed system-of-systems" (ODUSDAT, 2008). Furthermore, given the economic, environmental and social commonalities that exist across the MENA countries, as well as the abiding regional cooperation, there is an opportunity for the region to benefit from a shared learning curve. There is therefore a great opportunity for the MENA to emerge as a leader in integrated approaches to energy and water management.

4.2 Engineering systems modeling for integrated energy-water planning

In recent years, there have been a number of insightful publications on the energy water nexus that provide overviews of the associated challenges and discussions of various policy options for the amelioration of the risks (Olssonn, 2012; United Nations Education Scientific and Cultural Organization, 2012; USDOE, 2014; US Department of Energy, 2013; World Economic Forum, 2009; Siddiqi and Anadon, 2011; Stillwell et al.,

2011; Park and Croyle, 2012; Cohen et al., 2004) in recent years. Empirical evaluations of the electricity-intensity of water treatment technologies and the water-intensity of electricity generation technologies have also been reported and analysed (Macknick et al., 2012; Goldstein and Smith, 2002a, 2002b; Meldrum et al., 2013; Averyt et al., 2013). Furthermore efforts have been made towards physics-based models (Delgado, 2012; Rutberg, 2012) in which formulations for estimating water use by thermal power plants based on the heat balance of the plant have been derived, and towards frameworks for the quantification of the energy intensity of urban water end-use (Siddiqi and Weck, 2013).

Less literature, however, is available on the development of tools for integrated management of electricity and water supply systems. A decision support system for the United States based on an underlying system dynamics model is described in Tidwell et al. (2009). The model enables the exploration of various water and electricity policies and relies on statistical relationships between the independent variables of population and economic growth and the dependent variables of electricity and water demand. Recent work (Sattler et al., 2012) has interfaced the well known Regional Energy Deployment System (ReEDS) and Water Evaluation and Planning (WEAP) tools to create a platform for determining the water resource implications of different electricity sector development pathways. The platform uses empirical consumption and withdrawal coefficients (Macknick et al., 2012) for the interface.

Recent work (Farid and Lubega, 2013; Lubega and Farid, 2013a, 2013b, 2014a, 2014b; Lubega et al., 2014) has developed and applied a transparent physics-based model that interfaces a model of the electricity system to models of the municipal water and wastewater systems enabling an input-output analysis of these three systems in unison (Figure 3). This model arose from an awareness that the energy-water nexus has developed to be a major sustainable development challenge in part because the engineering of an industrial facility gives limited attention to the other industrial facilities upon which it depends. The required input and subsequent output flows are specified during the facility's design without the awareness that such flows cause suboptimal performance of the multi-facility system as a whole. Furthermore, given that cost/benefit and ROI analyses are often conducted purely within the scope of the facility design as a project, it is not clear that any design changes would occur even with greater awareness of the holistic system performance. For this reason, an appropriate system boundary for consideration of the energy-water nexus must be chosen judiciously.

Figure 3 presents a system context diagram encompassing the full energy-water nexus composed of the electricity, water, and wastewater systems. It may be viewed as a generalization of the energy-water nexus problem. Indeed, the interested reader may related each of the opportunities in the previous section back to the input and output flows identified in the Figure. It chooses such a system boundary that directly support holistic analyses. It also depicts the high level flows of matter and energy between them and the natural

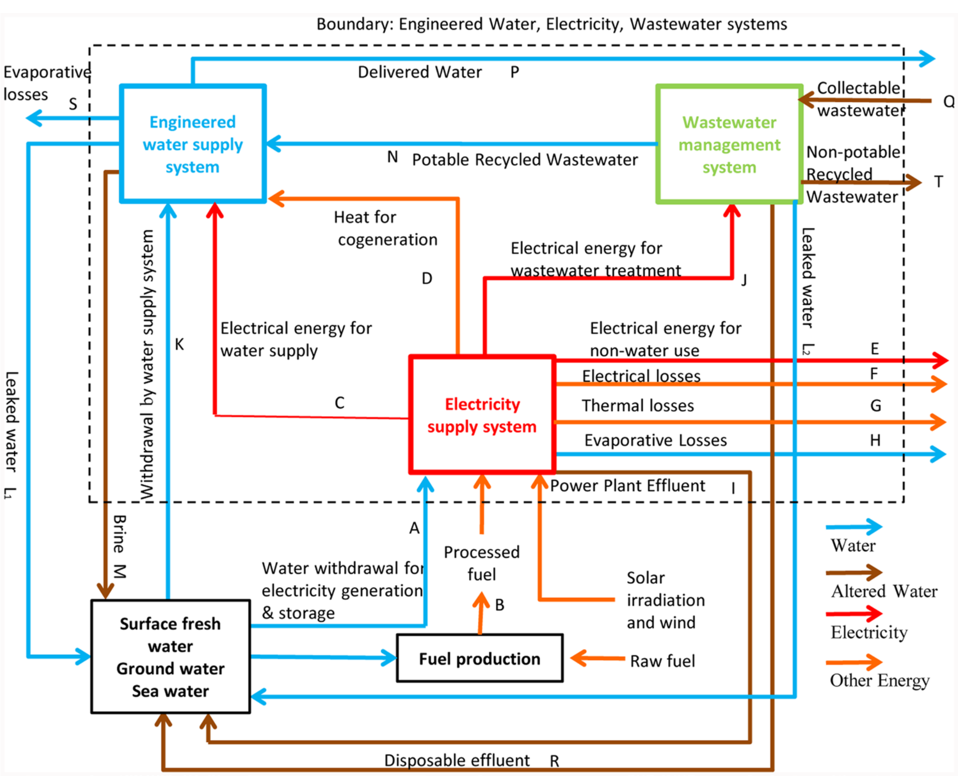

Figure 3

System context diagram for combined electricity, water & wastewater systems (Lubega and Farid, 2013a, 2013b, 2014a, Farid and Lubega, 2013).

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environment. The valued products of electricity, potable water, and wastewater are all stationary within the region's infrastructure. In contrast, the traditional fuels of natural gas, oil, and coal are open to trade and consumption by another sector if not consumed by the local thermal power generation. Consequently, the fuel processing function is left outside of the system boundary. Another advantage of this choice of system boundary is that the three engineering systems all fall under the purview of grid operators. Furthermore, in many cases in the MENA region, all three grid operations are united within a single semi-private organization. This work has been fully developed into a reference-architecture of the energy-water nexus (Lubega and Farid, 2013b; 2014a).

An engineering systems model to solve for the various exchanges of matter and energy identified in Figure 3 has been developed (Farid and Lubega, 2013; Lubega and Farid, 2013a, 2014b). Figure 4 instantiates Figure 3 to conceptual illustrate a geographical region served by a variety of water and electricity sources. The electricity system topology is modelled by means of the IEEE 14 bus test case (Milano, 2010) with slight modifications (Farid and Lubega, 2013; Lubega and Farid, 2013a, 2014b) while the water system topology is modelled as consisting of three water sources, as indicated, which are equidistant from an aggregated demand node of $6m^3/s$ or approximately 140 million gallons a day. No wastewater management system is modelled.

The model yields values for the flows of matter and energy identified in Figure 3. As a first application, aggregate system measures can be defined in terms of these flows (Farid and Lubega, 2013; Lubega and Farid, 2013a, 2014b). These can serve to inform monitoring, planning and analysis. They are determined for the illustrative case:

- Proportion of Generated Electricity used for Water Supply given by: $C/(C + E + J) = 3.2\%$
- Energy Intensity of Water Supply given by: $(C + D)\ /P = 0.39kWh/m^3$
- Water Intensity of Electricity Supply given by: $A/(C + E + J) = 52.2m^3/kWh$
- Water Leakage per unit Delivery given by: $L/P = 15\%$

Such measures can aid communication and holistic analysis of the status quo as well as analysis of anticipated or proposed changes to any of the three modelled systems. For example, if the energy intensity of water supply is of particular concern, as is the case in most of the MENA region, the extant situation is readily communicated to stakeholders with the metric above, and strategies to ameliorate the situation, such as substitution of thermal desalination with membrane processes and wastewater recycling can be compared in terms of their effects on this metric.

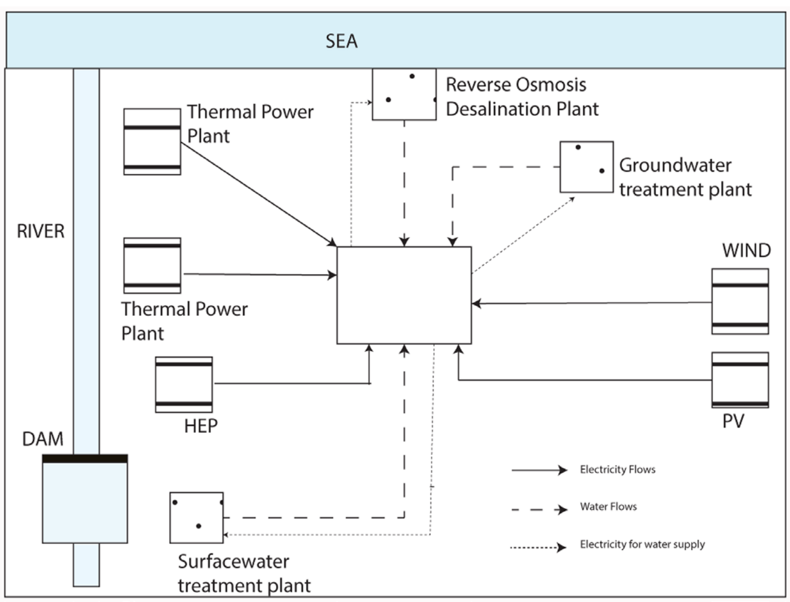

Figure 4
Illustrative energy-water nexus example.

doi: 10.12952/journal.elementa.000134.f004

4.3 Opportunities for integrated-energy water planning

The energy-water nexus reference architecture and the associated quantitative model presented in the previous section have the potential to inform numerous areas for integrated energy-water planning. These include 1) Shifts towards renewable energy, 2) Shifts in desalination technology, 3) Optimization of water distribution networks and leaks, 4) Usage of alternative forms of water, and 5) Integrated Environmental Management and Sustainable Development. This section briefly discusses the opportunities and importance of each these.

Much of the awareness surrounding the energy-water nexus arose out of the water withdrawal and consumption of thermal electric generation facilities. In that regard, renewable energy presents an interesting alternative not just for its carbon neutrality but because of its negligible water footprint. Neither solar PV, nor wind energy use water in operations and their upstream lifecycle processes have a limited impact on water resources. In the case of concentrated solar power, the in-built rankine cycle can be a cause for significant water use. However, this does not necessarily need to be the case. The recently built Shams 1 CSP plant in the UAE – the largest of its kind in the world at 100MW generation capacity – uses air cooling in spite of formidably hot ambient temperatures. While air cooling causes a marginal loss of energy efficiency, it has allowed the plant to be be situated in Madinat Zayed; very much inland from the Gulf waters. These advantages stated, the intermittency of renewable energy may cause the need for grid-level storage. If this storage were to come in the form of pumped-hydro – as the most cost effective and most mature storage technology – then the penetration of renewable energy would have be to be associated with the evaporation rates coming from the pumped hydro-facilities. Clearly, renewable energy poses interesting water-energy trade-offs that can be quantitatively assessed. If water consumption and withdrawal were monetized, perhaps over a certain per capita threshold to sustain life, the case for renewable energy would inevitably be a stronger one.

Another area for integrated-energy water planning is on the supply side in regards to shifts in desalination technology. As previously mentioned, reverse-osmosis uses significantly less energy per water volume than MSF desalination facilities. Nevertheless, in the MENA region, MSF co-production remains a viable option due to the quickly growing demand growth rates in both power and water. The optimal fleet of power and water generation capacity can be addressed with the same rigor as traditional power utilities execute generation planning. Furthermore, the existence of an integrated energy-water market can bring incentives for new separation technologies (e.g. membranes) which would create a long-term shift in energy-water planning.

Integrated energy-water nexus planning can also be applied to the water distribution network. This is the energy-water nexus analog of power transmission system planning. Here, the opportunities arise from the recognition that the topology of the water distribution system in terms of pipes, elevations, and pumps can be optimized for energy intensity and not just water flow capacity. Such an effort would naturally lead to a greater awareness of the energy-intensity of water leaks; that are often double-digit percentages of the total water originally treated. Integrated energy-water nexus modeling provides the opportunity to rationalize water leak improvement projects not just in terms of water not delivered to the customer but also the embedded energy required to pump, treat, and distribute this water. The associated return on investment calculations would more accurately reflect the true cost of leaked water.

Water distribution system planning, however, is not just the delivery of homogeneous water as it is in the case of transmission system planning. In reality, water *quality* is just as important as water *quantity*. Traditionally, water infrastructure has been divided into two qualities; one of potable quality and another of waste quality. More advanced water infrastructure (such as is found in Qatar and the UAE) will treat some of the wastewater to create a third network usually intended for agricultural use. The natural extension of a three-quality water infrastructure system is one that distinguishes water distribution into many potential water qualities. In such a way, the water infrastructure can deliver water of various types to the various industrial, agricultural and mining uses that exist within a geographical region. While making such planning decisions, it is important to not just minimize the use of natural water resources but also keep track of the embedded energy of the various water types flowing through the infrastructure. The planning of such an advanced water infrastructure would ultimately require the use of more decentralized water treatment facilities (Konig et al., 2015). Furthermore, the planning methods would have to rely on the state-of-the art in hetero-functional graph theory (Farid, 2014a, 2014b, 2015, 2016). That said the underlying principle is simple; the wastewater from one facility or sector can easily be the input water for another facility or sector with minimal levels of treatment and distribution.

These opportunities for integrated-energy water nexus planning suggest that integrated energy-water nexus modeling has a significant role to play in the future of environmental management and sustainable development decision making. Infrastructure planning decisions can and should demonstrate scenarios in which trade-offs in CO_2 emissions, water and energy resource consumption are all balanced. Actions can then be highlighted to make the largest improvements in environmental performance per unit cost.

5. Conclusion and policy implications

The goal of this paper has been to identify and motivate several opportunities for enhanced integrated operations management and planning of the energy-water nexus in the MENA region. The paper began with an exposition of the energy-water nexus, as it applies in an aggravated manner in the MENA region. Whereas much of the existing energy-water nexus literature focuses on the water intensity of energy (e.g. water consumption of power plants), the MENA regions experiences the energy-water nexus in both energy intensity of water and water intensity of energy. With these challenges in mind, the paper turned to opportunities to mitigate the energy-water nexus. The norm in electricity and water utilities is for siloed operations associated with the discipline of each product. This paper instead discusses several opportunities for enhanced

integration of operations and planning of the energy-water nexus from a multi-utility perspective. Section 3 focused on the opportunities in operations management while Section 4 discussed opportunities in planning for the sustainable development of water and energy resources.

From the discussions, two sets of policy implications are distilled and are summarized here. The central policy implication in operations is the shift towards integrated energy-water dispatch operation rather than addressing each product individually. Such a transition can be viewed in three successive steps of policy development.

1) The existing (regulated) approaches to dispatch of the individual products of power and water could be replaced by integrated energy-water dispatch as illustrated by Section 3.3. Such an approach would lead to more efficient utilization of cogeneration plants as the primary coupling point on the supply side of the energy and water value chains.

2) The regional trend towards the development of IPPs, IWPs, and IWPPs should be further supported. The current (static) implementations of fixed power and water purchase agreements can be replaced with a seamless integration with the energy-water dispatch. As in liberalized power systems, multiple time horizon markets with their respective clearing mechanisms would be required so as to provide dynamic incentives for greater cost and resource efficiency.

3) Similarly, the energy-water nexus also presents coupling points that engage the demand side of both power and water. Carefully designed demand-side management schemes, perhaps in the form of public-private partnerships, could present a vehicle for coordinating these coupling points in a cost-effective fashion.

Similarly, the central policy implication in planning is an integrated approach to energy-water infrastructure modeling. Here, such an approach can be applied to four concrete planning opportunities:

1) The benefits of renewable energy (e.g. wind, PV, and CSP) could be better rationalized on the basis of the relatively absent embedded-water intensity. If water consumption and withdrawal of power generation were monetized, the investment case for renewable energy would inevitably be a stronger one.

2) The relative benefits of MSF and RO desalination could be better rationalized in the context of aggressive growth rates in both power and water demand. While RO plants limit the energy-intensity of water production, from an integrated systems perspective, MSF plants provide a coproduction functionality that may be preferred over individual RO and power generation facilities.

3) While many water utilities across the region have made extensive efforts towards reducing water leakages, such efforts could be strengthened by considering the embedded energy and the associated economic and environmental cost of these leakages.

4) There exists both a necessity and opportunity to reduce the energy footprint of water supply in GCC countries through increased water recycling. Singapore's NEWater scheme (United Nations Education Scientific and Cultural Organization, 2012) which provides recycled water to industrial consumers at an attractive price can serve as an illustrative model. Such a wastewater recycling scheme need not be limited to a uniform treatment quality or use (e.g. agriculture). Instead, multiple water qualities and treatment levels can be planned to support a heterogeneity of uses (e.g. industrial, agricultural, mining, commercial). Decentralized strategies to water treatment offer a promising alternative in this regard over conventional centralized treatment (Konig et al., 2015).

In all, the integrated energy-water nexus planning models and optimization programs presented and cited in this work provide deeper perspectives than their single product alternatives found in the existing literature. Their application in the policy domain has a high potential for future work and extension in the MENA region. Furthermore, these techniques have the potential for use in regions of similar climate (e.g. South-West United States & Australia) or other electricity-water utilities around the globe.

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- Contributed the first draft of this work and guided subsequent revisions: AMF
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There are no competing interests with this manuscript.

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There is no additional data associated with this manuscript.

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