Potential Benefits of Innovative Desalination Technology Development in Kuwait

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Abstract

In this report we summarize the technological experience in Kuwait's desalination industry and compare it with other countries. Opportunities for R&D in desalination that can be areas of focus for Kuwait are identified based on the premise of their efficiency and the experience in desalination technology in neighboring countries and in Singapore. A model is devised for the appropriate level of investment given the time period sought for the development, the needs for the technology in Kuwait and the potential for world-wide benefit from the R&D efforts. General recommendations are made for improvement of the water supply and demand in Kuwait.

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Summary

The country of Kuwait relies almost exclusively on desalination for its potable water supply, and spends nearly a third of its annual oil revenue on water and electricity production. Meanwhile, it has among the highest per-capita water consumption levels in the World, and uses energy intensive Multi-Stage Flash (MSF) technology for desalination. Here we assess the opportunity for developing a domestic innovation-based desalination industry, either for fulfilling domestic needs or for export.

Kuwait has the opportunity to develop an innovative desalination industry that could help achieve several national priorities. It could provide industrial diversification and useful employment for citizens, thus driving economic growth. It could create products for export, particularly in the Arab Gulf region. It could increase water security, and it could lead to more efficient use of the limited oil resources. Each of these benefits is discussed in the report, and the technical obstacles are addressed. The cost of overcoming those obstacles is estimated using a simple innovation-investment model, and is shown to be small compared with the potential benefits.

The challenges of industrial diversification in oil-rich economies are discussed in general, and particular attention is paid to the situation of Kuwait. Kuwait is a small country with a limited domestic labor force, and so a promising area for growth and diversification lies in the development of human capital and the performance of research and development in strategic technologies. In the area of human capital, Kuwait could make dramatic improvements by bolstering the quality of primary education, incentivizing more Kuwaitis to become teachers, and improving higher education quality and participation. Kuwaiti students would benefit from more opportunities to be creative in the fields of science, and this would support entrepreneurship and innovation that would in turn produce technologies for export.

Kuwait can also support innovation by providing subsidies for private sector development in strategic industries, in R&D, and in diversified activities. In the report we discuss the subsidy options available to Kuwait along with some of their strengths and weaknesses. We look particularly to the desalination industry because it is a strategic industry, desalination is used widely in the region and thus attractive as an export target, Kuwait has decades of experience in desalination, and there are a wealth of innovation and R&D opportunities in water technologies.

We summarize the technological experience in Kuwait's desalination industry and compare it with those in other countries, identify opportunities for R&D in desalination that might be good areas of focus for Kuwait, and make recommendations for future actions Kuwait might take to improve its position.

Kuwait will need to build considerable desalination capacity in the coming decades, and is in a position to reduce costs, oil consumption, and environmental impact by upgrading to newer technologies. In the near term, some of the existing MSF plants in Kuwait are scheduled for major refits. In this case, an SWRO unit can be added to the plant, providing additional energy efficient water production that can complement the seasonal decrease in electric power demand. Several studies suggest that this "hybrid" plant arrangement holds economic benefit.

In the near to medium term, when Kuwait builds new water plants, for example, in the case of the Independent Water and Power Projects (IWPPs) at Az-Zour and Khirran, the most attractive option might be to build hybrid MED-RO plants. On paper, and based on cost per cubic meter of produced water, SWRO would be the logical choice, but Kuwait has several reasons to be cautious. Kuwait places a high value on reliability, and has little experience building, operating, or maintaining SWRO plants. Before moving to SWRO for a substantial fraction of its water supply, Kuwait should gain experience in operation and maintenance and should train technicians for the new technology. More importantly, the impact of local seawater and climate conditions on SWRO operation need to be studied.

We introduce an innovation investment model that allows us to assess the cost of bringing SWRO technology to acceptable reliability. Next, we evaluate the potential future savings of using SWRO instead of MSF for water production. Our calculations estimate the innovation investments needed to build SWRO demonstration plants and bring the availability of the plants to an acceptable level within 5 years at \$4.6 to \$45.6 million. If fuel is valued at \$60/bbl, those costs would be covered by the savings from one year's operation of a large (218,200 m^3/day) commercial SWRO plant. These results favor a move toward SWRO plants, and show that by building small plants to support initial learning, Kuwait could improve plant availability at a low cost before making large capital investments in commercial-scale plants.

In the longer term, Kuwait will want to keep abreast of the latest technological advancements. Oil reserves are expected to eventually decline, and energy efficiency will be an imperative. Membrane technologies show the most promise for future low-energy desalination, so Kuwait's long term vision might best be based on SWRO and more advanced membrane technologies that are not yet developed.

In terms of developing domestic industrial capacity, it would be best to focus on the state-of-the-art technologies, primarily SWRO and perhaps some MED. <u>By partnering with multinational companies in joint ventures to build small SWRO plants, Kuwaiti companies can take responsibility for the local site work and learn how to operate and maintain the plants from the manufacturers. A key area of learning is that of adapting to the local and fluctuating water conditions.</u> Most SWRO manufacturers do not have experience in the Arabian Gulf, yet there is a high demand there and in other high-salt waters. Kuwait could play an important role by supporting research, development, and experimentation with different pretreatment options, cleaning regimens, and optimal operation protocols for Gulf waters. Skillful operation of SWRO plants on the Gulf would be useful not only to Kuwait, but also to Saudi Arabia, Oman, Bahrain, UAE, and other countries. Innovations in pretreatment would be useful regionally and worldwide. The use of many small test facilities would give Kuwait a distinct advantage in experimenting with gulf-specific innovations. If this type of program is too large for Kuwait alone, the GCC would be a good instrument for investment in desalination demonstrations, and Kuwait should consider a proposal to the GCC.

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I. Introduction/Overview

The country of Kuwait relies almost exclusively on desalination for its potable water supply, and spends nearly a third of its annual oil revenue on water and electricity production. Meanwhile, it has among the highest per-capita water consumption levels and uses Multi-Stage Flash (MSF) desalination technology that is on the decline elsewhere in the world for its high costs and high energy consumption. Kuwait has the opportunity to develop an innovative desalination industry that could help achieve several national priorities. It could provide industrial diversification and useful employment for citizens, thus driving economic growth. There is export potential in developments that are within Kuwait's reach, particularly in the Gulf region. It could increase water security, and it could lead to more efficient use of the limited oil resources. Each of these benefits will be discussed in the following sections, and the technical obstacles will also be addressed. The cost of overcoming those obstacles is estimated using a simple innovation-investment model, and is shown to be small compared with the potential savings.

II. Industrial Diversification

Kuwait, like many resource-rich economies, seeks to diversify its industry for several reasons. Government revenues are 95% derived from oil income, so fluctuations in oil price can cause drastic volatility in revenues. Also, as oil production rates level out (or are constrained by OPEC participation), oil income cannot keep pace with a growing population; keeping GDP per capita on an upward trend becomes a challenge. The oil industry does not employ a large population, so other industry is needed to increase employment. Without that, the public sector is driven to employ a large portion of the citizenry (Richards & Waterbury 2008; Askari 2006; Moore 2004).

Diversification in oil-rich countries is hampered by several factors. One is an effect referred to as the "Dutch Disease," wherein the recovery and export of natural resources results in the strengthening of the exporting country's currency. This currency overvaluation tends to make manufactured goods in that country uncompetitive as exports. Macroeconomic policy, trade policy, and public investment can be used to reduce the effect. (Benhassine 2009; Richards & Waterbury 2008; Gelb 2008; Askari 2006)

Another challenge is that the development of new enterprises may be slowed by an attitude of complacency among the citizens. In Kuwait and many other oil-exporting countries, oil exports fund cradle-to-grave welfare assistance, high paying positions in the public sector, allowances, and subsidies to dramatically reduce the cost of essentials like water and fuel. This leaves scant incentive either to pursue higher education or to pursue entrepreneurial ventures (Richards & Waterbury 2008). But in Kuwait this is relatively less problematic than in other oil-rich economies. In fact Kuwait was one of the oil countries that emphasized education early, and the current generation of Kuwaitis is well educated.

Another problem is that the population of Kuwait is relatively small, and the labor needed for an industrial economy has to be imported. Even with the current economy, a large of fraction of the population is not born in Kuwait.

In *A Political Economy of the Middle East*, Alan Richards and John Waterbury describe five main economic development strategies used by governments looking to diversify their economies. The strategies are:

i. Agro-export-led growth
ii. Mineral-export-led growth (including oil)
iii. Import-substituting industrialization
iv. Growth led by manufactured exports
v. Growth led by agricultural development (Richards & Waterbury 2008)

The second strategy, mineral-export-led growth, is most applicable to Kuwait. In this scenario, the revenues acquired from oil exports are to be used to create the industrial base that will be needed to sustain the economy as oil production declines. Kuwait has used this strategy to build up a large pool of assets, which it has invested internationally. Income from those investments grew to be larger than that from oil exports in the 1980s, but the cost of rebuilding after the Iraqi invasion of the early 1990s depleted much of that. Richards and Waterbury are pessimistic about Kuwait, perhaps overly so, stating that "the absence of arable land, water, and non-oil mineral resources and the presence of a small, poorly educated population suggest that the future without oil may be bleak." But the identification of shortcomings is the first step toward mitigating them, and the Kuwaiti government has taken that step.

Kuwait has worked to support downstream industries with higher value-added products, including refineries, fertilizer production, and pharmaceuticals. These industrial activities are successful, but they are not independent of oil supply. When the oil resource is exhausted, Kuwait will no longer have any advantage in those activities, and as oil prices rise and fall there is some effect on those industries as well. Ideally, Kuwait should concentrate some industrialization efforts on non-oil industries, but thus far attempts to support manufacturing have not led to much growth. Kuwait does have some domestic architect-engineering firms and firms that manufacture large industrial items for use in domestic industrial plants, and one area for growth lies in expanding those activities. In general, non-tradeable goods like construction are provided domestically, but as a small country, Kuwait is only a small market for them.

A more promising area for growth and diversification lies in the development of human capital and the performance of research and development into strategic technologies. Human capital development has been crucial to other countries that have successfully diversified, including Finland and South Korea (Gelb 2010). In the area of human capital, Kuwait could make dramatic improvements by bolstering the quality of primary education, incentivizing more Kuwaitis to become teachers, and improving higher education quality and participation. The main weakness of the primary education is the limited opportunities offered to students to be creative in the fields of science, and to engage in hands-on experience while they are in primary and secondary education. The situation is only slightly better when it comes to higher education. This basic educational infrastructure is needed to support entrepreneurship and innovation, and the R&D that is performed by universities can be commercialized for domestic use and for export.

Another key ingredient to innovation and growth is good governance, and Gelb refers to this as "institutional capital." Mehlum et al (2006) found that avoiding the "resource curse" was correlated with having good institutions supportive of private business. Kuwait scores well in the area of institutional capital, so it is an asset to the country, and continual improvement should be a goal.

In addition to providing good governance and a well-educated workforce, Kuwait can provide subsidies for private sector development in strategic industries, in R&D, and in diversified activities. Figure 1 illustrates one way to categorize the subsidy options in terms of the degree of selectivity and the extent of the subsidy.

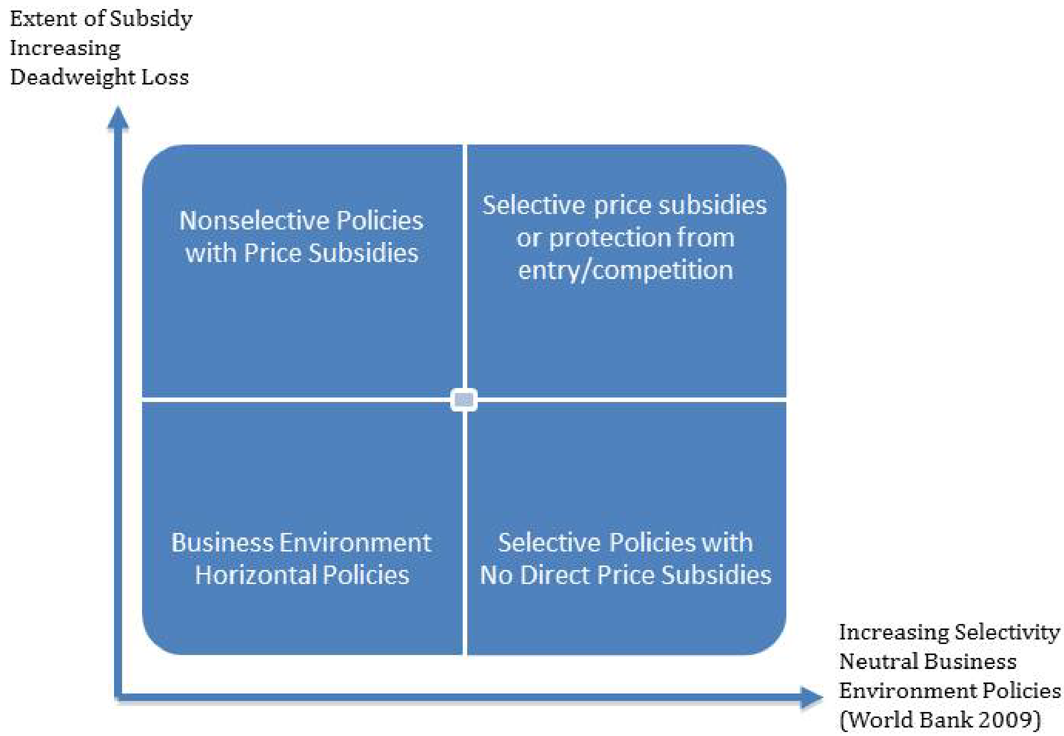

Figure 1: Subsidy Options for Developing Industry (Benhassine 2009)

Table 1: Key Figures for Kuwait, UAE, and Singapore

	Kuwait	UAE	Singapore
Percent of government revenues attributable to oil/gas revenue in 2012 [1]	95%	80%	
Percent of GDP based on oil/gas output in 2012[2]	50%	25%	
Internet Penetration 2007[3]	25%	35%	
Population (millions) 2013[4]	2.7	5.5	5.5
Per capita GDP PPP in 2012US$ PPP 2011 est.[5]	42,400	48,500	60,700
Adult illiteracy rate % (age 15+)[6]	18% (2003)	23% (2003)	7.5% (2000)
GDP per capita annual growth rate, 1980-2011, %[7]	3.6	0.2	7.5
GDP in 1980 (billions current USD)[8]	28.6	43.6	11.9
GDP in 2012 est. (billions current USD)[9]	174.6	361.9	276.5

[1]U.S. EIA Country Analysis Briefs, 2013
[2,4,5,9]CIA world factbook, 2013
[6]Richards & Waterbury, 2008
[7,8]The World Bank 2013

The Kuwait Research Review Panel (2007) recommended choosing several technology platforms from which to drive R&D, commercialization, and growth. They found that solar power, desalination, and petroleum-related technology were logical areas to pursue, and in this study we look specifically at desalination for several reasons. First, it is a strategic industry, since a secure water supply is vital to national security. Desalination is widely used in the region, and its use worldwide is growing. As an export, the strong local market and expanding global market make desalination technology very attractive. Kuwait has decades of experience in desalination, although not with the latest technologies, and there appear to be a wealth of R&D opportunities that could produce valuable innovations in water technology. Naming desalination as a strategic industry with government support would also fit in well with a much-needed campaign to decrease water waste in Kuwait and to increase water reuse.

Aside from diversifying the economy beyond the oil resource, Kuwait has another crucial need for a scarce resource: water. Specifically, Kuwait must import, produce, or recycle vast quantities of potable and de-salted water to meet domestic demand. Average per capita consumption of desalted water in Kuwait was about 600L in 2005, nearly all of which was produced using multi-stage flash (MSF) desalination plants within the country (Darwish & Darwish 2008; Bremere et al. 2001). Cogeneration power desalting plants (CPDP) produce electricity and desalted water, providing most of Kuwait's water and electric power supplies. CPDPs account for 54% of Kuwait's energy consumption, and of that 54%, 80% is derived from oil (Darwish & Darwish 2008). There are several disadvantages to the current system. Desalination consumes a great deal of valuable domestic oil that could otherwise be exported. Some projections show that in 25 years, if current practices continue, Kuwait could entirely consume its oil production domestically, leaving no oil for export (Darwish et al. 2008). While Kuwait has opted not to import large amounts of its water supply in order to increase water security (Murtaugh 2006), the current supply is also facing insecurities. It relies on the oil supply that is shrinking and that is also the country's main source of income, and it relies on foreign expertise, industry, and workers to install MSF plants.

In the next chapters we will summarize the technological experience in Kuwait's desalination industry and compare it with those in other countries, we will identify opportunities for R&D in desalination that might be good areas of focus for Kuwait, and we will make recommendations for future actions Kuwait might take to improve its position.

III. Desalination Experience in Kuwait

Kuwait has the highest global rate of potable water consumption, at 500 to 600 Liters per Capita per Day (LCD), but has very limited freshwater resources. This is compared with about 334 LCD consumed in the UK and 578 LCD in the US, both countries with much more plentiful water resources (KISR). Fresh groundwater is in short supply in Kuwait, and is primarily used to produce bottled water. Brackish groundwater is used for irrigation and other non-potable purposes, but is threatened by over-extraction. Currently Kuwait uses Multi-Stage Flash (MSF) desalination of seawater to provide nearly all of its potable water (95%+). Most of this is produced with Cogeneration Power Desalting Plants (CPDP), in which oil or gas is used to generate electricity and excess heat is used for the MSF process. CPDP's account for 54% of Kuwait's energy consumption, and 80% of that energy is from domestic oil (some is from natural gas). By the year 2050, or earlier by some estimates, Kuwait could consume its entire domestic oil production in CPDP's (Darwish 2008, KISR). Electricity and water production together are expected to consume at least one third of GDP by 2025. Currently it is estimated that Kuwait spends about one third of national oil revenue on water and electricity production, so any energy savings that might be realized in water production will have a valuable impact on Kuwait's national income and economy.

a. Technologies

The earliest desalination plants in Kuwait were of the submerged tube type. These quickly became obsolete due to poor performance and high maintenance requirements. They were replaced with MSF technology. Shuwaikh was the location for the first plants, including the submerged tube plants, several early flash evaporator plants, and, in 1960, the first MSF desalination plants to be commercially installed globally. Kuwait was closely involved in the development of the first MSF plant, including participating in a pilot project and making significant modifications to system design (Al-Wazzan 2001). Kuwait rapidly installed many more MSF plants, with the unit capacity increasing with time and experience. The first units had a capacity of 4,546 m^3/day; by 1970 a unit was built with 18,184 m^3/day capacity, by 1990, units of 32,731 m^3/day were built, and today's units are as large as 56,825 m^3/day. Over these decades, MSF technology was improved, and Kuwait's experience operating the plants grew. Technological improvements included new anti-scalants, stainless steel components, higher temperature operation, addition of demisters to remove brine droplets from water vapor, and an online cleaning system that increased plant availability (Al-bahou et al. 2007). Material selection was also improved, leading to systems with lower maintenance costs and longer lifespans (al-Wazzan 2001). Many plants were refurbished and upgraded over the years to take advantage of these improvements. Figure 2 shows the rapid buildup in MSF capacity in Kuwait, and more recently the addition of some Seawater Reverse Osmosis (SWRO) desalination.

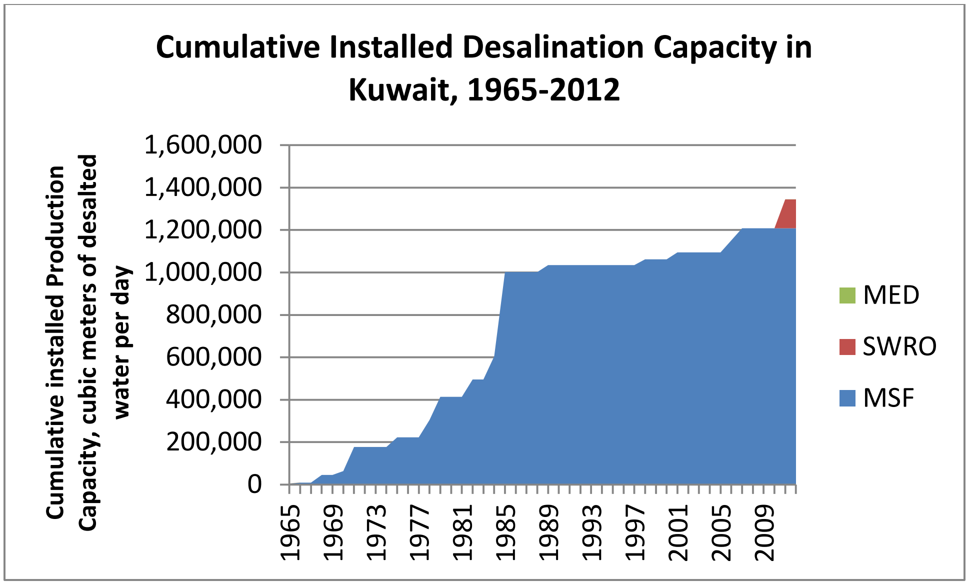

Figure 2: Cumulative Installed Desalination Capacity in Kuwait, 1965-2012 (Al-bahou et al. 2007).

Kuwait has performed some preliminary studies on Multi Effect Distillation (MED) desalination technology, but has not commissioned any major plants. In the 1980s, Kuwait had a demonstration program designed to assess the feasibility of SWRO in the local waters. The Doha Reverse Osmosis Plant (DROP) began operating in late 1984. The plant tested three types of Reverse Osmosis (RO) membranes: hollow fiber, spiral wound, and plate and frame. Economic assessments of actual operation showed that the hollow fiber and spiral wound membranes produced water at costs competitive with contemporary MSF plants, while the plate and frame membrane was substantially more costly (Akashah 1987). The plate and frame membrane experiment was shut down in 1988. Cost and performance studies of the DROP indicated that there was room for cost savings if the pretreatment system could be improved, with microfiltration and ultrafiltration suggested as promising alternatives (Ebrahim 1995).

Thanks to many years of cooperation between the MEW and the Kuwait Institute for Scientific Research (KISR), Kuwait's first large commercial SWRO desalination plant was commissioned by the MEW in 2010. The Shuwaikh SWRO plant has a capacity of 136,260 m^3/day, and is reported to be running well. In particular, its state-of-the-art pretreatment system so far seems to be up to the task of handling the gulf waters. Even during a red tide event in 2012, the pretreatment system functioned adequately. The system, designed by Pentair X-Flow, consists of a Dissolved Air Filtration (DAF) device and Ultra-Filtration (UF) membrane modules. This combination has so far handled turbidity levels up to 31 NTU at Shuwaikh. The same UF system has been selected for use in the UAE Al-Zawrah SWRO plant being built in Ajman. The Shuwaikh SWRO plant also uses modern energy recovery technology to minimize energy consumption, including pressure exchangers provided by Energy Recovery Incorporated (ERI). The EPC contract was for KWD88 million, or about $320 million. The new Ashod SWRO plant in Israel will make use of the same pressure exchangers designed by ERI.

b. Economic experience

The Ministry of Electricity and Water (MEW) has commissioned each MSF plant in Kuwait, and once the initial operating contract of a few years has been exhausted, the MEW has operated and maintained the plants. The MEW thus has amassed a great deal of institutionalized knowledge and expertise in the operation and maintenance of MSF plants. It has significant design review experience, as well, but does not own or develop any major technologies. The MEW has been important in solving system-level problems in Kuwait's water supply, and is evidently a very capable institution with the potential to contribute more.

Unit water production cost

Globally, Multi Effect Distillation (MED), Reverse Osmosis (RO), and several other technologies are used or in development. Kuwait has shown comparatively little interest in those until recently. While MED and RO are less well-developed and Kuwait has accumulated experience operating MSF plants, MED and RO consume less energy than MSF. RO, in particular, requires about 5 kWh/m^3 water produced, compared with 18 kWh/m^3 for MSF and 15 kWh/m^3 for MED. Figure 3 shows a collection of data points on SWRO, MED, and MSF specific energy consumption over several decades. The trends show that SWRO energy consumption has generally been falling, while MED and MSF are more scattered, and more project-dependent.

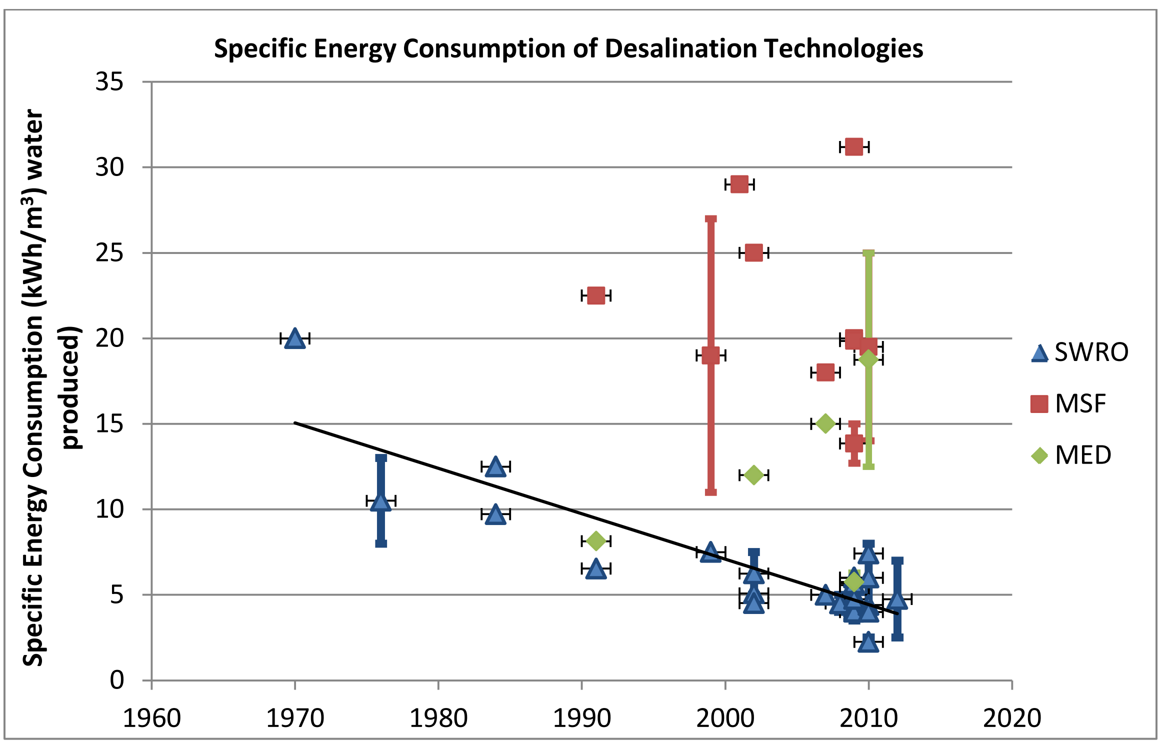

Figure 3: Specific Energy Consumption of Desalination Technologies

Currently experts estimate that there is a nearly equal cost of production in Kuwait from each type of plant (Al-bahou et al. 2007). However, with energy costs on an upward trend, MSF is more costly in many parts of the world. Figure 4 shows a collection of data on the cost of water production using MSF and SWRO in the Arabian Gulf and other high-TDS waters in recent years. SWRO is steady at about $1/m^3. MSF shows more variation, much of which can be explained through energy cost accounting methods. When energy is considered at market oil prices, MSF is much more expensive than SWRO, but in Kuwait, the cost of water produced using MSF is sometimes calculated using oil priced either at extraction cost, at a subsidized cost, or at no cost. Some researchers also estimate that the MEW underestimates the value of the energy used for desalination in the combined power and desalting plants (Darwish 2009, Wade 1999). Figure 5 shows cost figures over a longer time period, illustrating a broad upward trend in the cost of MSF and a downward trend in the cost of SWRO.

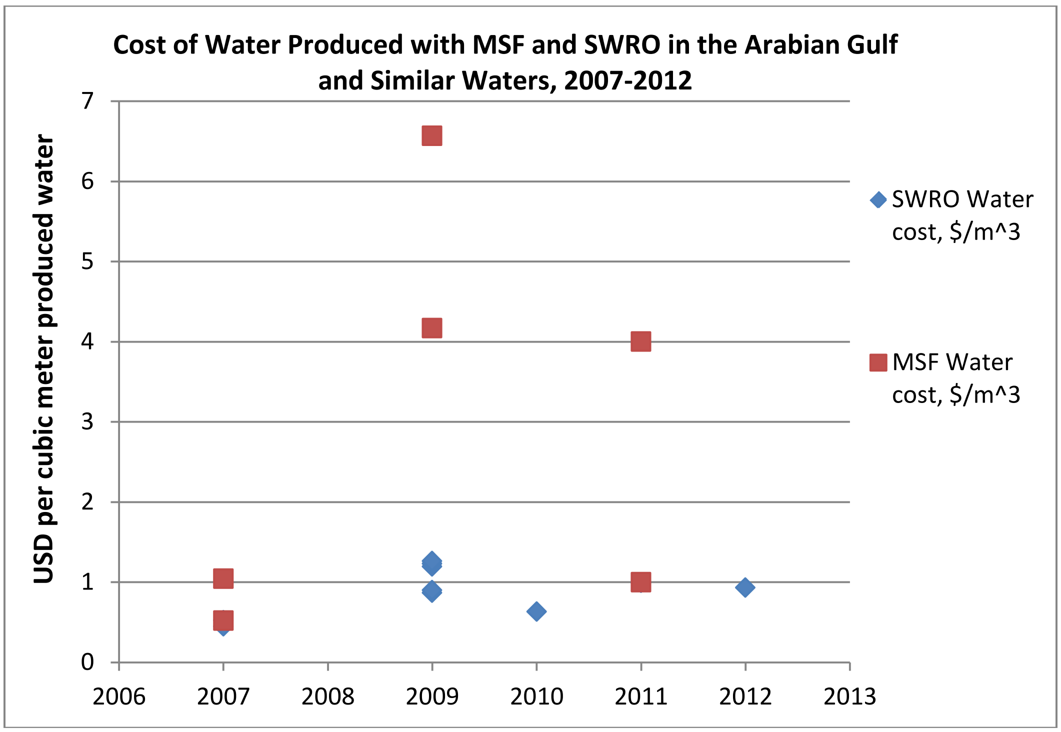

Figure 4: Cost of water production with MSF and SWRO in Arabian Gulf waters, 2007-2012

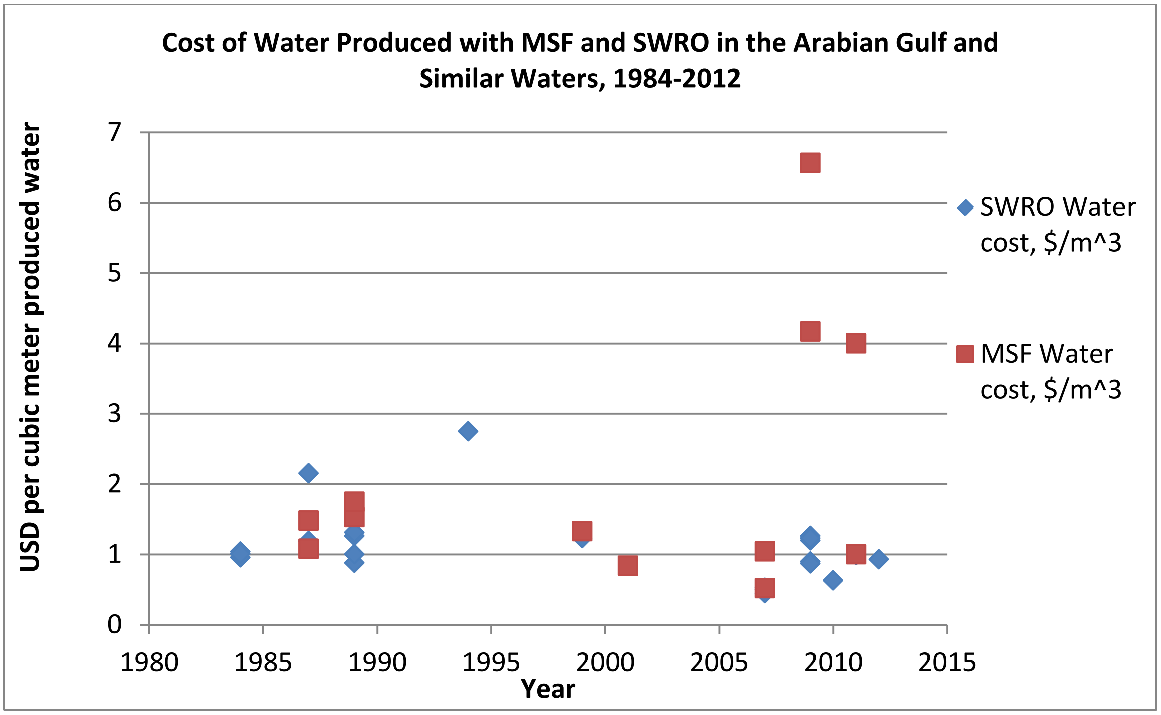

Figure 5: Cost of water production with MSF and SWRO in high TDS waters, 1984-2012

c. Resistance to replacing MSF

There are some technical features of SWRO that make its use less adaptable for Kuwait (Reddy & Ghaffour 2007), including the lack of experience with such high Total Dissolved Solids (TDS)[1] and high temperature waters. However, in an economy with a thriving innovation system, we might expect that the substantially lower energy consumption would prompt research and development. Kuwait, on the other hand, has conservatively focused on reliability and the use of proven technology in its desalination technology choices. Combined with the perception of a plentiful and low-cost energy supply, this has led to the choice of MSF.

Even within MSF, though, Kuwait has been wary of changes. Even though Kuwait has been using MSF plants to provide water for over 50 years, every plant has been designed and built by a foreign company, primarily on contracts that require the plant be operating smoothly before it is transferred to Kuwaiti operators (Al-bahou et al. 2007). Companies have often been required to build local prototypes to demonstrate the reliability of their plant design prior to construction. The plants have been built by companies from the U.S., Great Britain, Japan, France, Italy, and Korea, and the technological path is notable for its relatively slow progress. Some Kuwaiti firms have been used for general contracting and fabrication of large MSF vessels, but technology has consistently come from international companies. The 1984 specifications set by the Ministry of Energy & Water are indicative of the approach that was taken several decades ago. The specifications describe highly detailed design features, such as

[1] Total dissolved solids refers to the level of impurities in the water, primarily the salt content.

the height of demisters that enhance purity, maximum brine temperature, the type of feedwater treatment used, and many other items. These specifications had to be satisfied even to bid for a contract, so there was very little allowance for new design ideas or even small changes to older systems. This apparently slowed the consideration and uptake of the most efficient technologies, and is indicative of an atmosphere hostile to innovation.

d. Institutional Involvement

The atmosphere for innovation is heavily influenced by the institutions involved. In Kuwait, all desalination plants except for the most recent Shuwaikh SWRO plant have been purchased on behalf of the government by the Ministry of Electricity and Water and its predecessors. The Ministry of Electricity and Water (MEW) is responsible for owning, operating, and maintaining all of Kuwait's electric power and water systems. The MEW handles communications with consumers, including billing, and also plans for the long term sustainability of Kuwait's energy and water supply. The MEW orders all new plants and thus plays an instrumental role in guiding the technological direction of Kuwait's water supply facilities. Other institutions involved in desalination include the Kuwait Institute for Scientific Research (KISR), the Kuwait Foundation for the Advancement of Sciences (KFAS), Kuwait University (KU), the Kuwait Petroleum Corporation (KPC), the Public Authority for Industry (PAI), and recently, the Partnerships Technical Bureau (PTB).

KISR was founded in 1967, and since 1981 its stated goals have been "to carry out applied scientific research that helps the advancement of national industry and to undertake studies relating to the preservation of the environment, resources of natural wealth and their discovery, sources of water and energy, methods of agricultural exploitation and promotion of water wealth." KFAS was founded in 1976 as a non-profit organization. Currently the KFAS mission is to "Stimulate, support, and invest in initiatives and human resources that contribute to the building of a strong science, technology, and innovation system and culture and fostering an enabling environment (KFAS website)." KFAS has named four strategic thrusts:

1. Developing a strong advocacy for Science, Education and Scientific Culture.
2. Enhancing and integrating R&D Capacity in and among Kuwaiti Scientific Institutions.
3. Strengthening and Developing the National Science, Technology, and Innovation System.
4. Supporting the Development of the Private Sector's Scientific and Technological Capabilities and Participate in Building a Knowledge Economy.

Kuwait University (KU) was established in 1966. The university's mission is "to keep, develop, and disseminate human knowledge, in addition to developing national human resources in order to create leaders who are aware of national heritage and future needs in collaboration with other academic institutions of similar mission… (KU website)." KU includes 16 Colleges and has over 36,000 students. It is an important player in the education of future workers and researchers, and could play an important role in desalination research and development, if the government were to support such an initiative.

The Public Authority for Industry plays a role in the new efforts to establish public-private-partnerships and Independent Water and Power Projects (IWPP). The first IWPP has been delayed, but the IWPP framework has proved effective in encouraging new technologies in some gulf states (e.g. Bahrain).

Kuwait's experience has been dominated by MSF technology, with a few small projects in other desalination methods. In the wider region, however, some countries have been willing to adopt newer technologies like SWRO and MED. Two of these, Saudi Arabia and Bahrain, are discussed in the next section. Each has taken a very different approach, but both paths offer important information.

IV. Experience with SWRO and MED in the Gulf area

Much of the resistance to using SWRO and MED in Kuwait is based on concerns about the lack of experience with very high TDS waters and Arabian Gulf waters in particular, and the old views about the lack of durable membranes for the osmosis process in high salinity water. Some proponents of MSF technology believe that the water in the Gulf is not suitable for reverse osmosis treatment, or any other membrane-based treatment. Kuwait can also look back to its own experience with the Doha Reverse Osmosis Project, which did not operate well in a commercial sense. However, DROP was built as a testing platform for different membrane technologies, and so was not designed for commercial success. Subsequent experience in other Gulf States shows that SWRO and MED can both operate economically as desalination technologies for the Arabian Gulf waters.

a. Saudi Arabia (KSA)

Saudi Arabia has been operating SWRO plants in the Red Sea and the Arabian Gulf since the early 1980s. It is the world's largest producer of desalinated water, with about 17% of world production – over 10.5 million m^3/day. The dominant technologies are RO and MSF. Saudi Arabia has been a leader in installing seawater desalination plants since the 1970s (Hassan Jarrah 1989). The KSA's Saline Water Conversion Corporation (SWCC) was founded in 1974 as the independent, but government-owned entity that is responsible for supplying potable water to Saudi Arabia. For decades it has commissioned, owned, and operated desalination plants. It also has a research department, the Saline Water Desalination Research Institute (SWDRI), which has 3 internal departments:

1. Technical (Corrosion and Metallurgy, Chemistry, Marine Biology and Environment)

2. Engineering (Thermal, Seawater Reverse Osmosis)
3. Support (Planning, administration, pilot plants).

The SWCC's experience and development work have led to improvements in the four major problems in seawater desalination (scaling, fouling, high energy consumption, and corrosion) (Hassan et. al. 2002). Before embarking on a national SWRO program, Saudi Arabia tested small demonstration plants. The Arabian Oil Co., Ltd. Installed a 40m^3/day two-stage SWRO plant at Ras Al Khafji, and that plant began operating in 1977.[2] Saudi Arabia also had many small RO plants used to treat brackish water at distributed sites, so there was familiarity with RO, if not SWRO.

Once experience with small plants was gained, the first large commercial SWRO plant in Saudi Arabia was commissioned at Jeddah in 1979. The plant used spiral wound membranes and had a capacity of 12,000 m^3/day. The membranes and the plant were built by UOP Inc. of San Diego, CA, and as a term of the agreement, UOP operated the plant for the first two years. The Jeddah plant suffered from corrosion issues, and has since been refit several times, updating components as the best practices evolved. The first change was to switch the brine hoses from 316 SS reinforced neoprene hoses to solid metal 317 SS pipes after a hose burst (Madhah & Wojcik 1981). The plant's generators were not initially marine grade and had to be replaced as well. The plant's membranes malfunctioned, requiring higher than the specified pressures in the second year of operation, but they were replaced under warranty from the manufacturer. Despite these problems, the Jeddah SWRO plant was estimated to have capital costs about 40% less than the MSF plants on the same site, to possibly be built with shorter lead time, and to use less than half the energy per unit of produced water. The SWCC was apparently satisfied with the performance of SWRO and continued to build more plants. The Al-Birk plant (2,275 m^3/day) was commissioned in 1983 and used hollow fine fiber membranes made by DuPont. This plant was beset with biofouling problems, leading to research and development work to improve the membrane materials and water treatment regimens. The Umm Lujj SWRO plant (4,400 m^3/day) was commissioned in 1986 based on spiral wound membranes, and had better operations than the earlier plants. While the SWCC primarily relied on MSF technology, it has viewed SWRO as a promising replacement for some time, and has continued to install SWRO plants and to improve upon previous iterations. Over the years, the SWCC dealt with many corrosion issues and updated to newer and more corrosion-resistant metals as time went by. Initially using 316 SS, the SWCC found it to be inadequate and used 317 and 904L, among others. Equally important, the manufacturers of membranes saw the impact of the high TDS waters on their products, replaced some membranes under warranty, and had to adjust their quality control and manufacturing techniques accordingly. By 1987, the SWCC had declared SWRO plants commercially viable for large desalination projects (Nada, 1987).

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[2] (http://ac.els-cdn.com/S0011916400883861/1-s2.0-S0011916400883861-main.pdf?_tid=af8935c4-39af-11e2-945c-00000aab0f6c&acdnat=1354143930_808fac045490d36478ee254e1f36ae5b)

In the areas of biofouling (biological growth build-up) and scaling (salt deposition), the SWCC also made important progress. For MSF plants, biofouling can be controlled by chlorination of the water, but in SWRO systems, the polyamide membranes are damaged by chlorine, so the water must be thoroughly dechlorinated before it is sent to the membranes. Some of the work in this area has been focused on creating more chlorine-resistant membranes, and some has focused on water pretreatment, especially more effective dechlorination and alternative biocides and algaecides (Nada 1987).

In 1987, the Research and Development Center (RDC) at the SWCC was established. It was recognized by the Gulf Cooperation Council as a regional asset in water R&D in 2001, and its title was changed to the Saline Water Desalination Research Institute (SWDRI) in 2006 (GWI 2009). The SWDRI is organized into 3 internal departments:

1. Technical (Corrosion and Metallurgy, Chemistry, Marine Biology and Environment)
2. Engineering (Thermal, Seawater Reverse Osmosis)
3. Support (Planning, administration, pilot plants).

The SWCC and SWDRI spent decades improving the operating practices of SWRO plants, including developing pre- and post-treatment regimens and novel cleaning methods. The SWDRI also worked to understand the mechanisms of the different fouling and scaling effects and their interactions and consequences (Al-Ahmad & Aleem 1993). In the late 1990s, the Al-Birk plant was again having biofouling issues, and the SWDRI and partners designed a series of experiments that were performed at the plant to discover causes and possible solutions (Saeed 2000). Some useful conclusions came out of this, but at the same time a major breakthrough was in the works.

SWDRI began testing Nanofiltration (NF) for desalination in 1996. By 2001 it was commercially available and improving production output of older plants by 40% or more. It is a revolutionary technology in desalination pre-treatment, and many believe that it will allow SWRO plants to handle higher TDS waters at lower pressures with less membrane wear. NF also reduces environmental impact because it results in lower chemical treatment requirements. NF pretreatment can also benefit thermal desalination plants (Hassan 2002). The SWDRI holds a patent for the use of NF as pretreatment for RO and thermal plants, and has submitted two more patent applications (SWDRI Website 2012). With Japanese partners, SWDRI has fitted MED with NF pre-treatment; this has allowed the MED unit to run at up to 125degC, compared with 65degC using conventional pretreatment. Production efficiency has therefore increased.

The SWCC has historically operated with subsidies from the government, but it has been undergoing a transition in recent years to sell off and privatize some of its plants.[3] The progress has been slow, but the SWDRI has been concentrating on marketing its services commercially, since funding through the SWCC will be reduced. Among other things, the

[3] (http://www.thefreelibrary.com/SWCC+privatization+and+restructuring+program+on+track.-a0212164890)

SWDRI markets its lab and test facilities for experimental use. The group owns 10 prototype plants: 2 - MSF, 1 - MED, 5 - RO, and 2 – NF (GWI 2009).

Since this privatization plan went into place, private sector participation in the market has increased. In 2010, the Saudi Arabian company, ACWA Holding, formed a joint venture with Toyobo and Itochu Corporation to manufacture RO membranes in Saudi Arabia. The new venture is called the Arabian Japanese Membrane Company (AJMC). The company will initially sell and support RO membranes within the country, but ultimately intends to sell them to other areas in the Middle East and North Africa. Manufacturing began in May of 2012.[4] Another joint venture, ACWA Power Sasakura, provides rehabilitation, renovation, EPC services, and O&M services for RO, MSF, and MED plants in Saudi Arabia. This company recently refit the Jeddah RO plant and built 6 MED plants in Saudi Arabia.

In September 2012, the SWDRI signed a collaboration agreement with Dow Chemical Company. The two companies will work together on improving reverse osmosis and ultrafiltration technologies specifically for improved performance in the Arabian Gulf's warm high-salinity waters.[5] The SWDRI is working to increase international collaborations in its new role.

Saudi Arabia is a much larger country than Kuwait, and has more desalination capacity. The SWCC and others were willing to accept the learning costs of installing and operating new technology (RO and MED) in the difficult local waters. Early plants had various issues that negatively affected performance and component lifetime, but the flexibility to try new solutions and to build incrementally improved plants ultimately helped lead to the current successful use of SWRO and MED in Saudi Arabia. Some of these learning costs would have been too great for Kuwait to take on. Reliability, not cost, is the major reason – Kuwait has been struggling to increase capacity quickly enough to keep up with its rapid growth in water demand; the loss in output of some of the early Saudi RO plants' issues would likely have caused critical water shortages had they been in Kuwait. At this point, though, the learning investments made by the Saudis have accomplished much of what was needed. The SWRO and MED plants have been thoroughly tested over decades in the region, and they are competitive and use much less energy than MSF. Kuwait could now install and operate SWRO and MED plants with modest investments in human resources, rather than the large risky capital investments of first-of-a-kind plants. The SWDRI and other Saudi and international companies have amassed expertise in design, construction, and operation, and Kuwait should work with them to build new plants.

In addition to gaining experience through capacity-building, Saudi Arabia has benefited from the research and development accomplishments of the SWDRI and SWCC. As the SWDRI is reaching out to international partners, this would be an ideal time for Kuwait to consider collaboration. Kuwait could sponsor joint research and could discuss the possibility of sending

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[4] (http://www.globalwaterintel.com/archive/11/3/general/japanese-bet-on-saudi-membrane-market.html; http://www.itochu.co.jp/en/news/2012/120524.html)

[5] (http://www.dow.com/middleeast/news/releases/2012/20120916a.htm)

Kuwaitis to the SWDRI and its partners for training and of bringing Saudis to Kuwait to consult on operation of new plants.

The recent decision to privatize water production in Saudi Arabia has been beneficial in encouraging domestic development of companies and new technologies. The verdict is not yet out on whether the transition will be completed, but Kuwait should watch closely; as it begins to test privatization through IWPP's, Kuwait can begin to consider a plan to privatize more of the industry.

b. Bahrain

While Saudi Arabia's experience can be in many ways beneficial to Kuwait, Bahrain's experience provides a model Kuwait might follow. In 1990, Bahrain commissioned the Addur SWRO plant (45,000 m^3/day), and found that the plant had many operational problems related to its pretreatment system. Like Kuwait, Bahrain has moved in the direction of IWPP's over state-owned desalination plants, and its first IWPP was the Al Dur SWRO and power plant (218,200 m^3/day and 1,234MWe). The plant has been built by GDF Suez, and began full commercial operation in February 2012. It is too soon to know whether the operations will go smoothly, but the purchase agreement specifies that the Bahrain water authority will purchase electricity and water at fixed tariff rates of 14 fils per kilowatt/hr and 350 fils per cubic meter of water until mid-2033. At close to $1/$m^3$ water, that is on target with estimates of the costs of SWRO in the Gulf region, and is very competitive with MSF when fuel costs are accounted for.

The plant in Bahrain does not take advantage of nanofiltration technology; instead Degremont selected a system that includes ferric chloride dosing, coagulation, flocculation, dissolved air flotation, and dual media filtration (an aggressive traditional configuration). Prior to building the plant, a one-year pilot study was performed to test the performance of the pretreatment system and to fully characterize seasonal changes in the water. Such a testing program is a critical part of a successful start to using SWRO in Kuwait, and it is something that should not be overlooked. Bahrain's experience demonstrates the first steps that Kuwait might take in an effort to update its desalination technology.

V. Desalination experience in Singapore

The experiences of Saudi Arabia and Bahrain are the most relevant to Kuwait if the goal is to update the infrastructure and begin to collect domestic capabilities. But for a complete overhaul of the water economy and establishment of an innovation hub in Kuwait, Singapore is the country to watch.

In Singapore, the Public Utilities Board (PUB) is responsible for comprehensive management of the water supply. The PUB treats the task holistically, incorporating disposal, treatment, and conservation along with supply. A strong program of public education about water has resulted in more efficient usage, and the R&D program has resulted in several new technologies including NEWater and improved electrochemical desalination (The Economist 2011; PUB 2012). Singapore has also won a number of awards for innovation and performance with respect to water management.

Singapore's water industry benefits from several policies that are distinct from Kuwait's, and the country has a somewhat more pressing timeline for improved water usage. Despite the immediacy of their need, Singapore chose to develop a water management industry domestically; domestic companies not only build desalination plants in Singapore, they also export their technology and products. We will characterize the water desalination innovation system of Singapore and explore what features might be exploited to benefit Kuwait and other countries.

Singapore and Kuwait are both "water scarce," but for different reasons. Kuwait is in an arid climate with few supplies of freshwater. Singapore receives a lot of rain, but has very little land mass and a large, dense population, so there isn't enough land available to store the rainfall. Singapore has relied on Malaysia for a large portion of its water supply, but does not want to continue to bear the water insecurity and political vulnerability that accompany that relationship. In the 1980s and 1990s, Singapore updated its environmental policies and worked to control pollution.[6] Beginning in the late 1990s, Singapore made it a national priority to achieve a sustainable water supply. In setting out to develop an integrated water resource management plan, Singapore consolidated all of the water-related duties under one government agency, the Ministry of Environment and Water Resources (MEWR). The Public Utilities Board (PUB) is within the MEWR. This institutional reform enables the PUB to undertake the integrated planning of water resources, supply, sewer, sewage treatment, flood control, drainage, and water reuse. Since all of these belong to one connected water system, managing them together is preferable.

a. Four National Taps

Singapore uses a "four national taps" strategy to describe its water supply goals for the next 50 years. The four sources are:

1. Local Catchment. This involves harvesting as much rainwater as possible through drains, streams, reservoirs, canals, and other means in urban areas.
2. Imported Water. Singapore imports water from Johor, Malaysia under a 100-year contract that ends in 2061. Singapore plans not to renew that contract, and already allowed another contract to expire in 2011.(PUB)
3. NEWater. Singapore reclaims used water and processes it to exceed World Health Organization (WHO) drinking water standards. The process and

[6] http://www-wds.worldbank.org/external/default/WDSContentServer/WDSP/IB/2006/10/18/000310607_20061018094242/Rendered/PDF/377460ENGLISH011experience01PUBLIC1.pdf

product are branded “NEWater.” Use has been growing steadily; in 2011 about 30% of water demand was met with NEWater. Its use is almost exclusively in manufacturing, industry, and power generation, though – only a very small fraction of NEWater is used as potable domestic water.(PUB)

4. Desalination. Singapore has one seawater reverse osmosis plant (136,000m^3/day) that supplies 10% of water demand. By 2060, the country plans to have enough capacity to meet 30% of demand. This will involve a ten-fold increase in desalination capacity.

b. Demand Management

Singapore has a strong demand management program as a part of its water strategy. All water must be metered unless special permission is given, and all water has a cost to the consumer. The tariff schedule for potable water has increasing costs as consumption per household rises, and includes a fixed charge for each water-drawing device. There are strict efficiency rules for faucets and other items, and unauthorized water withdrawal comes with heavy fines. Singapore also has mounted a broad public awareness campaign to inform people about the scarcity of the water, the need to conserve it, and the high quality of the NEWater (many citizens are reluctant to use reclaimed water). The campaign is in primary schools, but also throughout the culture. Singapore has worked to create parks and hold events based around reservoirs to give people an appreciation and respect for the water. All of this effort appears to have paid off. Singapore’s daily per capita water consumption was 153 liters per day in 2011, down from 165 liters in 2003. This average is also much lower than Kuwait’s, which is over 500 liters per day.

Singapore’s PUB has also worked to reduce losses through leakage, also known as unaccounted for water. This has been reduced as well, and at about 5% it is quite low; in many countries the figure is between 10% and 30%. Kuwait could benefit from emulating Singapore’s efforts to reduce water waste, and this should be a part of any water strategy going forward.

c. Desalination R&D

Singapore set out to create an innovative water industry domestically, and the Environment and Water Industry Program Office (EWI) has had a leadership role. The EWI is led by several organizations, including the PUB, and has a strategy of encouraging technology development, cluster development, and internationalization to help the industry excel. The National Research Foundation has funded over S$470 million in R&D, and since 2006, the number of water research centers in Singapore has grown from 3 to 25.[7] The PUB has collaborated with those centers and other private companies in 348 R&D projects.

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7 http://www.iesingapore.gov.sg/wps/portal/WCMPreview?WCM_GLOBAL_CONTEXT=/wps/wcm/connect/ie/My+Portal/Main/Press+Room/Press+Releases/2012/Singapores+water+industry+doubles+to+100+companies

All of this has resulted in many start-up companies, several large domestic firms that now export technology to Asia and the Middle East, and local manufacturing plants. Singapore's water sector has grown from 50 companies to 100 between 2006 and 2012, and those companies have secured export contracts worth about S$9 billion. International corporations have chosen Singapore as a hub for water technology, with Siemens Water establishing their headquarters there, and Toshiba and others opening R&D centers. Joint ventures between multinationals and domestic firms have also been common, and technological advances have been substantial.

Singapore has made energy efficiency of desalination a research priority, and has several research projects underway. One aims to use industrial waste heat for seawater desalination, and another is a partnership with Siemens working to improve electrochemical processes. Singapore has targeted a 50% reduction in specific energy consumption for desalinating seawater. Newer methods still in early development are also under study. R&D extends to other aspects of water supply, including new technologies to increase the rainwater collection capacity. Singapore has many other ongoing development projects, and has a strategic plan to study industrial water solutions, intelligent water management systems, and the water-energy-waste nexus, going forward.[8]

Singapore is a model for any country wishing to generate an innovative industry environment, and Kuwait can apply some similar support mechanisms. By reaching out to partners in other countries, Kuwait can share the burden and the benefits of R&D. Saudi Arabia, in particular, would make a good partner going forward, and the GCC provides another opportunity. Kuwait could also benefit from emulating the efforts in Singapore to reduce waste and educate the public about the scarcity of water.

VI. Recommendation for Kuwait's future desalination path

Kuwait will need to build considerable desalination capacity in the coming decades, and is in a position to reduce costs, oil consumption, and environmental impact by upgrading to newer technologies. This chapter lays out our recommendations based on our review of Kuwait's existing infrastructure and available options.

[8] http://www.iesingapore.gov.sg/wps/portal/WCMPreview?WCM_GLOBAL_CONTEXT=/wps/wcm/connect/ie/My+Portal/Main/Press+Room/Press+Releases/2012/Singapores+water+industry+doubles+to+100+companies
http://www.ewi.sg/pdf/publication/InnovationWater_vol2.pdf

a. Near Term Retrofit Strategy

In the near term, some of the existing MSF plants in Kuwait, all combined power and desalination plants, are scheduled for major refits. The configuration of these plants as CPDPs dictates the use of a thermal desalination technology for at least part of the water production. The thermal technology should be chosen on a case-by-case basis, as the specific needs of the refit may favor preserving some of the MSF equipment. Where the refit involves a near total rebuild of the thermal desalination plant, MED technology would be the most effective choice because of its superior energy efficiency and mature technology. In either case, an SWRO unit can be added to the plant, providing additional energy efficient water production that can complement the seasonal decrease in electric power demand. Several studies suggest that this "hybrid" plant arrangement holds economic benefit. Because MSF product water has very low TDS, and SWRO product water has higher levels, mixing the two output streams can produce very acceptable potable water, and the SWRO plant can be single-stage, if desired, since it needn't produce very low TDS water. A stronger argument for the addition of SWRO units will be made in the next section.

b. Medium Term New-Build Strategy

In the near to medium term, when Kuwait builds new water plants, for example, in the case of the Independent Water and Power Projects (IWPPs) at Az-Zour and Khirran, the most attractive option might be to build hybrid MED-RO plants. On paper, and based on cost per cubic meter of produced water, SWRO would be the logical choice, but Kuwait has several reasons to be cautious. Kuwait places a high value on reliability, and has little experience building, operating, or maintaining SWRO plants. Before moving to SWRO for a substantial fraction of its water supply, Kuwait should gain experience in operation and maintenance and train technicians for the new technology. More importantly, the impact of local seawater and climate conditions on SWRO operation need to be studied. The seawater intake system, the pretreatment methods, and the membrane cleaning and replacement regimen will all depend on highly localized phenomena. Algal blooms (such as red tide) can require adjustments or even temporary shutdown of SWRO plants, and while SWRO resistance to red tide is improving with experience, it is not yet at a mature and reliable stage.

Given these reasons for caution, building the most efficient fully-tested technology (MED), might be the conservative choice. However, building hybrid MED-SWRO plants has several distinct advantages:

1. During the winter, when electricity demand falls, excess CPDP electricity can be used to produce more water with the SWRO units. Operating with throttled-back power production is less efficient for the thermal desalination plant, so this optimizes utilization.
2. Mixing the SWRO product water with the very low-TDS MED product water can reduce the cost of SWRO, since the output needn't be as heavily desalinated.

3. Building a small SWRO unit on the CPDP site allows the unit to take advantage of shared resources, including electric power, seawater intake, and personnel.
4. Training the current O&M crews of the thermal plants to work on SWRO plants is simplified by the co-location and integration of systems.
5. Building several small SWRO units allows for experimentation with various technologies and technology providers without a massive capital investment.
6. SWRO units can be added over time so that they comprise a larger portion of supply, but only as reliability and demand permit.
7. If Kuwait would like to develop manufacturing, design, or research and development capabilities in SWRO, building small units is one way to begin that process.

All of these advantages to the hybrid plant confer significant strategic value – something not easily quantified. One approach to quantifying this is through real-options analysis, although this method is typically applied to the maintenance of R&D programs. Since here we are looking instead at primarily capacity-building, rather than just front-end R&D, it makes sense to take a somewhat different approach.

First we introduce an innovation investment model that will allow us to assess the cost of bringing SWRO technology to acceptable reliability. Next, we evaluate the potential future savings of using SWRO instead of MSF for water production. Comparing those costs and benefits will inform Kuwait's desalination strategy.

i. Innovation Investment Model

Public investments in new technology development, improvement, optimization, and commercialization are investments in innovation, and it is helpful to see those within the context of the innovation process and an innovation system. In the case of water desalination in Kuwait, the innovation system includes the MEW, KISR, KU, private industry, multinational corporations, and others. The innovation process can be broken down into four key stages. Figure 6 shows the four stages of creating options, demonstrating viability, early adoption, and improvements-in-use, described in more detail below (Lester & Hart 2012):

Option Creation. The goals at this stage are to open up a broad range of innovation pathways by encouraging experimentation with new ideas and concepts, by attracting new entrants to participate in the process, by ensuring that knowledge about the options being explored is generated transparently, and by guaranteeing broad access to that knowledge. Option creation is closely associated with R&D, but the two are not synonymous. Although big new technical ideas often grow out of organized, well-executed R&D programs, ideas for new products and services—including new business models—can arise anywhere and at any time.

Demonstration. At the demonstration stage the primary objectives are to enable technology providers, investors, and users to obtain credible information about cost, reliability, and safety under conditions that approximate actual conditions of use. This typically entails building, operating, and debugging full-scale prototypes. Other important tasks at this stage include settling on standards and infrastructure requirements and identifying key legal and regulatory barriers that will need to be overcome for widespread use. Private innovators and their investors assume an increasing share of costs and risks in the demonstration stage, compared to the option creation stage. In some cases they assume all the cost and risk. But the time horizon may be too long and the risk level too high for private investors to be willing to underwrite demonstrations for complex, large-scale technologies on their own.

Early Adoption. Early adoption involves the most forward-looking users, or perhaps those with the strongest need to use the innovation. The main goals in this stage are market development, accelerated learning, and early adoption of the infrastructures needed for scale-up. Innovators establish manufacturing and distribution capabilities and other key parts of the supply chain, while the early adopters (sometimes known as 'lead users') also play a key role, providing feedback that allows valuable features to be enhanced and practical problems to be sorted out. Proprietary knowledge about processes builds up during early adoption and unit costs generally come down (although aggregate costs may mount rapidly as adoption of these early units proceeds).

Improvement-in-use. The market and regulatory environments in this final stage settle into stable and predictable patterns. But designs continue to be refined, production systems and business models are improved, and the behavior of customers comes to be better understood. Frequently the cumulative impact of evolutionary improvements to a technology during its lifecycle in the marketplace greatly exceeds the performance gains achieved when the technology is first brought to market.

In general, the degree of technological uncertainty declines as one moves from left to right in Figure 6. On the other hand, the magnitude of the investment at risk typically increases rapidly from one stage to the next.

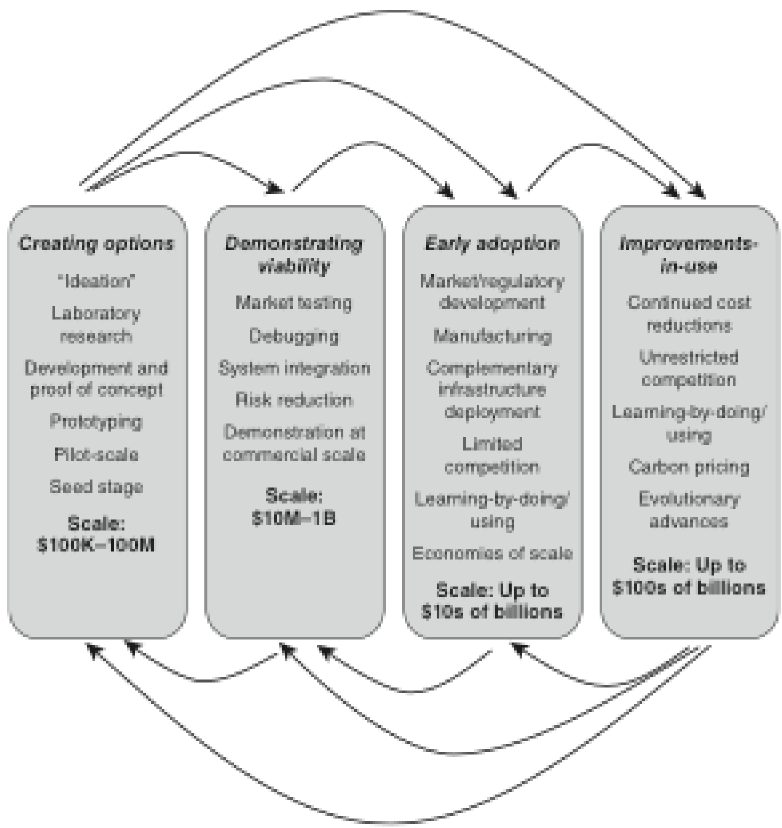

Figure 6: Stages in the energy innovation process (Source: Lester & Hart 2012)

ii. A Simplified Two-Stage Model of Innovation Investment

Here we consolidate the activities in Figure 1 into the simplified two-stage model of the innovation process shown in Figure 7 (Finan Ph.D. Thesis 2012).

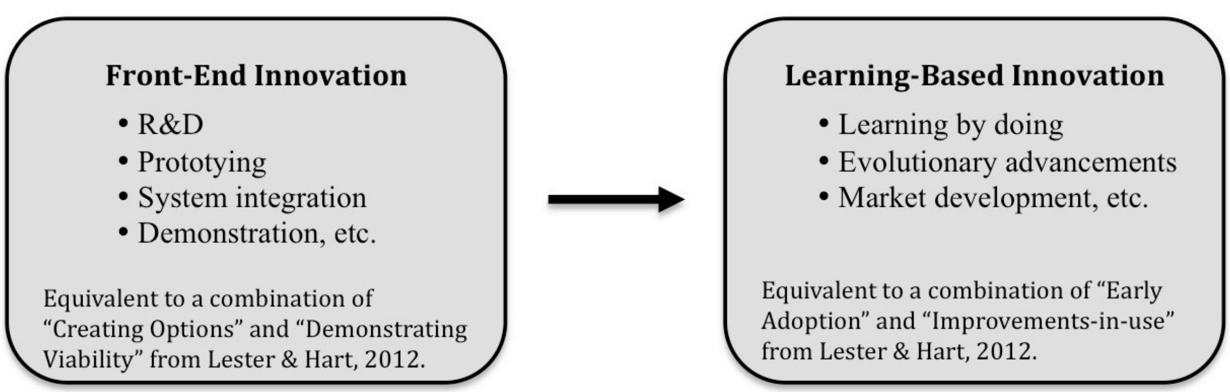

Figure 7: Simplified two-stage model of the innovation process

The first stage includes those activities that are aimed at reducing the cost and increasing the viability of a technology before it is introduced to the market. The second stage incorporates improvements to the technology that occur after market introduction. Improvements at this stage are enabled by 'learning' and other incremental advances.

The model specifies three states of technology and distinguishes between three types of innovation investment. In previous work, to further simplify the model, the objective of all innovation efforts was to reduce the capital cost of the technology (Finan Ph.D. Thesis 2012). In this case, we consider innovation aimed at increasing the operational Availability Fraction (AF) of an SWRO plant in Kuwait. This is a measure of the fraction of time spent operating over the course of a year. In practice, since learning curves are used to estimate the *reduction* of costs, we use Unavailability Fraction (UF) as the factor being *reduced* with experience (we seek to *increase* AF). Forced and planned outages, including maintenance and repair outages, account for unavailable time. Availability is simply 1-Unavailability, so it is trivial to move from one measure to the other.

In cases where learning leads to reduced capital costs, it is in the construction and planning stages of the project. Thus, capital costs fall as more units are built. When learning leads to improved availability, though, it is largely gained through operating experience, so availability improves as more reactor-years of operation are completed. Table 2 below shows some of the main mechanisms for cost reduction during the construction phase and during the operating phase.

Table 2: Main mechanisms for cost reduction during technological learning

Construction	Operations and Maintenance
i. Lower Owner's Costs a. Lower contingency factor as technology matures b. Lower interest during construction c. Lower interest rates d. Faster construction time e. Lower licensing/delay/litigation costs ii. Lower EPC costs a. Mass production, b. Improved quality control, c. Established manufacturing partnerships, d. Lower contingency	i. Increase in labor productivity ii. Membrane cleaning regimen improvement iii. Lower chemical consumption iv. Improved pre-treatment system performance/tuning v.

Although learning curves are typically used to show cost declines with increased installed capacity, here we use them to describe how availability improves with reactor-years of operating experience. A real-world example of this trend is shown in Figure 6, which illustrates the improvement in capacity factor in the US nuclear fleet.

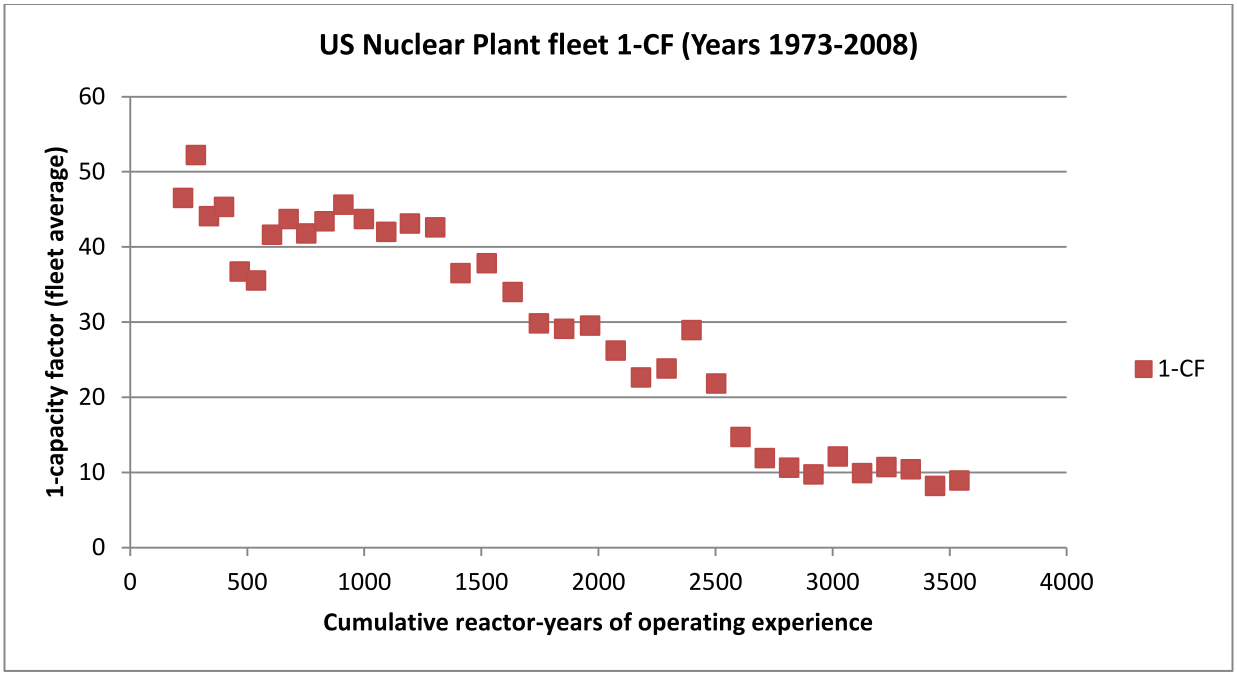

Figure 8: U.S. Nuclear Power Capacity Factor Improvement with Operating Experience (Source: NEI 2012)

At time t_0 we assume the technology has an initial unavailability fraction UF_{init}. In this example we assume no reactor-years of experience operating SWRO plants in Kuwait (RY(0) = 0).[9] From this initial state, we assume that no further RD&D is performed before commercial use begins. Instead, SWRO plants begin operating in Kuwait and the technology enters the post-commercialization stage of innovation.

The Unavailability Fraction of the technology during this second phase is assumed to follow a version of the standard learning curve:[10]

$$\mathrm{UF(t)} = \mathrm{UF_{IS}}\left(\frac{\mathrm{RY(t)}}{\mathrm{R}Y_{\mathrm{IS}}}\right)^{-b}$$

where
UF(t) = Unavailability Fraction (1-AF) of technology at time t
UF_{IS} = Unavailability Fraction of technology at the start of the 'learning' phase of innovation
RY(t) = Cumulative reactor-years operating experience at time t
b = learning coefficient
and
"progress ratio", PR = 2^{-b}

Thus, for each doubling of reactor operating experience, the Unavailability Factor declines by a factor (1-PR), the 'learning rate.' This continues until the UF falls to UFFin, at which point the technology is considered competitive in the marketplace (or at a level of availability acceptable

[9] This assumption can be adjusted to account for experience.
[10] Jamasb (2007), IAEA (2000)

for a critical function like water supply). At this point, we assume that we have reached the policy goal of bringing the technology to a competitive state, and the model period ends. In reality, learning would continue, but improvements occur increasingly slowly, and a subsidy is no longer required to support the deployment of the technology.

Table 3: SWRO Innovation Model Input Assumptions

Plant unit capacity	5,000 m^3/day
Unit Capital Cost	\$900/m^3/day
Total Overnight Capital Cost per plant	\$4.5 million
Fixed annual operating costs	\$221,200/yr
Variable O&M rate	\$0.9/m^3
Interest Rate	15%
Amortization period	20 years
Starting Availability Fraction	Varies
Desired Availability Fraction	0.95
Progress ratio (learning rate)	Varies

iii. Choosing a learning rate

Learning rates vary from one technology and one form of learning to another. There is no accepted learning rate for improving SWRO operating availability, so we use several sources to make an estimate. First, the experience of the U.S. Nuclear industry is helpful. Figure 8 gives unavailability versus reactor-years of operating experience from 1973 through 2008. This directly parallels the information we would like to model for SWRO in Kuwait, and a nuclear power plant is a similarly complex operation. The data in Figure 8 correspond to a progress ratio of 0.66, which means that for each doubling of operating reactor-years, unavailability falls by 34%. The nuclear industry experienced many hiccups during the time period, including extended outages due to the Three Mile Island accident and delays associated with rule changes in the aftermath, so operational learning might occur more quickly in an industry without those factors (e.g. SWRO).

The operation of the pretreatment system for the Doha Reverse Osmosis Plant (DROP) in Kuwait provides some further data for comparison. Availability (or Down Time) information for DROP is not available, but between 1984 and 1989, the pretreatment system was carefully studied (Ebrahim et al 1995). The focus of the study was to improve the quality of the pretreated water entering the osmosis process while reducing and/or optimizing the consumption of expensive chemicals. One of the most expensive chemicals in use was $FeClSO_4$, and efforts to reduce consumption were successful. Figure 9 shows the annual trend. These results correspond to a progress ratio of 0.75 (a learning rate of 25%).

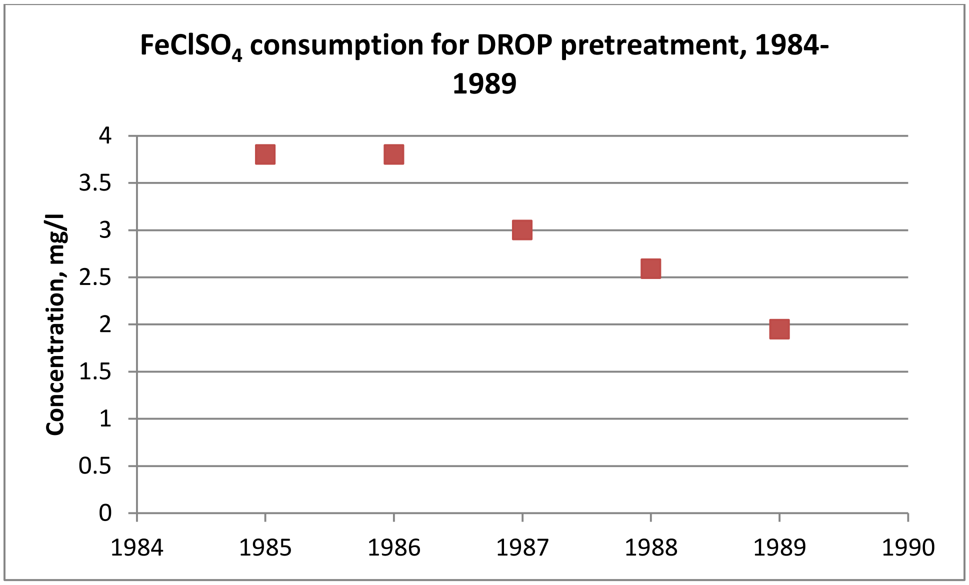

Figure 9: $FeClSO_4$ consumption for DROP pretreatment from 1984-1989

These two cases suggest that a progress ratio between 0.60 and 0.75 is a likely value for operational learning at an SWRO plant in Kuwait. We use the innovation investment model described above to estimate the time and cost to bring SWRO to an acceptable availability level in Kuwait.

The target availability factor was set at 90%, and we explored the implications of starting availability of 50% to 70% and progress ratios of 0.60 to 0.75.

iv. Results

Figure 10 shows the plant-years of operating experience required to achieve the 90% availability factor under the varying conditions. At a progress ratio of 0.60, the operating time ranges from about 4.5 to 9 plant-years, depending on the initial availability. With two small operating SWRO plants, this learning would take about 2 to 5 years, and for 5,000 m^3/day plants, the capital investment would be about $9 million. Since the plants are small, they have higher unit capital costs that a full-size commercial plant, which would likely be at least 200,000 m^3/day, or forty times larger than the plants suggested here for learning purposes.

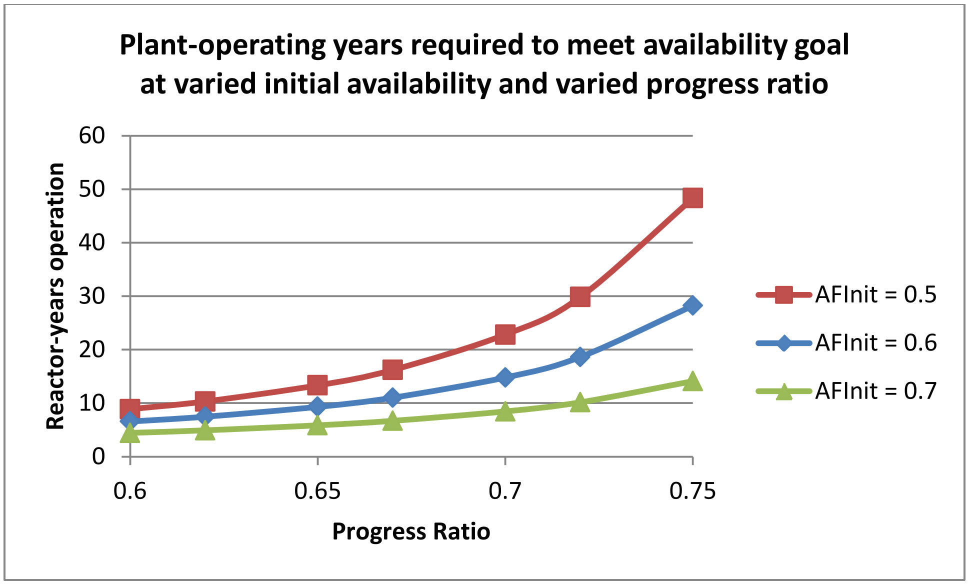

Figure 10: Plant-Years of operation to achieve target availability

During the learning period, the water produced by the SWRO plant is produced at a cost higher than the target cost, since plant availability is lower than the target availability, so aside from the capital investment, there is some additional cost associated with the water production. This can also be considered investment in innovation, since it is made for the purpose of bringing the technology to competitive use. Figure 11 shows the volume of water produced during the learning phase under different conditions.

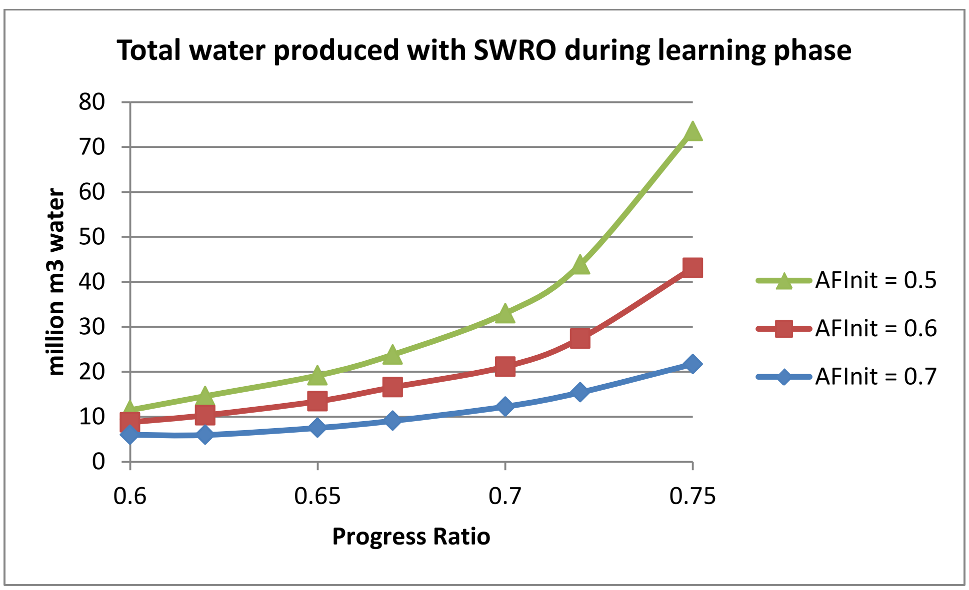

Figure 11: Total water produced with SWRO during learning phase

Figure 12 shows the total excess operating and maintenance cost associate with the produced water. This is the O&M spent above the baseline competitive O&M cost. This turns out to be a minor cost, ranging from $75,000 to $673,000.

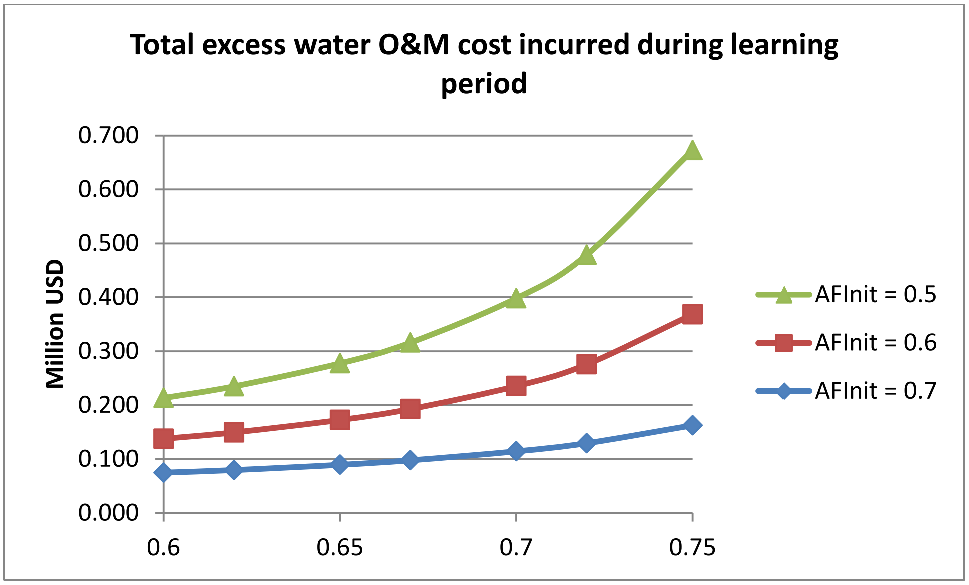

Figure 12: Total excess water during O&M cost incurred during learning phase

If we choose a target timeframe for learning, we can estimate the total cost of that learning. For example, if learning is to be completed within 5 years, considering the range of progress ratios and starting availability considered above, between 1 and 10 small SWRO plants would need to be built at a cost of $4.5 million to $45 million, for total (capital + O&M) innovation investments of $4.58 to $45.67 million.

The next step is to estimate the potential savings associated with the use of SWRO instead of MSF/MED in the future.

v. Future Savings Associated with SWRO Technology

Here we look at the hypothetical situation in which a new desalination plant will be installed and a decision needs to be made between SWRO and MSF technology. The hypothetical plant will have a capacity of 218,200 m^3/day, comparable to other plants that have been recently constructed. The cost of production of water from MSF is fairly well-established, and we use values drawn from a 2011 article in *Desalination* by Mezher, Fath, Abbas, and Khaled. The values for MSF are dependent on the price of oil, while the values for SWRO are calculated based on varied availability fractions. These values are listed in Table 4.

Table 4: Unit water cost for comparison of MSF and SWRO

Cost of Oil for MSF ($/bbl)[11]	Cost of MSF Produced water $/m^3		Availability of SWRO plant	Cost of SWRO Produced water $/m^3
20	1		0.9	1.15
60	2.5		0.7	1.22
100	4		0.6	1.27
			0.5	1.35

The annual savings for installing an SWRO plant instead of an MSF plant are shown in Figure 13. In the event that the value of oil consumed in the MSF plant is $20 per bbl or less, the MSF plant is more cost effective than the SWRO, and the SWRO plant is associated with a relative loss of $10 to $14 million per year. However, if the fuel oil is valued at $60/bbl, the SRWO plant offers substantial savings of nearly $100 million per year at 90% availability. At $100/bbl, the savings are even larger.

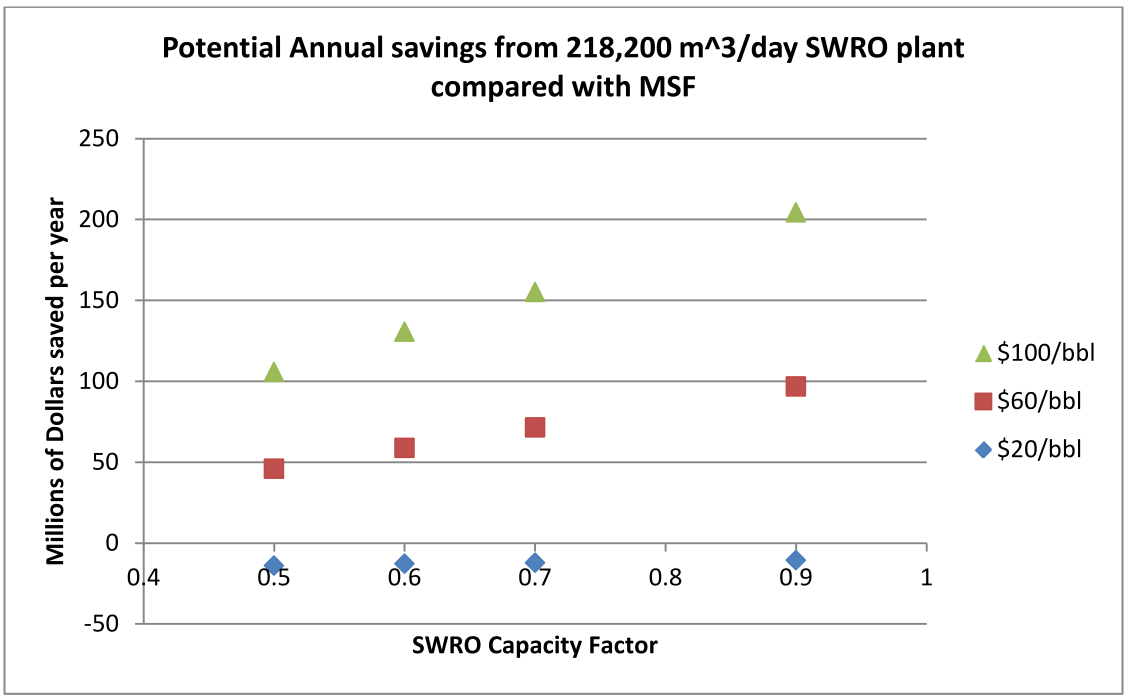

Figure 13: Potential future savings or loss associated with SWRO vs. MSF

[11] Mezher, Toufic, Hassan Fath, Zeina Abbas, and Arslan Khaled. "Techno-economic assessment and environmental impacts of desalination technologies." Desalination 266 (2011) 263-2

vi. SWRO Development Costs versus Potential Savings

Our earlier calculations estimated the innovation investments needed to build SWRO demonstration plants and bring the availability of the plants to an acceptable level within 5 years at $4.6 to $45.6 million. If fuel is valued at $60/bbl, those costs would be covered by the savings from one year's operation of a large (218,200 m^3/day) commercial SWRO plant. (This size is based on the Al-Dur SWRO plant in Bahrain.) These results favor a move toward SWRO plants, and show that by building small plants to support initial learning, Kuwait could improve plant availability at a low cost before making large capital investments in commercial-scale plants.

To enable an eventual transition to these more energy efficient membrane-based technologies, building small RO units in conjunction with MED and MSF plants is a logical course until SWRO reliability is acceptable in Kuwait's waters.

c. Long Term Strategy: Domestic Industry and R&D

In the longer term, Kuwait will want to keep abreast of the latest technological advancements. Oil reserves are expected to eventually decline, and energy efficiency will be an imperative. Membrane technologies show the most promise for future low-energy desalination, so Kuwait's long term vision might best be based on SWRO and more advanced membrane technologies that are not yet developed.

In terms of developing domestic industrial capacity, it would be best to focus on the state-of-the-art technologies, primarily SWRO and perhaps some MED. By partnering with multinational companies in joint ventures to build small SWRO plants, Kuwaiti companies can take responsibility for the local site work and learn how to operate and maintain the plants from the manufacturers. A key area of learning is that of adapting to the local and fluctuating water conditions. Most SWRO manufacturers do not have experience in the Arabian Gulf, yet there is a high demand there and in other high-TDS waters. Kuwait could play an important role by supporting research, development, and experimentation with different pretreatment options, cleaning regimens, and optimal operation protocols for Gulf waters. Skillful operation of SWRO plants on the Gulf would be useful not only to Kuwait, but also to Saudi Arabia, Oman, Bahrain, UAE, and other countries. Innovations in pretreatment would be useful regionally and worldwide. The use of many small test facilities would give Kuwait a distinct advantage in experimenting with gulf-specific innovations. If this type of program is too large for Kuwait along, the GCC would be a good instrument for investment in desalination demonstrations, and Kuwait should consider a proposal to the GCC.

To support such a program, chemical and mechanical engineers will be needed. The oil and gas industry relies heavily on the same skillsets, so the educational needs would be complementary in this way, and a growing desalination development program would be well-placed to absorb workers from the oil industry if that industry were to contract in the future.

Moving progressively farther from applied and towards basic research, there are myriad options for innovating in the desalination field. Several lie in the combination of low-carbon energy sources with SWRO. Low-carbon energy reduces greenhouse gas emissions while also reducing oil consumption, preserving Kuwait's natural resources and freeing up oil for export. The alternative energy sources that are most often suggested are photovoltaic solar power, and nuclear power (Refs). In either case, since electricity is the output of the power plant and the input to the SWRO plant, this is merely a matter of linking the two plants and thus drastically reducing the emissions related to the SWRO plant. The real development work here lies in improving the cost and reliability of the applicable power plant.

There are several new technologies in the early research and development stages that aim to improve desalination. Those include electrodialysis, which is currently too costly for large-scale applications, nanoporous membranes (graphene), and directional solvent extraction. A brief explanation of each concept follows:

Electrodialysis

Electrodialysis has primarily been used only for brackish water desalination on a small scale. It uses electrical energy to drive the salt ions through a membrane, but is energy intensive when seawater is used as a feed. Research is continuing, particularly with the advent of nanomaterials, but this is not likely to become a technology that meets Kuwait's needs.

Graphene

Nanoporous graphene membranes can separate salt ions from water molecules based on particle size. However the pore size tolerance is very tight. This water production method shows the potential to be much less energy intensive than RO and to be more modular, supporting smaller desalination plants. Simulations show that at equal salt rejection rates, graphene has several orders of magnitude greater water permeability than current RO membranes (Cohen-Tanugi and Grossman 2012). These results suggest the promising attributes of nanomaterials for application to water desalination based on molecular size discrimination. This is an emerging area of research with little experimental work completed and is an opportunity to enter an area early in its development.

Directional Solvent Extraction

Directional solvent extraction does not use a membrane. It uses low-grade heat, organic solvents, and fatty acids. Organic solvents dissolve water as the mixture is heated, but do not dissolve salts, which can then be removed. When the solution is cooled, the organic solvent separates from the water and the water can be recovered. This method has been demonstrated at a lab scale.

VII. Recommended Policies, Institutional Changes, and Initiatives

a. Administration

There are several steps that Kuwait could take to reduce water waste and encourage the development of energy-efficient and water-efficient innovations. While a removal of energy and water subsidies may be politically impossible, a gradual reduction of the subsidy would do much to reduce waste and improve efficiency.

A public education campaign on the scarcity and environmental impact of water, beginning in primary schools, would also be helpful, both in encouraging careful use of water and in encouraging students to pursue relevant areas of study.

b. Research

Kuwait should consider either supporting a desalination research and development program on its own or through the GCC. Kuwait's immediate needs center around the improvement of SWRO pretreatment systems and reliability, so a program in this area should be the first priority. In the longer term, basic R&D into promising new desalination technologies could be beneficial, but for now addressing the practical requirements of a transition to SWRO would be most helpful to Kuwait and the surrounding region.

c. Education

Kuwait could make dramatic improvements to its human capital by bolstering primary and secondary education, particularly by including more opportunities for hands on experience in laboratories and machine shops, incentivizing Kuwaitis to become teachers, and improving higher education quality and participation. As part of improving higher education, support for expanded research would encourage innovation and entrepreneurial activity.

A strong commercialization program could seek to encourage the full development of research outcomes. Kuwait University has over 36,000 students and could be a key player in desalination research and development if an initiative could be launched. The university is the place to undertake research on the basic science and the more risky technology. KISR can also play a key role in addressing the integrated system performance.

d. Privatization

In an effort to counteract the challenges of doing non-oil business in an economy dominated by oil exports, Kuwait can provide subsidies for private sector development in strategic industries like desalination. Kuwait's water industry has been largely public in the past, but Kuwait is just beginning to use the IWPP model to commission new capacity. This has worked well in Bahrain, and in Saudi Arabia, more widespread privatization of the industry has encouraged domestic development of companies and new technologies; Kuwait should observe the transition in Saudi Arabia as it considers further privatization of its own water and power supply system.

e. Innovation Investments

As shown in the previous section on desalination recommendations, Kuwait would benefit from a program of investing in innovation in the desalination industry. In particular, when MSF or MED plants are being upgraded, refitted, or newly constructed, each case should consider the possibility of linking a small SWRO unit to the larger plant. This strategy will pay off in improving reliability so that SWRO can ultimately be a major water production method in Kuwait. The co-location will have benefits both in utilizing shared facilities and in helping to train the current technical staff to work with the new technology. Ultimately, the savings in oil consumption will justify the small investments that are needed in these pilot plants. A single desalination plant could save over $200 million annually, so spending several billion dollars of government funds on desalination R&D could quickly pay off. If exports are part of the goal, much more spending could be justified, on the order of several billion, dollars. The size of the export market must be estimated to further specify worthwhile spending on R&D.

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