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Ecological–economic modeling to optimize a desalination policy: Case study of an arid rentier state

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ABSTRACT

Achieving long-term sustainability in potable water production is one of the greatest challenges facing countries with an arid climate, such as Kuwait. The socioeconomic environment of the country has created a rare paradox of staggering water consumption and chronic water scarcity. This research formulates a mathematical model that can identify the best policy to produce desalinated water while focusing on ecological and financial indicators. The parameters derived from each indicator are coupled with a weighted normalization scheme to generate a composite sustainability index based on the relative importance of each indicator from a rentier socioeconomic perspective. Seven desalination settings coupled with the available energy options, including fossil-fuel types, solar power and nuclear energy, were compared based on ecological and financial aspects and incorporated into a mathematical model. The ecological aspect was evaluated with a life cycle assessment (LCA), and the financial aspect was calculated using net present value (NPV) formulas with a nominal discount rate. The optimization model was formulated with a mixed integer program (MIP). The optimized policy indicates that two main desalination plants should maintain the Multistage-Flash Desalination while operating on natural gas, the remaining plants should use Multi-Effect Distillation with solar energy.

1. Introduction

Sustainability in water production is arguably the greatest global sustainability challenge, that is no longer associated with arid climates alone. The persistent paradox of chronic water scarcity and staggering water consumption represents a threat to sustainability that calls for immediate action at the political level in Kuwait and neighboring Gulf Cooperation Council (GCC) countries. This antithetical situation is a result of the "rentier" socioeconomic environment of GCC countries. Oil-wealthy rentier states, such as Kuwait, rely almost solely on oil revenues [1,2] for everything, including water production, and they are not motivated to diversify, reform, or otherwise change for the better [3]. In Kuwait, an overwhelming one-third to one-half of the oil production is consumed by the co-generation of electricity and water, which is very telling [4–6]. The situation is further aggravated by the high consumption resulting from the nominal water/electricity tariff, in which in public consumption is discounted by 80 to 90% because of high government subsidies. In Kuwait alone, these subsidies amount to $8.8 billion/y [7]. Researchers have argued that government subsides of conventional fuel products and electricity are related to the slow implementation of renewable energy projects [8].

Energy-intensive desalination plants (DPs) result in huge ecological and health impacts that can no longer be overlooked [4,5,9–15]. One distressing consequence is that Kuwait and other neighboring countries of the GCC are ranked among the top five per capita carbon dioxide emitters worldwide [16]. In response to this environmental crisis, the mid- and long-range development plans in 'Kuwait 2035' include strategies that are consistent with the UN Millennium Development Goal No. 7, 'Ensuring Environmental Sustainability' [17,18]. Therefore, the government of Kuwait has announced that renewable energy will account for 15% of Kuwait's consumption by 2030 [19]. Consequently, the new GCC strategy reform commits to investing up to $100 billion in

Abbreviations: AC, acidification; AD, abiotic depletion; AE, annual equivalent; CML2, database that contains characterization factors for life cycle impact assessment; CO, crude oil; CSI, composite sustainability index; DP, desalination plant; ELCD, European Reference Life Cycle Database; EUT, eutrophication; GAMS, General Algebraic Model; GCC, Gulf Cooperation Council; GDP, gross domestic product; GHGs, greenhouse gases; GO, gas oil(diesel); GWP, global warming potential; HO, heavy oil; HT, human toxicity; IR, ionizing radiation; KD, Kuwait Dinars; KEPA, Kuwait Environmental Public Authority; LCA, life cycle assessment; LCI, Life Cycle Inventory; LCIA, Life Cycle Impact Assessment; MAE, marine aquatic ecotoxicity; MED, Multi-Effect distillation; MEW, Ministry of Electricity and Water; MIP, mixed integer program; Mm^3, Million cubic meters; MSF, Multistage Flash Desalination; NC, nuclear energy; NG, natural gas; NPV, net present value; OZN, ozone layer depletion; PO, photochemical oxidation; PV, photovoltaic; RO, reverse osmosis

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renewable energy projects over the coming two decades [19]. Such robust funding indicates that the perceived development priority [20] in the GCC is finally transitioning to sustainability. The work presented in this paper aims to develop a framework for identifying the best policy to produce desalinated water in Kuwait while minimizing the environmental impacts and considering the economic aspects. The core of this framework is a mathematical model that includes major and detailed environmental and financial parameters and accommodates practical constraints and associated logistics [84]. The parameters derived from each perspective, i.e., environmental and financial, are aggregated through a weighting and normalization scheme to derive a composite sustainability index [20] based on the significance of each parameter from a strategic perspective [21,22]. Two desalination technologies, Multi-Effect Distillation (MED) and RO, are compared with the dominant Multistage Flash Desalination (MSF) technology coupled with available fossil-fuel energy options, solar power or nuclear energy. The environmental impacts manifested in a life cycle assessment (LCA) are evaluated using the four methodological stages of ISO 14042. The financial aspects are expressed as capital and fuel costs, which are evaluated via economical net present value (NPV) calculations for local data that were obtained from local ministries and literature reviews and discounted by the annual interest rate. The ecological and economic factors are formulated into a mixed integer program (MIP) mathematical model that optimizes an overall composite index using the General Algebraic Model (GAMS) platform.

2. Background

The widening gap between the consumption and availability of water is at its peak in Kuwait [23–25]. Kuwait and its neighboring GCC countries are unique because of their extreme arid environment, which is characterized by irregular sparse rainfall (< 100 mm/y) and high evaporation rates (> 3 K mm/y) [26]. The GCC countries score lowest worldwide in the renewable water resource index [27–29]. The average annual per capita renewable water resources have already reached the so-called chronic water scarcity line (< 500 m^3 per capita/y) [30]. To satisfy their demand for water, Kuwait and other GCC countries primarily rely on expensive seawater desalination followed by non-renewable groundwater resource extraction [14,31,32]. Approximately 81% of the total desalination production is generated in the GCC alone [33], which has an estimated total production capacity of 4.7 billion m^3/y [34]. Kuwait alone accounts for approximately 15% of the total desalination production in the world and 19% of the total GCC desalination production [35]. The per capita water consumption in Kuwait is one the highest worldwide at 500 l/capita/d [7], and an average increase of 3.6% per annum is observed (see Fig. 1). For most of the GCC, the percentage of extracted water resources far exceeds the amount of renewable water resources; in Kuwait, this rate has shockingly reached 2075% [37]. The total conventional and available freshwater resources in Kuwait are 6 Mm^3 per year, whereas the annual water demand has exceed 350 Mm^3 [38]. Over the past decade, water consumption has increased almost 12-fold, and the population of Kuwait has almost tripled during the same period [38]. A total of 44% of the potable water is consumed in the municipal sector alone, which far exceeds the 15% international average consumed in that sector. This indicator reflects that the high consumption rate is because of lifestyle choices. Because potable water is provided to consumers at a low tariff, the largest portion of the expense is subsidized by the government [32].

The predominant desalination technology is thermal, namely MSF. Because this technology requires vast amounts of energy, it is prevalent only in the GCC, where fossil fuels have long been widely available at a relatively low extraction cost [32]. A staggering average of approximately 50% of the oil production of Kuwait is consumed by co-generation to power DPs [4,5,39]. The burning of this fuel produces considerable ecological and health impacts because of emissions, including greenhouse gases (GHGs), which add to the growing impacts on urban air quality. The urban air is already exhibiting clear signs of elevated levels of air pollution [4,12,13], and significant amounts of heavy metal contamination, including nickel, vanadium and mercury, have been observed, especially in locations where crude oil is used [9]. Furthermore, desalination brine with high salinity and residual traces of chlorine and heavy metals (because of corrosion) is released along with anti-scalant and antifoaming agents [10,14]. These residues combined reduce the amount of dissolved oxygen and lead to serious suffocation of costal organisms, which constitute the marine food chain [9,11].

Currently, nine DPs are located in Kuwait; two operate using reverse osmosis (RO) (Shuwaikh and Zour) and the remainder operate using MSF. The location of these DPs and the average proportion of fuel types used are shown in Fig. 2. The gross annual and installed capacities of distillate water from distillation plants are shown in Fig. 3. The capacity is projected to rise as more distiller units are installed [40].

3. Desalination settings

The first four desalination settings use MSF combined with natural gas (NG), heavy oil (HO), gas oil (GO) (aka diesel) and crude oil (CO) (see Fig. 4). MSF has been reported to mass-produce large quantities of distilled water and exhibit high reliability, long-running times between cleaning (6–24 months), ease of operation [25], and robustness in distilling feed-water turbidity and salinity. Numerous reports in the literature have indicated that the MSF's largest drawback is its high energy requirement [23,41], which is known to be the cause of a high environmental burden [25,42,43].

The fifth desalination setting combines concentrating solar thermal

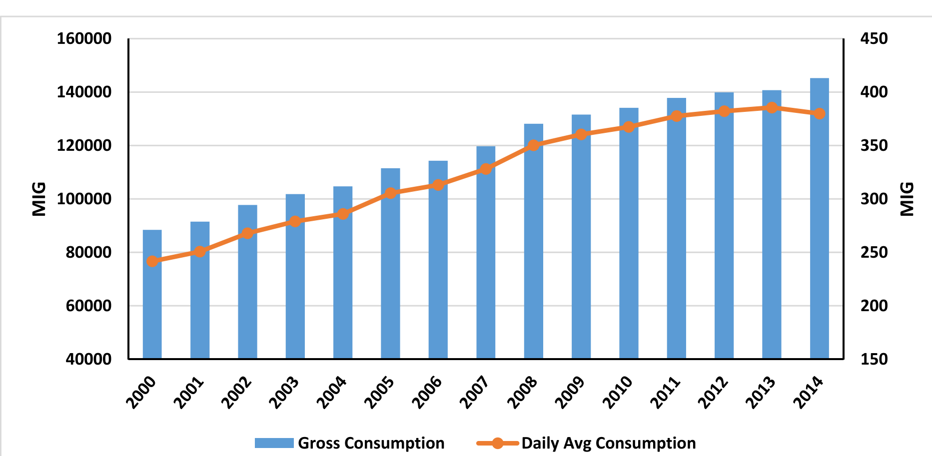

Fig. 1. Gross annual and daily consumption of potable water in imperial gallons from the ministry of planning records [36].