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Characterizing the fossil fuel impacts in water desalination plants in Kuwait: A Life Cycle Assessment approach

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ABSTRACT

This study provides a detailed quantified baseline for the environmental effects of desalination in Kuwait. Life Cycle Assessment (LCA) is applied to model the environmental impacts of all nine desalination plant in the country both using Multistage Flash Desalination (MSF) and Reverse osmosis technologies at two scales: per one ton and on annual production. Analysis of Variance (ANOVA) is used to investigate which fossil fuel types is significantly contributing to increased environmental burden of desalination. The results indicate that although 12.2% of Kuwait's electrical energy is generated using crude oil, crude oil alone contributes 63% to the global warming. The results also show that desalination in Kuwait contributes 7.89E+08 kg Sb eq. to abiotic depletion, 1.15E+08 kg SO_2 eq. to acidification, 1.91E+07 kg PO_4 eq. to eutrophication, 2.71E+10 kg CO_2 eq. to global warming, 2.47E+04 kg CFC-11 eq. to ozone layer depletion, 6.45E+09 kg 1,4-DB eq. to human toxicity, 6.03E+12 kg 1,4-DB eq. to marine aquatic ecotoxicity, and 7.53E+06 kg C_2H_4 eq. to photochemical oxidation. ANOVA reveals that natural gas has the lowest environmental impact, except on abiotic depletion; and that crude oil contributes almost four times more to global warming than other fuels used.

1. Introduction

The widening gap between the consumption and availability of potable water is arguably the greatest sustainability problem worldwide [1], nevertheless it is at its peak in Kuwait [2–5]. The arid climate of Kuwait and its neighboring Gulf Corporation Council (GCC) countries is characterized by irregular, sparse rainfall (<100 mm/y) and high evaporation rates (>3 K mm/y) [6]. Additionally, GCC countries score the lowest worldwide on the renewable water resource index [7–9]. The average annual per capita renewable water resources have already reached the so-called chronic water scarcity line (<500 m3 per capita/y) [10]. To satisfy their demands for water, Kuwait and other GCC countries primarily rely on expensive seawater desalination followed by non-renewable groundwater resource extraction [11–13]. Approximately 81% of the total global desalination production is generated in the GCC alone [14], which has an estimated total production capacity of 4.7 billion m3/y [15]. Kuwait alone accounts for approximately 15% of the total desalination production in the world and 19% of the total GCC desalination production [16]. Despite water scarcity, the per capita water consumption in Kuwait is one the highest worldwide at 500 L/capita/d [17], and an average increase of 3.6% per year has been observed (see Fig. 1). Over the past decade, the population of Kuwait has almost tripled; however, water consumption has greatly increased by almost 12-fold during the same period [18]. Many researchers and activists believe that the excessive water consumption is a result of the nominal water/electricity tariff, which is discounted by 80–90% because of high government subsidies [19,20]. In Kuwait alone, these subsidies amount to $8.8 billion/y [17]. Researchers have argued that government subsides of conventional fuel products and electricity also contribute to the slow implementation of renewable energy projects [21].

The predominant desalination technology is thermal, specifically, Multistage Flash Desalination (MSF) [5]. Because this technology is energy intensive, it is prevalent mostly in GCC, where fossil fuels have long been available at a relatively low extraction cost [12]. Approximately 50% of the oil production in Kuwait is

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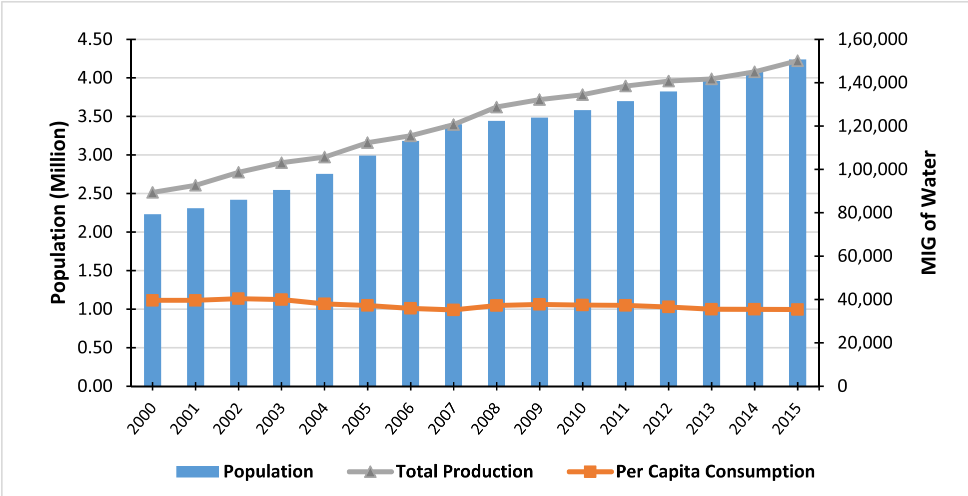

Fig. 1. Gross annual and per capita consumption of potable water in imperial gallons [22].

consumed by co-generation to power DPs [23–25]. The extremely high cost of desalination is not the only overwhelming fact; the emissions from burning the fuels used for desalination also have a considerable ecological and health impacts. For example, greenhouse gases (GHGs) add to the growing loads on urban air quality [13,23,25–31]. Urban air already exhibits clear signs of elevated levels of air pollution [23,26,27], and significant levels of contamination with heavy metals, including nickel, vanadium and mercury, have been observed, especially in locations where crude oil is used [28]. 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 [32]. Moreover, desalination brine of high salinity and residual traces of chlorine and heavy metals (because of corrosion) is released into coastal waters along with anti-scalant and antifoaming agents [13,29]. These combined residues reduce the amount of dissolved oxygen and lead to serious suffocation of costal organisms that constitute the marine food chain [28,30].

The objectives of this study are three-fold to: 1. conduct an up-to-date data collection on fossil fuels consumed in desalination of seawater, 2. model and compare the environmental impacts for all operating DPs in the country, and 3. statistically investigate which fossil fuel types are significantly contributing to increased environmental burden of desalination.

The first objective is realized by conducting a thorough data collection on fossil fuel consumption per type for each DP in the country and observing trends thereof. For the second objective, we use the data collection to model the DP processes using using Life Cycle Assessment (LCA). LCA have been used to systematically evaluate environmental loads throughout a life cycle, i.e., cradle-to-gate, and they are associated with different desalination technologies and fuel types [1,3,4,33–45]. The *goal and scope* of the LCA is to evaluate of the environmental burdens of the nine existing DPs in Kuwait. The LCA was conducted twice for each DP, first using a *functional unit* of one ton of desalinated water and then addressing the total annual production per DP, which depends on capacity and demand. Because the literature indicates that over 95% of GHGs are attributed to the operational phase [41] as opposed to construction (Vinice et al., 2008), the system scope encompasses the operation/treatment phase only. The LCA also models electricity generation in Kuwait because it partially supplies necessary power to major DPs in the country.

Finally, to achieve the third objective of this study, we apply analysis of variance (ANOVA) to compare the load of different fossil fuels on each environmental impact category. The design was replicated by the number of DPs in Kuwait, and the entire design was repeated for each response variable or impact category of LCA against two confidences levels, 95% and 99%. Data for this study is obtained from local Ministry of Electricity and Water (MEW) records [22] for a period of 12 years.

2. Methodology

Potable water in Kuwait is produced by nine DPs, seven of which operate using MSF. The remaining two operate using reverse osmosis (RO) (Shuwaikh and Zour). DPs consume the largest share of oil production, which is supplied to desalination/electricity turbines in four forms: crude (CR), heavy fuel oil (HF), gas oil (GO, i.e., diesel), natural gas (NG), or a hybrid mix of the fusssssels. As depicted in Fig. 2, the methodology starts with conducting extensive data collection using available MEW records [22] for a period of 12 years. The data collection includes desalination system types, fuels, water quantities, chemical additives, electricity and any other materials required. Gross annual and installed capacities of distillate water produced by distillation plants [22] and consumption of CR, NG, HF, and GO by desalination/power plants are plotted and analyzed.

Next, LCA (see Fig. 2) is used to simulate the environmental burden for each DP and associated fuel types. The *goal and scope* of the LCA are to model all the nine existing DPs, including all materials and energy associated. The LCA is modeled twice for each DP, first using a *functional unit* of one ton of desalinated water and then addressing the total annual production per DP, which depends on capacity and demand (see Fig. 2). Because the literature indicates that over 95% of GHGs are attributed to the operational phase [41] as opposed to construction [38], the system scope encompasses the operation/treatment phase only. The system boundaries are of a second order, according to which all processes, energy requirements, materials and additives during operation were included (i.e., cradle-to-gate). The scope excluded the infrastructure of the different DP settings and disposal of capital goods. Water delivery was excluded. The LCA also models electricity generation in Kuwait because it partially supplies necessary power to major DPs in the country.