Assessing Seawater Desalination using Reverse Osmosis and Multi-effect Distillation for Kuwait using Life Cycle Assessment: fossil fuels versus solar power

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Abstract. Sustainable water production is one of the top five challenges facing humanity within the upcoming decade, for arid regions the situation is aggravated. Countries worldwide are urged to balance of the SDG 6 (clean water and sanitation), SDG 7 (affordable and clean energy) to contribute to SDG 13 (climate action). This research evaluates seawater desalination in arid regions using multi-effect distillation (MED) and seawater reverse osmosis (SWRO) using fossil fuels versus solar power versus solar collector system (SCS) and and photovoltaic (PV). Four alternatives were investigated MED (NG), MED (SCS), SWRO (NG) and SWRO (PV) using life cycle assessment (LCA) to desalinate one cubic meter of seawater using a second-order boundary (i.e., cradle to gate) in which the operational parameters include: energy, materials, chemicals and additives in accordance with ISO 14040/4. The foreground data is based on field data collection that considers water intake characteristics: salinity and turbidity. The background inventories are based on Ecoinvent database v.3. The life cycle impact assessment is based on midpoint analysis using ReCiPe midpoint (H) v1.10. The results indicates that the primary fuel exergy and the allocation of energy in water electricity co-generation is the defining factor.

1. Introduction

The UN water report [1] have shown that the Gulf Cooperation Council (GCC) states are top countries worldwide in water scarcity index. Increasing population, changing lifestyle and hotter weather due to climate change have resulted a six-fold growth of global water demand over the past century [1]. Countries such as Kuwait commitment to Sustainable Development Goals (SDGs) No. 6, of clean water and sanitation has improved, however the price seem to be paid by the SDG No. 13: climate action. In the GCC, a staggering 30-50% of oil production is consumed by the cogeneration of electricity and desalination [2, 3], which due extensive energy change has its toll on the environment and the economy. The COP21 in Glasgow, UK and The 2019 UN Environment Programme’s Emissions Gap Report figures indicates that not enough action is taken worldwide to mitigate carbon emissions [4]. The report concludes that to achieve the Paris Agreement, emissions need to drop 7.6% annually by 2030 for the 1.5°C target. For this seemingly ‘impossible’ task, the European Union (EU) launched a new world challenging mission to reach the objectives of the Paris Agreement to reduce global warming to pre-industrial era levels, the ‘Mission possible’. For the same urgent cause, the United Nations has also launched the “Decade of Change” mission to mobilize everyone, everywhere to increase momentum and take immediate action and gather forces to deliver the 2030 promise [5]. It has long been agreed that energy efficiency at the end-use stage is the fastest and most cost-effective solution for reducing greenhouse emissions [6]. Countries worldwide have established targets to achieve sustainable energy and electricity systems, consistent with the SDGs [7].
The focus of this paper is on the multicriteria evaluation of water and electricity cogeneration, and this duality has been discussed in the renowned water–energy nexus [8]. Part of the recognition of the nexus approach is that it addresses the production and consumption tradeoffs that have been amplified by water scarcity over the last few decades and the management of both tradeoffs simultaneously [9-11]. Depending on the underlying technology, water and energy can be assessed independently, but could miss interdependencies that is not realistic to be considered otherwise [9]. Our area of focus, the GCC [12], presents an intricate paradox of severe water scarcity coupled with staggered water consumption, which is a result of rentierism, socio-economic situation of the GCC region. The GCC regions have long relied on costly thermal seawater desalination, followed by high abstraction of nonrenewable groundwater resources, to satisfy their demand for water [3, 13, 14]. The availability of fossil fuels at a low extraction cost has slowed the conversion to energy efficient desalination in the GCC, such as multistage flash distillation (MSF)[2, 14]. Currently, mega desalination projects in the GCC are migrating to membrane-based desalination plants (DPs) [15-17]. For instance, Yanbu seawater reverse osmosis (SWRO) DP in KSA is one of the largest RO plants in the Middle east. The plant started its operation in 2020 with a total capacity of 450K m$^3$/day [18]. Similarly, Taweelah RO DP is expected to start its operation in 2022 with a capacity of 450,000 m$^3$/d [18].

The work presented in this paper aims to compare multi-effect distillation (MED), seawater reverse osmosis (SWRO) using fossil fuel, solar thermal power for MED, and photovoltaic (PV) systems for SWRO to the modus operandi MSF. The environmental impacts were evaluated through life cycle assessment (LCA).

2. Materials and Methods

The environmental assessment for four desalination/energy systems considered include MED and SWRO coupled with different energy systems: natural gas (NG), solar thermal, and photovoltaic (PV). Technical aspects include the net power output, and efficiencies, among others [2, 14]. We used local electricity and proposed alternative energy models, including solar power and solar energy [7]. The solar thermal power with MED for alternative (3) uses concentrated solar irradiation based on Moser, et al. [19].

For the environmental indicator, the goal of the LCA is to assess the environmental impact of the four desalination alternatives. A functional unit (FU) of 1 m$^3$ of desalinated water is used, and the system scope includes a second-order system (i.e., cradle to gate) in which operational parameters including: energy, materials, chemicals and additives are considered. Infrastructure, water distribution and disposal of capital goods are excluded. The LCI incorporates the technical aspects of the different alternatives. The RO process configuration consists of an intake system using subsurface seashore pipelines of three pumps (2 in duty and 1 stand by)[20]. The pretreatments considered in the system include dissolved air flotation (DAF) and ultra-filtration (UF). The system is assumed to consist of eight DAF units, including air compressors and saturation systems. The second pretreatment stage is UF.

The chemicals additives and energy consumption for the RO system follows the actual operation conditions at Shuwaikh SWRO DP in Kuwait as in Table 1. MED, the plants operate at 11.7 MGPD capacity with a 30% recovery rate as in Al-Zour North plants in Kuwait. The pretreatment applied at the plant are electro chlorination to maintain chlorine value in addition to the chemical treatment using Antiscalant and Antifoam. Chemicals consumption at the MED plants are also provided in Table 1. Mezher, et al. [21] indicated that 1.5 – 0.5 kWh/m$^3$ of electricity is required for operation compared to 41.67 - 61.11 kWh/ m$^3$ of thermal energy. For MED/SWRO hybrid, the plants operate at 486 K/136 K m$^3$ as per Al-Zour North MED and Shuwaikh SWRO plants respectively. Polyamide membranes are used for SWRO from thermoplastic polymers. We adapted thermoplast processes in Ecoinvent. The infrastructure is excluded due to its insignificant impact compared to the energy consumed during operation [22]. For the SWRO (PV) scenario, the multi-crystalline silicon based photovoltaics system is applied based on Frischknecht, et al. [23]. The solar collector system (SCS) is made of Cu flat plate.
Table 1. Inventories

| RO Inventories       | Amount | MED Inventories         | Amount    |
|----------------------|--------|-------------------------|-----------|
| Anti-scalant (g/m³)  | 6.699  | Antiscalant (g/m³)      | 11.71799  |
| Caustic Soda (g/m³)  | 56.03  | Sodium sulfite (g/m³)   | 0.534505  |
| Ferric Chloride (g/m³) | 41.88 | Tri(sodium Phosphate) (g/m³) | 0.051395 |
| Sulfuric Acid (g/m³) | 108.31 | Antifoam (g/m³)        | 0.67841   |
| Sodium Bisulfate (g/m³) | 2.236 | Limestone (g/m³)       | 82.23149  |
| Sodium Hypochlorite (g/m³) | 20.14 | Sodium Hydroxide (15% solution) (g/m³) | 12.95146 |
| EDTA - Edetic Acid (g/m³) | 1.003 | Electrical energy (kWh/m³) | 0.086343 |
| Soda (g/m³)          | 0.056  | Thermal energy (kWh/m³)  | 61.11     |
| Citric Acid (g/m³)   | 5.36   |                         |           |
| Ascorbic Acid (g/m³) | 0.452  |                         |           |
| Polymer A (g/m³)     | 0.09   |                         |           |
| Polymer C (g/m³)     | 0.325  |                         |           |
| Electrical Energy(kWh/m³) | 5.2   |                         |           |
| SWRO Membrane (g/m³) | 1.35868 |                        |           |
| BWRO Membrane (g/m³) | 0.30249 |                        |           |
| UF Membrane (g/m³)   | 2.23048 |                        |           |

The environmental impacts on both characterized and normalized levels are generated using ReCiPe midpoint (H) v1.10 for climate change human-health (CCH), climate change-ecosystems (CCE), ozone depletion (OZD), photochemical oxidant formation (POF), human toxicity (HTX), particulate matter formation (PMF), ionising radiation (IOR), terrestrial acidification (TAC), freshwater ecotoxicity (FEX), marine ecotoxicity (MEX), metal depletion (MDP), eutrophication (EUT), agricultural land occupation (ALO), terrestrial ecotoxicity (TEX), urban land occupation (ULO), fossil depletion (FDP), and natural land transformation (NLT).

3. Results

3.1. Overall comparison

The characterized results for the four scenarios are shown in Figure 1. Over 90% of the environmental impact of MED (NG) is attributed to NG production. For this MED (NG) had most adverse impact on CCH, POH, PMF, CCE, TAC, NLT, and FDP. The SWRO (PV) in Kuwait had a had a restively higher characterized LCA values with respect to OZD, HTX, IOR, EUT, TEX, FEX, MEX, ALO, ULO, and MDP. However, in normalized results (see Figure 2), MED (NG) is highest in CCH and FDP. SWRO (PV) is considerable mainly in MDP. Obviously, the scenarios that impacts the CCH and FDP are those powered by NG.
3.2. Scenarios operating on NG

In characterized analysis, MED (NG) overall has a higher adverse impact on the environment except compared to SWRO (NG) except for OZD, EUT, ALO, ULO and few others. However, as shown in Figure 3, in magnitude it is negligible. For SWRO (NG) 91% of the impact is due to energy use and 9% is due to chemicals. For MED over 99% of the environmental impact is due to energy
required. For SWRO (NG), more than half of the impact on MDP category is due to Ferric Chloride (54%).

Figure 3: Normalized impacts using the ReCiPe midpoint (H) v1.10 for a FU of 1 m³ for MED and SWRO using NG

3.3. Scenarios operating on solar power

As shown in Figure 4, changing the source of energy from NG to solar for Kuwait favors MED (SCS) over SWRO (PV). For MED (SCS) most of the adverse environmental impact is due Copper in the SCS, which account to 58.2% of the impact, followed by Aluminum (7.04%) and steel (6.65%). For the SWRO (PV) 74.3% of the burden was due to PV, while 8.8% was due to Ferric Chloride. For the PVs, 40% of the impact was from the manufacturing of the panels, while 24% was from the mounting system.
4. Discussion

As depicted in Figure 5, the source of power changes the preference of the technology between MED and SWRO. The relatively high heat rejection temperatures due to Kuwait warm climate and, are ideal for integration with MED for distillate production from seawater. This is because due to the energy consumed for water/electricity cogeneration in MED is only 13-20% of the energy required. This resulted in a reduction in the environmental impact of MED (SCS) extensively. However, given that extensive power is required for the power plant, with MED dissecting the comparison of the desalination plant to compare it with SWRO might not be practical. The expanded system of pre-heater sweater power source, although seems feasible with the 13-20% allocation to use a solar source, most of the power required might require a hybrid system. In addition, the system does not encompass energy storage required for reliable uninterrupted production, which is another layer of complexity that needs to be discussed.
Figure 5: Normalized results single score results for the four desalination systems

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