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Abdulrahman Al-Kaabi, Huda Al-Sulaiti, Tareq Al-Ansari, Hamish R. Mackey

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# Assessment of water quality variations on pretreatment and environmental impacts of SWRO desalination

Abdulrahman Al-Kaabi [a], Huda Al-Sulaiti [b], Tareq Al-Ansari [a], Hamish R. Mackey [a,*]

[a] Hamad Bin Khalifa University, College of Science and Engineering, Doha, Qatar
[b] Hamad Bin Khalifa University, Qatar Environment and Energy Research, Doha, Qatar

H I G H L I G H T S

- SWRO environmental performance was assessed across 19 locations using LCA.
- A SWRO plant was modelled at the different sites based on water quality measurements.
- Global warming potential varied by 25% across the different locations.
- Wind energy lowered GWP and AP, but doubled MAETP, the largest normalized impact.
- Chemical selection could reduce MAETP by 30% in individual pretreatment stages.

A R T I C L E I N F O

*Keywords:*
Chemical dosing
Pretreatment
Seawater reverse osmosis
Feedwater quality
Life cycle assessment (LCA)

A B S T R A C T

Seawater reverse osmosis (SWRO) desalination is a widely adopted desalination technology given its cost effectiveness and lower energy consumption compared to thermal methods. However, SWRO is sensitive to intake water quality and requires strict pretreatment, which requires significant chemical inputs. This study evaluates the relative environmental impacts of water quality (site selection) and specific selection of chemicals on the overall environmental burden of the SWRO process. A life cycle assessment was carried out of environmental emissions based on an existing SWRO plant in the Arabian Gulf, which was remodelled and sized in AqMB® software based on different intake water quality gathered from seawater samples collected from 19 locations across 563 km of Arabian Gulf coastline. The study concluded that a total reduction of close to 25% in different environmental impacts was possible only by optimizing the location of plant, while careful selection of chemicals, particularly those in coagulation, disinfection and pH neutralization, could significantly influence environmental impact categories with high normalized impact such as marine ecotoxicity potential (MAETP). In comparison, renewable energy in the form of wind provided large reductions in certain significant impact categories, but provided a large increase in MAETP compared to natural gas.

## 1. Introduction

According to the Food and Agriculture Organization of the United Nations (FAO), global water shortage is caused by an increase in activities, rapid population growth, and inadequate natural resources. Demand for fresh water has continued to rapidly expand as the global population continues to increase; while fresh water supply has remained limited. In fact, it is projected that by 2025, more than 4.0 billion people will probably live under conditions that are water stressed with about 1.8 billion occupying areas that are considered water scarce [1,2]. Therefore, water scarcity was ranked among the leading global risks by the 2008 World Economic Forum with regard to its potential of negatively impacting human life over the years to come [3]. In order to mitigate water scarcity, water desalination has become a prominent solution for securing fresh water.

Desalination processes are categorized into membrane and thermal processes. For both membrane and thermal desalination processes, capital and energy costs are the two main financial cost components [4]. Membrane technologies have significantly progressed and attracted more attention across the globe compared to thermal desalination processes. For instance, seawater reverse osmosis (SWRO) has a lower total energy requirement and has been shown to have overall lesser

* Corresponding author.
*E-mail address:* hmackey@hbku.edu.qa (H.R. Mackey).

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environmental burden using agglomerated impact factors (such as Ecoindicator 97, Ecopoints 99 and CML2 baseline) than thermal based technologies [5]. Despite improvements over thermal techniques, membrane processes are associated with various environmental issues such as high energy demands, chemical dosing and brine disposal [48]. For instance, the global warming potential (GWP) arising from typical water consumption in the Arabian Gulf region sourced solely from SWRO is equivalent to more than 15% of the GWP associated with a typical European lifestyle [6]. Moreover, per capita marine aquatic ecotoxicity potential (MAETP) arising from typical use of SWRO sourced water is roughly five times greater than the MAETP resulting from all other annual activities combined. Consequently, there is a pressing need to further improve SWRO processes.

An SWRO desalination plant consists of the intake, pre-treatment units and reverse osmosis (RO) filtration stages. For the salt separation process, the semipermeable RO membranes hinder the movement of dissolved salts while allowing the processed potable water product to pass. The feed water to the RO membranes must be of excellent quality to avoid fouling and subsequent increase in energy use. This is achieved through both effective intake design and location, as well as pretreatment systems, which involve the extraction of suspended matter, adjustment of the pH, disinfection to prevent biological growth and addition of chemicals to prevent scaling. Despite the critical role of pretreatment on the overall SWRO system performance, most research focuses on improved membrane design and reduced energy usage through process technologies such as pressure retarded osmosis and energy recovery devices.

The growing concern over the depletion of natural resources and environmental contamination resulting from an increase in desalination has initiated a number of LCA studies over the past two decades on different aspects of desalination. Initial studies compared different traditional desalination technologies, demonstrating SWRO was significantly better than thermal techniques [5,7–9]. Subsequent studies have focused on integration of renewables [6,9,10], differentiating impacts between chemicals and electricity [10], centralized vs decentralized networks associated with economy of scale and distribution [21], use of open vs subsurface intakes [6,11], use of forward osmosis and energy recovery devices [12], brine dilution [13] and hybrid or solar type desalination systems [14,15]. These studies have in general shown the high importance of electricity and its associated emissions, particularly related to (GWP) in the environmental impacts of these processes. However, chemicals contribute significantly to pretreatment burdens [10]. Moreover, when environmental burdens of SWRO are normalized, marine ecotoxicity potential is the greatest environmental burden of SWRO by an order of magnitude [6,12], which is mainly associated with chemical usage in the pretreatment stage. Therefore, there is a need for assessing water quality and its impacts on both pretreatment and RO inputs and emissions to determine overall SWRO sustainability, which remains unexplored.

Several pre-treatment setups exist and identifying an appropriate pre-treatment setup, depending on feed quality, is key to any RO plant operation [16]. For instance, in 2008–2009 several SWRO desalination plants utilizing granular media filtration (GMF) across the Arabian Gulf went through either forced partial or full shutdown. Those facilities were faced with instant biofouling due to severe red tide algal blooms, which led to extensive clogging of the GMF, and subsequently, biofouling of SWRO membranes by both biological and organic foulants [17]. In areas that may experience harmful algal blooms (HAB) such as the Arabian Gulf, dissolved air filtration (DAF), ultrafiltration (UF) and cartridge filters as a pretreatment setup is recommended [18].

The aim of this study is to quantify how water quality and pretreatment requirements influence the environmental impacts of SWRO through modelling and life cycle assessment of a SWRO plant in different locations in a specific region of the Arabian Gulf. The Arabian Gulf was selected for the case study as the Gulf Cooperation (GCC) countries are some of the most reliant on desalination globally [19] and operate in some of the harshest seawater conditions. Therefore, understanding the role of water quality and identifying the most suitable locations for future SWRO establishments can potentially contribute to both the reduction of $CO_2$ emissions as well as other environmental impacts more closely linked with pretreatment systems and their chemical inputs.

## 2. Material and methods

### 2.1. Life cycle assessment (LCA)

The growing awareness related to environmental protection issues and the possible effects connected to manufacture and consumption have made it necessary to develop standardized methods to understand and decrease such effects. The life cycle assessment (LCA) methodology is one method that is popularly used in order to accomplish this purpose. LCA can quantify and compare the associated impacts to human health and environment in a systematic and repeatable way that allows detailed insight into various impacts from different stages of construction and operation [20]. LCA has proved efficient in exploring the environmental impacts of RO processes. Previous applications include assessing intake alternatives, centralized vs decentralized SWRO options, solar desalination, integration of renewable power or forward osmosis, hybrid osmotic dilution desalination and comparisons between established seawater desalination and wastewater reclamation processes [6,11,12,14,21]. The current study utilizes LCA methodology to identify how SWRO plant location and associated feed water quality influence the environmental impacts associated with plant operation. LCA is conducted in four stages consisting of: goal and scope definition, development of life cycle inventory (LCI), life cycle impact assessment, and interpretation. The LCA used in the study follows the ISO 14040 standard.

### 2.2. Goal and scope

The goal of this LCA is to quantify operational life cycle impacts of a large SWRO plant with the same treatment configuration simulated in 19 different locations across 563 km of the Arabian Gulf in order to identify how the water quality at the various locations influences the environmental impacts of the SWRO process. Qatar was selected for this study as it has over 700 km of coastline with an interesting variation in salinity (Fig. 1) ranging from 39 to 58 ppt, a range of coast near industrial sites as well as more pristine waters with TOC ranging from 0.46 to 3.0 ppm, and is located in the middle of the Arabian Gulf [22]. Hence, it serves as an ideal model for this study.

The scope of the study is cradle to gate for the operational phase of the plant and the functional unit is $m^3$ of desalinated water produced. The construction phase as well as filter and membrane replacement were excluded as they have previously been shown to have a small overall impact across all categories, but add significantly to data requirements for the LCI [23] and would have held large uncertainties if estimated. The scope boundary and system layout are shown in Fig. 2. The scope boundary includes the disposal of sludge, mainly from the DAF unit, but excludes impacts associated with brine. This is in part due to the difficulties in modelling brine impacts and because the impacts of brine are primarily related to salt [13], which originated from the ocean near the plant and are rapidly diluted to non-harmful levels within a short distance of the outfall.

### 2.3. Life cycle inventory

Water quality data was derived from Loganathan et al. [24] which describes the sampling methodology in detail. The data was from a one-time sampling campaign at 19 locations along 563 km of the Arabian Gulf coastline during the month of January 2017. Seawater data included pH, salinity, temperature, turbidity, total organic carbon (TOC) as well as various anions and cations: $Cl^-$, $SO_4^{2-}$, $Na^+$, $K^+$, $Mg^{2+}$, and

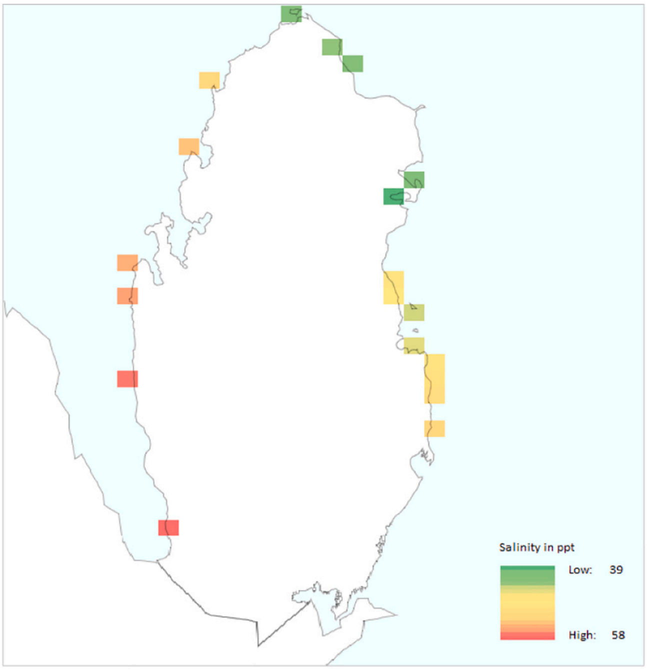


**Fig. 1.** Salinity variation across Qatar [24].

$Ca^{2+}$; and metal and other species: As, Sb, Al, Cd, Pb, Si, V, Ag, Zn, Cr, Mn, Ba, Co, Ni, Sr, Be, Cu, Tl, B, Fe, Se and N. The main parameters are shown in Table S1 (online supplementary material).

Operational data were obtained from an existing SWRO plant situated in the Arabian Gulf and is provided in Table 1, representing dosage during normal operation (non-red tide). The SWRO plant layout is illustrated in Fig. 2 and has a capacity of close to 275,000 $m^3$/d. The operational data for the existing plant together with the water quality data from the 19 locations were utilized to model a similar capacity SWRO plant in each of the 19 locations using Aqueous Material Balance (AqMB®) software. AqMB® is a commercial water process modelling software built on widely accepted theories and empirical process engineering models with various in-built individual unit operations [25]. It conducts material balances, sizes process units, calculates electricity consumption and chemical dosages, and allows rapid evaluation of process options [26]. AWCProton® software was also used to assist in sizing and selecting membrane elements and performance prior to AqMB®. The design data utilized in the AqMB® model for various unit processes is given in Table 2.

The electricity mix utilized was that of Qatar which is mainly natural gas (95%). For assessing the influence of renewable energy sources, impacts for heavy fuel oil (HFO), natural gas (NG), photovoltaics (PV) and wind energy were taken from the GaBi® database for Slovenia since the Qatar database does not contain wind power. Slovenia was chosen as its natural gas impacts are the most similar to Qatar. The Qatar grid mix, consisting of 95% natural gas, was compared against Slovenia natural gas and provided comparable results. The electrical requirements were determined using AqMB® software.

Sodium hypochlorite dosing for shock disinfection remained constant at all sites, based on the findings of Gallandat et al. [27] who found that turbidity and TOC over a large range (0–300 NTU and 0–100 ppm, respectively) had little effect on the residual chlorine when hypochlorite was dosed at 2 and 4 mg-$Cl_2$/L. This assumption is further supported by a study in Qatar at a marine site near Ras Laffan Industrial City where no observable impact was found from TOC present in seawater samples (1.9–2.4 ppm) on chlorine decay [28]. Sulphuric acid, which is used to control the pH, was calculated using AqMB® and AWCProton® based on the water quality data and the inbuilt chemistry equilibria models. Ferric chloride dosage for coagulation was estimated using a linear relationship between turbidity and ferric chloride presented by another study within the same geographic region [29]. Antiscalant, used to avoid salt precipitation in the membranes, was estimated using AqMB® in built models. Sodium bisulphite, used for dechlorination and sodium hydroxide, used for pH neutralization were considered constant based on the results of AqMB® software and literature [27,30].

The electricity grid mix and impacts from transportation of the chemicals were taken from the ThinkStep GaBi® databases. Chemicals were transported from Europe where available, and the USA otherwise in order to control transportation environmental impacts (Table S2). Where at least one chemical could only be sourced from the USA, the impacts for the best overall chemical from the other options was compared when sourced from both Europe and the USA and the comparisons are given in Table S3. GaBi® LCA modelling tool was utilized to obtain the environmental impacts associated with the SWRO plant at each of the 19 locations.

### 2.4. *Life cycle impact assessment*

The life cycle impact assessment was conducted for mid-point using ThinkStep's GaBi® platform based on the CML 2001 method and for each of the 19 locations. CML method is recommended in desalination studies due to its comprehensive data assessment for the inventory and impacts, and general nature with respect to location and system [20]. Impact assessment characterization considered global warming potential (GWP) in kg $CO_2$ equivalent, acidification potential (AP) in kg $SO_2$ equivalent, ozone layer depletion (ODP) in kg R-11 equivalent, abiotic depletion potential (ADP) in kg Sb equivalent, human toxicity potential (HTP) in kg DCB equivalent, and marine aquatic eco-toxicity potential (MAETP) in kg DCB equivalent.

In addition to the assessment of location and its effects, the role of electricity and selected chemicals were investigated, since these are the primary two factors to drive environmental impacts of SWRO. Electricity is particularly important with regards to global warming potential. Natural gas was the primary energy source in this study, as it is the cleanest fossil fuel and the main form of energy within the study country. Two applicable renewable energy sources for the region, (PV) and wind energy, were also considered, as was HFO, which is widely used in other Middle East states. Furthermore, chemical sensitivity was carried in order to identify alternative chemicals and their associated environmental impacts, since particular chemicals may be favoured from region to region based on economical and logistics considerations. Such exercise would help in choosing desalination chemicals depending on environmental concerns. Plant wide impacts on process parameters and required doses of other chemicals were considered when altering chemicals associated with specific pretreatment processes. However, no consideration was made for changes in asset lifetimes and replacement. Normalization was conducted based on total annual per capita consumption of 220 $m^3$ desalinated water [31] and using the CML World2000 impact factors [32]. Further details of normalization are provided in Al-Kaabi and Mackey [6].

### 2.5. *Identification of critical factors*

For impact categories where significant variations occurred between sites attributional LCA was used to identify the main inputs (specific chemicals or electricity) that contributed to the impacts. Multiple linear regression was then undertaken with various water quality parameters as independent variables against these inputs as dependent factors to understand the dominant ambient factors influencing specific environmental impacts. Multiple linear regression was conducted in JASP using the forward elimination method which stops with the highest adjusted Pearson correlation coefficient ($R^2_{adj}$). Models were also checked for overall certainty based on the analysis of variance (ANOVA) fit ($p < 0.05$), the degree of collinearity (VIF less than 5) and level of confidence in independent variable gradients ($p < 0.05$). These secondary statistics

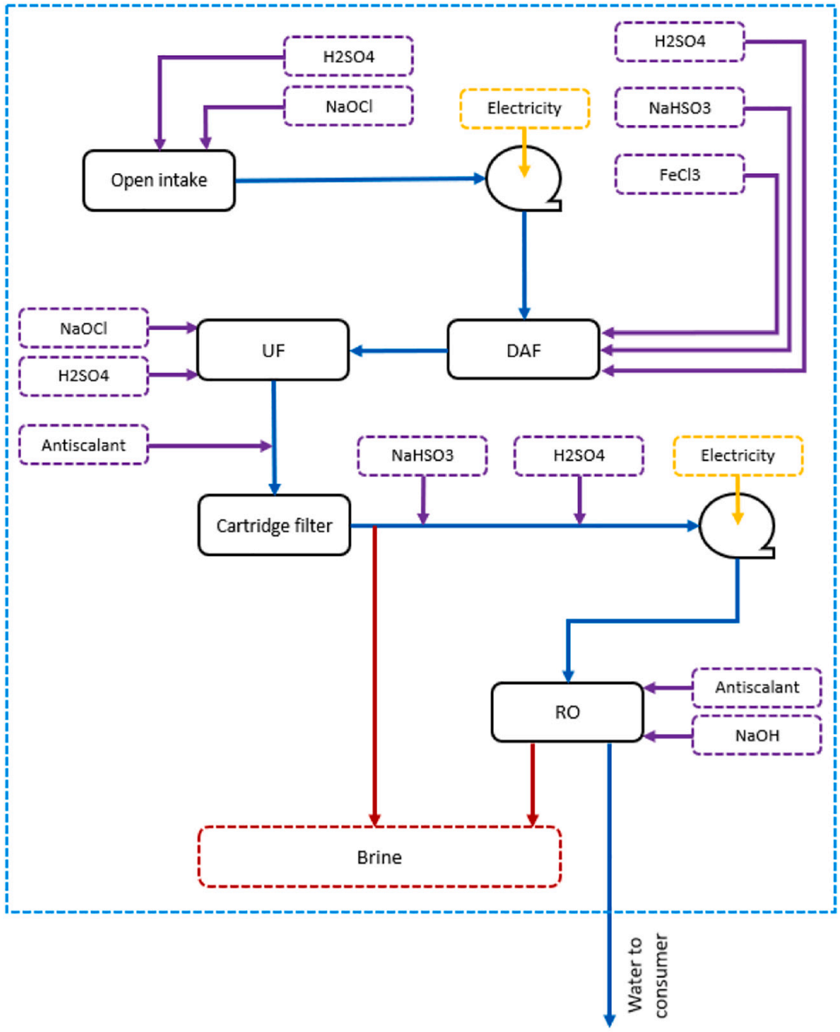


**Fig. 2.** SWRO plant operation layout and process inputs.

**Table 1**
Existing SWRO plant data used for the initial design in AqMB® software.

| | Average | Unit |
|---|---|---|
| Electricity | 4.5 | kWh/m$^3$ |
| Chemicals | | |
| Sodium hypochlorite (shock biological disinfection) | 11 | ppm |
| Sulphuric acid (pH control) | 20 | ppm |
| Ferric chloride (coagulation before DAF) | 3.6 | ppm |
| Sulphuric acid (shock biological disinfection) | 80 | ppm |
| Antiscalant (avoid salt precipitation) | 3 | ppm |
| Sodium bisulphite (dechlorination) | 5.9 | ppm |
| Sodium hydroxide (pH increase) | 11 | ppm |

were used to simplify models where collinearity existed. Statistical outputs are provided in the online supplementary information (Tables S5–S18).

## 3. Results

### 3.1. Water quality

Variation in water quality data was observable between the 19 locations. Variation in water quality data across the Arabian Gulf coastline is due to multiple reasons including the high evaporation rate, marginal enclosed nature of the gulf and inputs from multiple industrial activities

**Table 2**
Key design values for each of the main processes in the AqMB® model.

| | | |
|---|---|---|
| DAF | Number of trains | 1 |
| | DAF type | Conventional |
| | DAF recovery, specified [%] | 99.5 |
| | Hydraulic loading rate, design [m/h] | 5 |
| | Design air to solid ratio | 0.06 |
| | Solid loading rate, design [kg/h-m$^2$] | 20 |
| | Solid removal [%] | 95 |
| | Calculate TOC removal via coagulation chemistry? | True |
| UF | Number of trains | 1 |
| | Online recovery, specified [%] | 93 |
| | Product name | ZW1500-550 |
| | Surface area per module | 51 |
| | Design flux (inst.) (specified) [lmh] | 68 |
| | Clean trans-membrane pressure, TMP [kPa] | 50 |
| | Backwash flux (specified) [lmh] | 68 |
| | Backwash duration [min] | 1 |
| | Air scout flux (specified) [Nm$^3$/h-m$^2$] | 0.16 |
| RO | Number of trains | 3 |
| | Total recovery, specified [%] | 48 |
| | 1st stage RO membrane type | Seawater, extra high rejection |
| | 2nd stage RO membrane type | Brackish, standard |
| | Surface area per module | 440 |
| | Membrane fouling factor | 1 |
| | TOC removal (by rejection) | 95 |

within the region [18,24]. Salinity variation, for example, can be noticed in Fig. 1. Higher salinity was noticed from samples collected in semi-enclosed locations and with less tidal movements on the east coast of the country. Higher salinity increases the power consumption due to increased pumping pressure to overcome osmotic gradients. Samples collected near industrial locations and major populated cities had higher pH values, and consumed more pH control chemicals when modelled. Samples collected from shallow areas with higher tidal activities and near major seaports showed higher TOC, possibly due to increased algal and plankton growth. This leads to higher dose requirements for ferric chloride to control TOC. Turbidity values did not correlate with TOC values, and were low on the west coast where salinity is higher and circulation is less. The highest turbidity was measured outside the capital and at the entry to two estuary systems, most likely representing silt. Understanding feed water quality is necessary as it can significantly impact the electrical and chemical consumption required for an SWRO project and therefore its economics and sustainability.

### 3.2. Impact on desalination

Fig. 3 shows the average impact in percentage across the 19 locations for electricity vs. chemicals for the various impact categories investigated in this study. Electricity is the major contributor to GWP, AP and HTP while chemicals are the major contributor to ODP, ADP and MAETP. The relative contributions of various chemicals and electricity to the different impact categories were similar across the different sites with further breakdown details given in Fig. 4.

GWP, AP and HTP all showed similar trends in the magnitude of the impacts between the different test sites due to the dominant contribution of electricity (Fig. 4a–c). The main consumer of electricity in the SWRO process is the RO membranes and the five sites with highest GWP were all shallower and more enclosed locations with less tidal movements. S13 showed the highest GWP while S07 showed the lowest. AP focuses on emissions that increase the acidity of water and soils. It is influenced strongly by $NO_x$ and $SO_x$, which are primarily related to combustion and production of electricity from fossil fuels [33]. However, compared to GWP, the chemical contribution to AP is higher due to the consumption of sulphuric acid for pH control. Salinity was observed to be the main water quality factor to affect electricity consumption, with $R^2_{p,salinty}$ of 0.948. Temperature, TOC and $Ca^{2+}$ were also significant contributing covariates ($R^2_{adj}$ = 0.919). All covariates had partial correlations of 0.495 or greater, with increasing temperature the next most significant water quality factor.

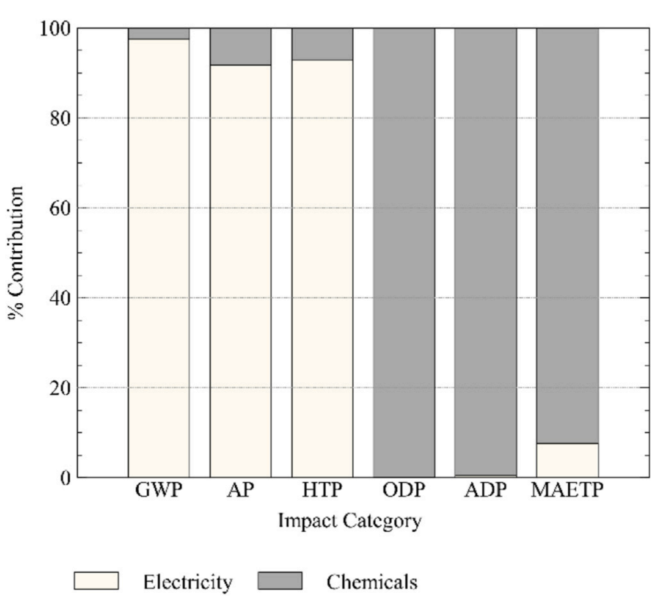


**Fig. 3.** Average relative contribution of electricity and chemicals across the 19 study locations for each environmental impact category.

For both ODP and ADP, the contribution of electricity was insignificant and chemicals were the major contributor for all 19 locations as illustrated in Fig. 4d and e. Sodium hypochlorite (shock biological disinfection) has the biggest impact on ODP and accounted for as much as 93% of the total ODP impacts, with sodium hydroxide contributing the next most significant portion. As sodium hypochlorite is typically dosed at a constant rate, the ODP values among the sites were very similar. However, optimization of disinfection dose could potentially be made based on factors such as chlorophyll or live cell counts. Moreover, while TOC has little impact on residual chlorine consumption [27], soluble TOC and nutrients that persist beyond the dechlorination step into the membranes may result in more biofouling, requiring more frequent clean-in-place maintenance of the membranes, which was not considered.

ADP encompasses the depletion of non-renewable resources such as minerals and fossil fuels [45]. Fig. 4e illustrates the percentage contribution of chemicals and electricity to ADP for each site. Sodium hypochlorite has the biggest impact on ADP and accounts for close to 50% of the total ADP impacts, followed by sodium bisulphite (dechlorination) which accounts for 30% of the total ADP range, as well as sodium hydroxide. Therefore, optimization of disinfection dose could have a large impact in reducing ADP.

HTP includes both inherent toxicity and generic source-to-dose relationships for pollutant emissions to the human terrestrial environment while MAETP quantifies the impact related to the emissions of all chemicals to marine aquatic surroundings [34,35]. The geographic extent of both HTP and MAETP indicators establishes the fate of a material and can differ between local and global scale. The result from this study focused on general (global) overall impacts of HTP and MAETP and not for emission impacts to a specific human or marine terrestrial dimension. Fig. 4c illustrates the percentage contribution of HTP from each plant simulated in the 19 locations. The HTP showed a correlation with salinity and subsequent electricity usage from the RO stage. HTP can be therefore be reduced by investigating renewables as a source of energy. Fig. 4f illustrates the percentage contribution of MAETP from each plant simulated in the 19 locations. In contrast to HTP, MAETP was influenced by chemical use and all chemicals utilized had a significant contribution with the exception of ferric chloride. Sodium hypochlorite (shock biological disinfection) was the most dominant contributor followed by sodium hydroxide (pH neturalization).

For chemicals that had varying dose between the sites, regression analysis was conducted to determine the key water quality factors influencing the chemical's consumption. Sulphuric acid consumption was positively correlated with pH, temperature and sulfate concentration, with an $R^2_{adj}$ of 0.983, and partial correlations of 0.992, 0.854 and 0.692 respectively. The main role of sulphuric acid is to reduce the pH prior to coagulation-flocculation, hence the strong relationship to pH, which is itself influenced by temperature and salinity/sulfate. Considering pH alone resulted in an $R^2_{adj}$ of 0.944. Antiscalant dose was associated with temperature and $Mg^{2+}$ concentration with an $R^2_{adj}$ of 0.894, and partial correlations of 0.586 and 0.948 respectively. Ferric chloride did not show any correlation to water quality parameters other than turbidity, due to the linear relationship used to define the ferric chloride dose.

### 3.3. Chemicals sensitivity analysis

As demonstrated in Section 3.2, chemicals have a significant role in certain environmental impact categories. Different chemicals are utilized for different reasons in SWRO desalination such as for pH adjustment, TOC removal, disinfection and dechlorination. From the previous analysis, it was shown that sodium hypochlorite is the most significant chemical contributing to environmental impacts, with the largest contribution in ODP, ADP and MAETP (Fig. 4d–f). In this chemical

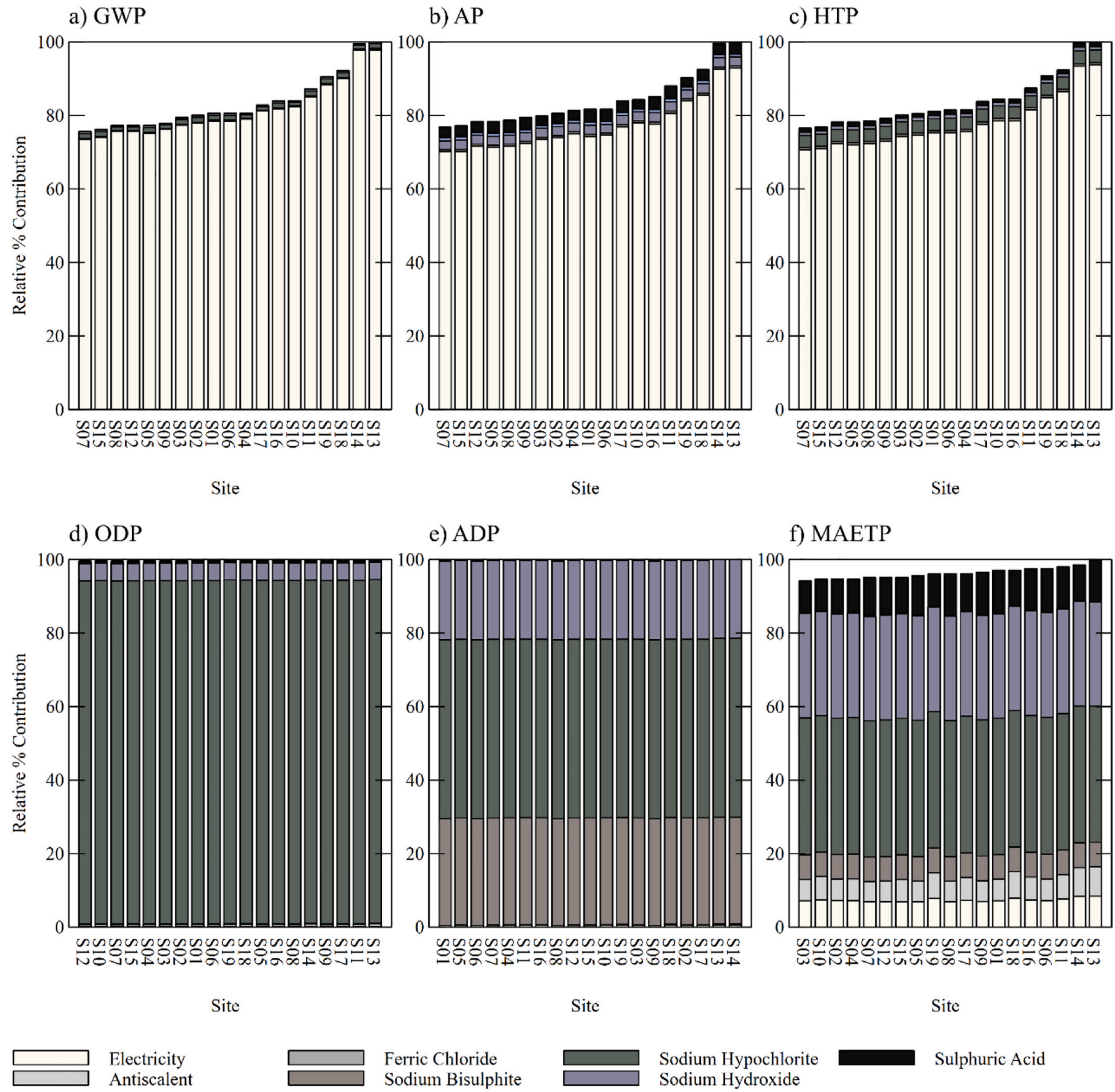


**Fig. 4.** Contribution of chemicals and electricity (%) for the 19 simulated SWRO plants to each of a) GWP, b) AP, c) ODP, d) ADP, e) HTP and f) MAETP.

sensitivity analysis chemicals for disinfection, pH control (lowering), TOC removal/coagulation, dechlorination and pH readjustment/neutralization were considered. Fig. 5a–e shows a comparison across alternate chemicals that can be used in different SWRO desalination stages. Furthermore, Fig. 5a–e shows a comparison between S13 and S03 as both sites exhibited the highest and lowest MAETP impact respectively (Fig. 4f).

Fig. 5a shows three chemical alternatives to sodium hypochlorite which were investigated for disinfection as it had the highest influence in ODP, ADP and MAETP compared to chemicals used in other unit processes. The disinfection chemicals considered were calcium hypochlorite, chlorine and chlorine dioxide. Results for the alternatives were all comparable, and performed much better than sodium hypochlorite. The impact where they had the largest reduction was for OD, but this is a relatively minor impact category overall (see Section 3.6). It should be noted sodium hypochlorite was sourced from the USA as it was not available from Europe in the database. Chlorine, was used for comparison to check the impact of USA sourcing. Although sourcing from USA increased ODP by 156%, all other impact categories were either improved from the USA or similar to Europe indicating the different locations was not the primary cause (Table S2). The higher impacts of sodium hypochlorite are therefore likely to come from the use of sodium hydroxide in its production, as discussed later. While providing environmental benefits, calcium hypochlorite could provide increasing scaling issues, while both gaseous chlorine and chlorine dioxide pose increased onsite safety requirements and risks which must be considered.

Fig. 5b shows different pH control chemicals for lowering the pH

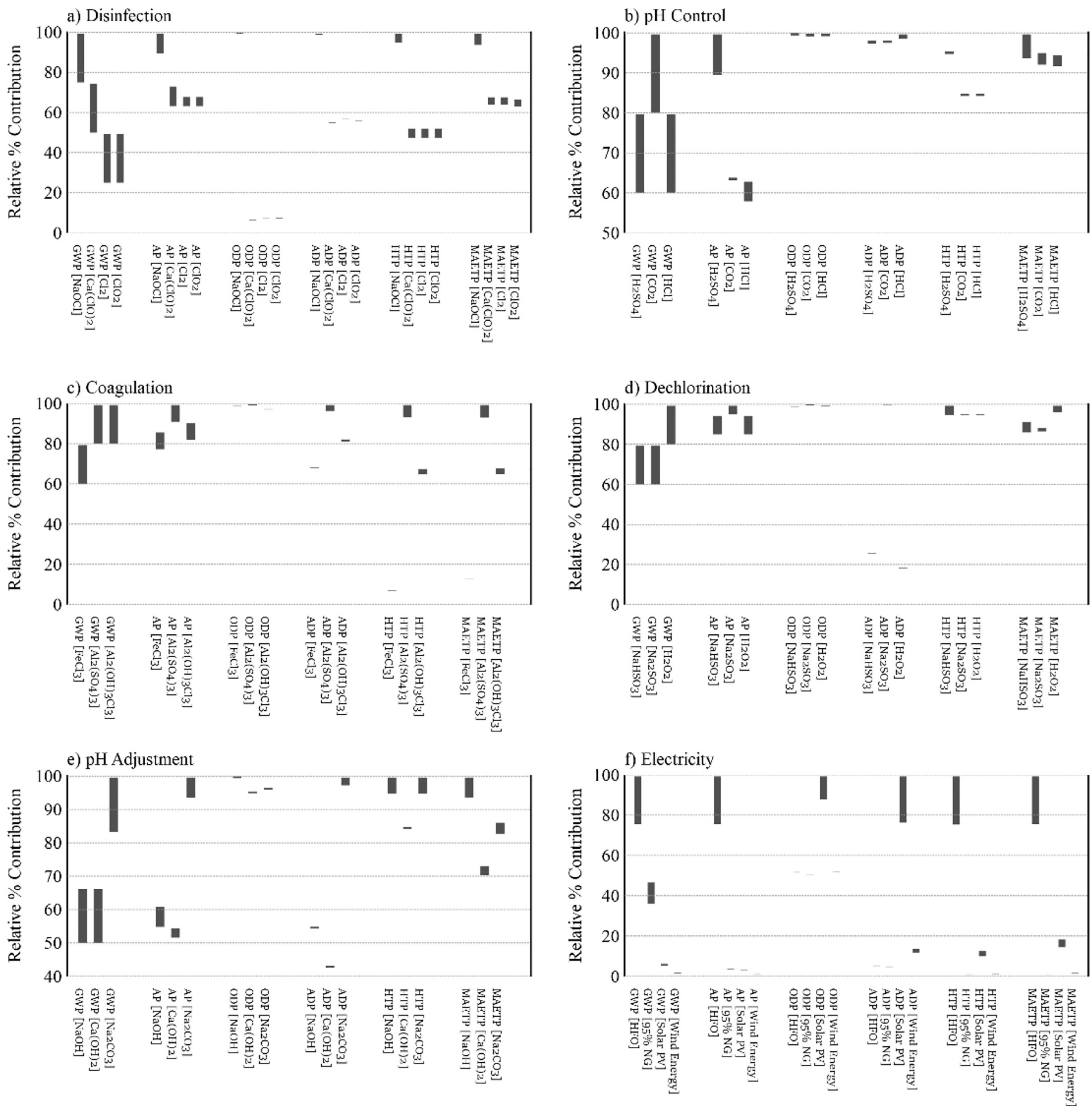


**Fig. 5.** Relative environmental impacts of alternate chemicals for a) disinfection; b) pH control; c) coagulation; d) dechlorination; and e) pH neutralization for both for S13 (top of bars) and S03 (bottom of bars). Relative environmental impacts of alternate energy sources for both S13 (top of bar) and S07 (bottom of bar) are shown in f).

prior to coagulation-flocculation and their related environmental impacts. Of the chemicals assessed, hydrochloric acid had the lowest MAETP, while the MAETP impact of sulphuric acid was considerably higher than both carbon dioxide and hydrochloric acid. Carbon dioxide was competitive in terms of all environmental impacts except for GWP. Overall, Fig. 5b shows that the performance of the three acidic pH control chemicals varies, depending on environmental impact category, but given the impact of sulphuric acid is comparably higher in MAETP and that MAETP is the largest normalized impact category from SWRO desalination (see Section 3.6), the adoption of either hydrochloric acid or carbon dioxide is logical. Given many desalination plants, even SWRO plants, are co-located with power plants or other industries in the Arabian Gulf, the latter option using flue gas could form a suitable form of $CO_2$ utilization that offsets chemical (acid) production, but would require radical change to the plant pretreatment design and would need to include flue gas treatment to remove other flue gas contaminants.

Two alternative chemicals, aluminium sulphate and polyaluminium chloride (PAC), were investigated for coagulation and TOC reduction (Fig. 5c). The figure illustrates that ferric chloride performed significantly better overall for both locations and for all impacts than either of the aluminium salt alternatives, justifying its continued use. For dechlorination, two alternative chemicals to sodium bisulphite were investigated (Fig. 5d). These were sodium sulphite and hydrogen peroxide. Overall, sodium bisulphite performed better which justifies its continued use. Sodium sulphite and hydrogen peroxide performed differently across the different environmental impacts. Although sodium bisulphite was sourced from the USA, this was not influential (Table S2).

Fig. 5e shows two alternative chemicals to sodium hydroxide (caustic soda) which are slaked lime ($Ca(OH)_2$) and soda ash ($Na_2CO_3$). Soda ash was the worst performing chemical in most impact categories. For MAETP, sodium hydroxide was the worst. In the GaBi® database the impacts are a weighted averaged based on the mix of technologies used in the country of origin. Sodium hydroxide is produced via the chlor-alkali process. Mercury-cell plants are a common but older technology for this process and are a potential cause of the higher MAETP. However, all chlor-alkali processes produce various compounds that could contribute such as chlorates, bromates, sulfites, sulfates and halogenated organics. Slaked lime was always the best, or near best, performing chemical across all impact categories. However, compared to sodium hydroxide, lime can cause an increase in sludge production and may increase scaling. While this was accounted for in environmental impacts, it means sodium hydroxide may still be preferable for economic reasons [36].

### 3.4. Energy source and environmental benefits

Electricity is a key contributor to various impacts in SWRO desalination, particularly GWP. Hence, it is important to understand the role of transitioning to renewable energy sources that are applicable. Both PV and wind energy are gaining attention in the region. For this analysis sites S13 and S07 were selected as they had the highest and lowest energy requirements. Fig. 5f shows the LCA for the different energy alternatives across all impact categories at these two sites. Compared with the NG dominated grid mix the two renewables provided notable reductions in GWP and AP environmental impacts for both locations, with GWP being by roughly an order of magnitude difference. Nevertheless, the grid mix showed the lowest ODP, ADP, HTP and MAETP compared to both solar PV and wind power. Overall, wind energy was the best performer across the various environmental impacts, either performing best, or close behind for each category compared to NG and solar PV, therefore recommended for further investigation. Compared to NG and wind, PV performed worse in four out of six categories, with impacts being four to ten times higher in these categories than either wind or NG dominated grid mix. It is important also to note that the remaining 5% of the grid mix consists of heavy fuel oil, which has been shown to be a poor performer across all categories [6]. Within the Arabian Gulf, utilization of HFO as a source of energy is still dominant. Across many impact categories including GWP, AP, HTP and MAETP the environmental impacts of HFO were much higher than other energy sources, often by an order of magnitude (Fig. 5f). This highlights that in these locations, even more significant benefits could be realised through both the reduction in electricity requirements by optimum location selection; as well as from changing energy source.

Energy and chemical use are interconnected for RO water treatment. The greater the improvement achieved in water quality through pre-treatment with chemicals, the less energy and chemicals are need for RO. For instance, chemicals are added to the feedwater following screening (i.e. chlorination) to reduce the rate of bacterial growth in the tank and along the pipes while sodium bicarbonate is added to precipitate divalent ions that would otherwise scale and foul the membrane. Flocculants are also added at the DAF unit to reduce colloidal matter and precipitate phosphates and some soluble organic material. These chemical additions have a significant impact on the chemicals and energy used during the later processes of the RO [37,38]. The evaluation only considered optimum design doses via the software output, as time-based fouling processes are not well accounted for. However, experimental evaluation of variations in chemical dose against average long-term energy demand is a follow-up area of investigation to further reduce environmental burdens.

### 3.5. Site selection impact in reducing environmental impacts

Fig. 6 compares the relative reduction in impacts for each simulated plant site to the worst performing site, S13 for each environmental impact category. The results indicate that total reductions of at least 25% could be possible for different environmental impacts within the Arabian Gulf through careful selection of future plant locations. However, it should be noted that the assessment was based on a set of one-time measurements that may not be fully representative of average conditions. Nevertheless, the predominant water quality parameter influencing environmental emissions is salinity, which followed expected and reported ranges around the country [22,28]. Moreover, the modelled energy and chemical consumption for the real plant location using the single water quality point was very close to the average reported chemical dose and energy consumption of the plant (Table S2).

Traditionally in the GCC, thermal desalination plants have dominated, which need to be co-located with power generation requirements, which usually stipulate site requirements. SWRO, particularly those driven by renewables, open up a wider range of locations for plant situation. Still, there are other practical considerations for choosing a plant site. Accessibility, existing infrastructure, security and proximity to populations must also play a key role. S12, for example, exhibited one of the lowest environmental impacts; however, it is located a large distance away from major populated areas compared to the other modelled plants and environmental impacts associated with transportation of water would also need to be included, which were outside the scope of this study.

### 3.6. Normalization of data

As per Section 3.2, S13 exhibited the highest environmental impacts overall while S07 had the lowest GWP and had one of lowest environmental impacts overall. Therefore, these two sites were used for normalization and comparison of how site selection, different chemicals and energy sources could reduce environmental impacts. Table 3 shows normalized environmental impacts associated with a 220 $m^3$ annual per capita supply of desalinated water, as per Qatar consumption, relative to World2000 per capita annual impacts. Values greater than 100%

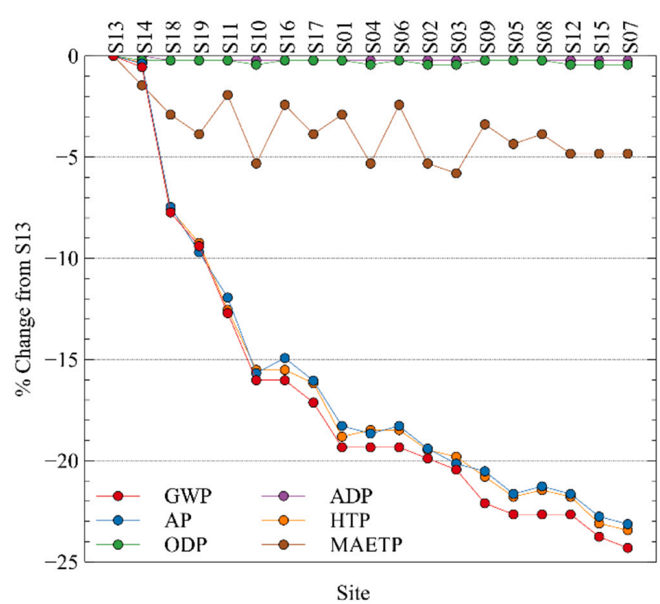


**Fig. 6.** Percent change in environmental impacts compared to S13 (overall highest environmental impact site) by placing the SWRO plant at other sites in this study.

**Table 3**
Normalization of impacts based on annual SWRO per capita water consumption compared to World2000 annual per capita contributions as a percentage (%). All comparisons are made for Site 13 (except of moving to Site 07). Electricity changes are made relative to Slovenia natural gas. Changes <80% or >120% of normalized percent weighting from the S13 reference case are marked in bold.

| | Qatar Grid Mix | | | | | Slovenia | | |
|---|---|---|---|---|---|---|---|---|
| | Reference | Site | Disinfection | | Neutralization | Reference | Electricity | |
| | S13_95% NG | S07_95% NG | S13_Ca(ClO)$_2$ | S13_ClO2 | S13_Ca(OH)$_2$ | S13_NG | S13_Solar PV | S13_Wind |
| GWP | 20.61 | **15.72** | 20.50 | 20.38 | 20.61 | 19.47 | **2.80** | **0.73** |
| AP | 4.24 | **3.26** | 4.16 | 4.14 | 4.21 | 1.96 | 1.61 | **0.42** |
| ODP | 1.05E−05 | 1.04E−05 | **7.21E−07** | **8.16E−07** | 1.00E−05 | 1.06E−05 | **2.08E−05** | 1.10E−05 |
| ADP | 2.73E−05 | 2.73E−05 | **1.54E−05** | **1.58E−05** | **2.15E−05** | 3.63E−05 | **7.34E−04** | **1.06E−04** |
| HTP | 1.63 | **1.25** | 1.58 | 1.58 | 1.61 | 0.60 | **8.11** | 0.70 |
| MAETP | 157.91 | 150.28 | **113.67** | **112.14** | **118.24** | 215.13 | **5835.84** | **535.52** |

indicate impacts where consumption of desalinated water results in more impact than the sum of all other activities associated with an average lifestyle. The normalization process can help to pinpoint the highest environmental impacts overall. It can be seen from Table 3 that MAETP is the most significant environmental impact by an order of magnitude, followed by GWP. AP and HTP follow hereafter, roughly 1 order of magnitude less than GWP. All of these impact categories are very high relative to a per capita estimate of emissions/impacts using the World2000 dataset, demonstrating the high burdens of desalinated water. Notably, when desalinated water is the sole source of domestic supply, its consumption contributes more to MAETP than all other typical activities, while consumption of only desalinated water would contribute roughly 15–20% of a person's total GWP footprint. It is therefore imperative to focus on solutions that reduce the impacts of MAETP, GWP, AP and HTP, in that order of priority, for the most benefit.

Site relocation could reduce relative impacts across many of the impact categories by roughly 25%, and MAETP by close to 5%, making it an effective consideration for reducing impacts. From the normalized perspective, this is an 8% reduction in typical per capita MAETP contribution and 5% reduction in GWP. Shift to renewables provided large normalized benefits for GWP reductions, reducing per capita normalized contributions from over 19% to less than 1% of a standard person's footprint using wind. Wind power also reduced all other impacts to less than 1% of a typical per capita burden with the exception of MAETP, which roughly doubled the already large contribution. PV on the other hand, reduces GWP to a few percent of a typical per capita footprint but increases HTP to 8% of a standard per person contribution and the most significant impact, MAETP, to roughly 58 times a standard per person contribution, making it a questionable energy source. Alternative pH control chemicals (acids) and dechlorination chemicals had no significant influence on normalized impacts, while alternate coagulation chemicals had a large negative impact on MAETP and HTP. These values are not shown in Table 3, but are available in Table S19 of the online supplementary information. Alternate chemicals for disinfection ($Ca(ClO)_2$ and $ClO_2$) and for neutralization ($Ca(OH)_2$) contributed to large normalized impact reductions in the critical MAETP category of 40–45% (absolute) per capita without any notable impacts to other categories. It is therefore clear that changes to chemicals used in disinfection and neutralization are strongly beneficial, while careful consideration of the trade-offs in GWP and AP reductions versus the increase in MAETP need to be considered for uptake of wind power renewables coupled with SWRO. The normalization also shows careful site selection can play an important role in reducing key impact categories of MAETP, GWP, AP and HTP.

## 4. Conclusion and recommendations

Seawater desalination plays a very critical role in enhancing the progressive long term social-economic development that is taking place in all countries located across the Arabian Gulf and will play an increasing role in economic and social wellbeing for other countries around the globe under increasing water stress. Increasing seawater desalination capacity seems the only solution to meet the estimated future water requirements in some regions. However, owing to the large environmental impacts that accompany desalination processes, optimal design and location of these plants is necessary to minimize these environmental burdens. LCA is an effective method to explore approaches of reducing the environmental impacts of RO processes. This study considered the role of location and associated seawater quality on the overall environmental sustainability of the process. The results from this study can give insight for other locations worldwide in order to limit threats from environmental pollution. The shallow, enclosed sites displayed more environmental impacts in comparison to the other locations. These are typical characteristics of the Arabian Gulf region, and highlight the potentially greater impact of desalination in this region. It was evident that certain locations near existing cities and ports resulted in poor water quality and subsequent performance of the SWRO plant. Total reductions of close to 25% in different environmental impacts was possible only by optimizing the location of the plant. As a result, future decisions on construction of RO plants should place proper emphasis on location, but need to be balanced with water transportation requirements and locating the plant away from environmentally sensitive areas. Chemical alternatives for disinfection and neutralization could provide large reductions also in the most significant impact category, MAETP, and provide another alternative to reduce burdens. Utilizing wind energy coupled with SWRO appears to be one of the most effective routes to improve the overall sustainability of the desalination process, reducing impacts in most major impact categories, but unlike the proposed chemical alternatives and site location, it results in a large increase in MAETP, which must be considered carefully.

## CRediT authorship contribution statement

**Abdulrahman Al-Kaabi:** Conceptualization, Methodology, Formal analysis, Investigation, Writing - original draft. **Huda Al-Sulaiti:** Writing - review & editing. **Tareq Al-Ansari:** Writing - review & editing, Supervision. **Hamish R. Mackey:** Conceptualization, Methodology, Formal analysis, Writing - review & editing, Supervision.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.desal.2020.114831.

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