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Optimal design and techno-economic evaluation of renewable energy powered combined reverse osmosis desalination and brine treatment unit

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ABSTRACTS

The reverse osmosis (RO) desalination technique has been identified as a viable means of freshwater production, but its high energy requirement, high cost, and waste (brine) remain serious challenges. This study, therefore, explores efficient energy from renewable energy sources (RES) and brine management in the production of freshwater using the integration of RO, electro-dialysis (ED) and crystallization methods. The objective of this study is to minimize the levelized cost of energy and brine production whilst maximizing freshwater and salt production. The proposed design is such that the feed water (saline water) is passed through the RO unit for desalination; the brine produced from the RO unit is further desalinated by the ED method, leaving a very high concentration to be crystallized into soluble salts thereby achieving a zero brine production. Furthermore, for energy-efficient management, an optimal sizing of energy sources which includes grid power, wind power and solar power, was carried out considering mitigation of carbon emission and its cost and the intermittent limitation of the RES. This integrated design ensures that the internal and external costs of desalination are evaluated and minimized.

Keywords: Optimization; Renewable energy sources; Reverse osmosis desalination; Brine

1. Introduction

Continuous growth in population, constant water pollution and other water stress have made freshwater scarcity a major problem around the world [1]. Treatments such as water reuse, seawater desalination have become prominent in recent years owing to the vast availability of seawater around the world [2]. The seawater usually contains a large deposit of salt, making it difficult and unhealthy for drinking. Desalination is, therefore, the separation of freshwater from seawater (in other cases, brackish water), leaving behind more concentrated saline water known as the brine. Indiscriminate brine disposal is harmful to the environment. Also, most desalination plants around the world still largely depend on fossil energy sources, especially convectional grid generators. The direct consequence of this is high greenhouse gas emission, which also has cost implications alongside its environmental impacts. The cost implications of emitted carbon gas and brine management are considered as the external costs of desalination [3]. Therefore, the main challenges of seawater desalination are, hence, energy requirement and brine management. These challenges make seawater desalination quite expensive both in terms of cost and environmental impacts of energy supply source and brine disposal. Hence, efficient energy supply and brine management are crucial to carbon emission reduction [4] and cost evaluation of desalination.

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To tackle these challenges, renewable energy sources (RES) have been highly exploited and integrated into desalination systems to cut down the cost and gas emission of conventional fossil energy supply [5,6]. Hossam-Eldin et al. [5] investigate the economic viability of a desalination system powered by RES with the objective of minimizing excess energy using an optimization program developed to determine the best hybrid RESs. Koutroulis and Kolokotsa [6] proposed an optimization methodology for sizing photovoltaic (PV) modules and wind generators to power a desalination system for a small community of residential households at minimal total system cost.

The thermal process of desalination is more energy and cost-intensive than the membrane process; hence, the predominant use of the reverse osmosis (RO) technique. One major limitation of the RO method is the volume of brine (concentrate) produced during the desalination process [7]. Different brine management approaches have been proposed, and some implemented [1,7,8]. Most available brine treatment technologies like desalination technologies are thermal-based or membrane-based. Most often, the same techniques are used in a specific combination for both desalination and brine treatment. In this study, RO is used for desalination while electro-dialysis (ED) and crystallizer (CRY) are used for further treatment of the concentrate. ED being a membrane technology is cost-effective for brine treatment, as it utilized ion selectivity to further separate freshwater from the concentrate. This process does not entirely convert the brine to potable water and salt. Its performance is limited by scaling soluble salt on the membrane. Therefore, further treatment of the highly concentrated brine is required. The crystallization of the remaining volume of brine can lead to zero brine discharge as the resulting product will be crystals of salt and evaporated freshwater, which can be condensed and collected for drinking. The feasibility of RO-ED-CRY was presented by Panagopoulos et al. [9], and a framework for cost and energy needs model was established. A comparison of RO-ED-CRY and the same system that include a 2-stage high-pressure reverse osmosis (HPRO) was made, and the results show that adding HPRO is uneconomical.

For sustainability and environmental friendliness, when considering seawater desalination, the cost and proper management of energy supply and brine production must be put into consideration. The contribution of this study is, therefore, (i) to evaluate the optimal cost of the freshwater output considering carbon emission, demand response and brine treatment cost, (ii) to minimize the impact of carbon emission, (iii) to maximized freshwater production, and (iv) to minimized brine discharged. Thus, the remainder of this paper is organized such that section II details system models; section III presents a case study; section IV presents and discusses the results, while section V concludes the study.

2. System models

2.1. System architecture

Fig. 1 describe the system design which has two basic sections; (i) the power section which integrates RESs of wind and PV with grid power and (ii) the desalination and brine treatment section which integrates RO, ED and CRY units. The power sources are optimally scheduled with time of use (TOU) demand response and considering carbon emission to achieve minimal levelized cost of energy (LCOE) whereas, the desalination and brine treatment section is designed such that the RO unit desalinates 40% of the feedwater (seawater) to freshwater, leaving 60% as brine. This brine is passed into the ED which further desalinates 20% of the feedwater into freshwater (i.e., 33.3333% of the brine passed into ED) leaving a more concentrated brine into the CRY unit. The crystallization unit evaporates 10% of the feed water (16.6667% of the original brine form RO) which is condensed and collected as additional freshwater. The remaining 30% of the feedwater (which is 50% of the original brine from RO) forms crystals of salt leaving zero discharge.

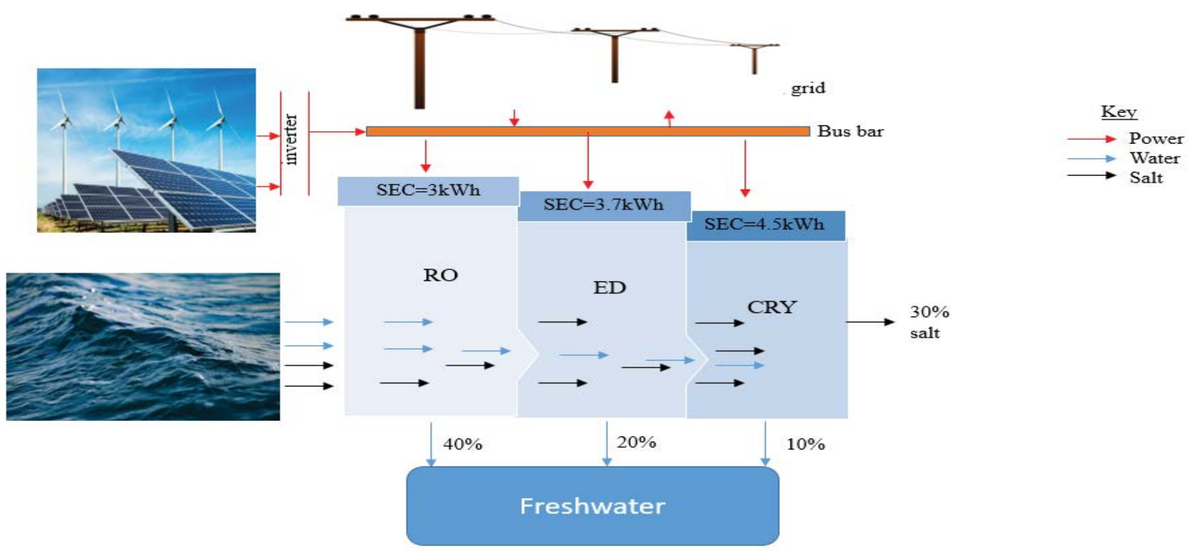

Fig. 1. Schematic diagram of combined desalination and brine treatment process.

2.2. Grid power and cost model

The hourly power supply from the grid serves as a backup to satisfy the load demand of the desalination unit such that in the case of intermittency of RES, the desalination unit will depend on the grid for power supply. When there is excess energy as a result of high-power output from the RES or as a result of demand response, the excess energy can be sold back to the grid. Therefore, the hourly power ($GP_i(t)$) imported from the grid and the hourly power ($GP_e(t)$) exported to the grid are optimized variables ranging from zero to maximum hourly load demand by the RO unit as expressed in Eqs. (1) and (2) respectively.

$$0 \le GP_i(t) \le GP_i^{\max} \tag{1}$$

$$0 \le GP_e(t) \le GP_e^{\max} \tag{2}$$

The maximum transferable power to and from the grid is assumed to equal:

$$GP_i^{\max} = GP_e^{\max} \tag{3}$$

The cost of grid power is dependent on the energy price and the difference between imported power and exported power to the grid. It is assumed that the unit cost of purchase power is equal to the unit cost of selling power back to the figures. Hence, excess energy production that is not needed by the desalination unit is sold back to the grid to compensate for the cost of imported power or at least reduce the importation cost of power from the grid.

$$CGP_i(t) = GP_i(t) \times P(t) \tag{4}$$

$$CGP_e(t) = GP_e(t) \times P(t) \tag{5}$$

$$CGP = \sum \left(CGP_i(t) \times P(t) - GP_e(t) \times P(t) \right) \quad \forall t = 1,2,3,\cdots 8760 \tag{6}$$

where $P(t)$ is the hourly unit price of transferable grid power and CGP is the total annual cost of transferable grid power.

2.3. RES and cost model

2.3.1. PV power and cost model

The hourly output power ($P_{PV}(t)$) supply by the PV array is given as [10,11]:

$$P_{PV}(t) = APV \times \eta' \times SI(t) \tag{7}$$

where APV is the area of the photovoltaic array in (m^2), SI(t) is hourly solar irradiation and ή is the PV efficiency.

Evaluation of PV cost is based on the area of PV array, initial capital cost and annual maintenance cost expressed as:

$$IC_{PV} = APV \times C_{PV} \tag{8}$$

$$AMC_{PV} = APV \times MC_{PV} \times r \tag{9}$$

2.3.2. Wind power and cost model

The hourly power output of the wind generator ($W_p(t)$) is given as [10].

$$W_p(t) = \frac{1}{2} \times \eta'_w \times \rho_{air} \times C_p \times AWT \times V(t)^3 \tag{10}$$

where $ή_w$ is the efficiency of the wind generator, ρ_{air} is the air density, C_p is the power coefficient, AWT is the swept area of the wind turbine (WT) and $V(t)$ is the hourly wind speed given as [12]:

$$V(t) = V_R \times \left[\frac{h}{h_R} \right]^{\propto} \tag{11}$$

where $V(t)$ is the hourly speed at projected height (h), V_R is the hourly speed at reference height (h_R) and α is the power-law exponent equivalent to 1/7.

The economics of using wind power for desalination is similar to that of PV and in this study it is analyzed based on the initial capital cost (IC_{WT}) and total maintenance cost (TMC_{WT}), depending on the area of the WT as follows:

$$IC_{WT} = AWT \times C_{WT} \tag{12}$$

$$AMC_{WT} = AWT \times MC_{WT} \times r \tag{13}$$

2.4. RO desalination plant power demand and cost model

The hourly power demand ($P_{WD}(t)$) of the RO desalination unit depends on the specific energy consumption (SEC) to produce 1 m^3 of freshwater, which in this study is 3 kWh/m^3 and the actual volume of water (QW(t)) produced per hour [13,14].

$$P_{WD}(t) = QW_{RO}(t) \times SEC \tag{14}$$

The daily water production capacity is given as:

$$DQW = \sum_{t=1}^{24} QW_{RO}(t) \tag{15}$$

The water dispensation model and network are not considered in this study. Thus, water tank capacity (W_{TK}) express in m^3 is assumed to be twice-daily water production capacity to make enough space available, even if there is water remaining from the previous day.

$$W_{TK} = DQW \times 2 \tag{16}$$

RO desalination cost model includes the initial capital cost (IC_{RO}), annual maintenance and operational cost (AMC_{RO}), annual membrane replacement cost (AC_{MR}), annual treatment chemical cost (AC_{CH}) and water tank cost (CW_{TK}) [15,16].

$$\mathrm{IC_{RO}} = C_{\mathrm{RO}} \times \mathrm{DQW} \quad (17)$$

$$\mathrm{ICW_{TK}} = \mathrm{CW_{TK}} \times W_{\mathrm{TK}} \quad (18)$$

2.5. Brine treatment power demand model

The brine treatment section includes the ED and crystallization units. The volumetric quantity of brine produced (QB) from RO plant depends its water production capacity and water recovery ratio (RR) expressed as [2]:

$$\mathrm{DQB} = \frac{\mathrm{DQW}}{\mathrm{RR}} \times (1 - \mathrm{RR}) \quad (19)$$

where RR is the percentage of volume freshwater produced by the RO desalination to the volume of saline feed water (QF) [8], it is assumed to be 40% in this study.

$$\mathrm{RR} = \frac{\mathrm{QW}}{\mathrm{QF}} \times 100 \quad (20)$$

This implies that QB can also be calculated as [8]:

$$\mathrm{QB} = \mathrm{QF} - \mathrm{QW} \quad (21)$$

Also, Eq. (19) is modified to consider hourly brine production as:

$$\mathrm{QB}(t) = \frac{\mathrm{QW_{RO}}(t)}{\mathrm{RR}} \times (1 - \mathrm{RR}) \quad (22)$$

Therefore, the hourly power demand ($P_B(t)$) of the brine treatment unit depends on the sum of SEC by ED and the crystallization unit, which in this study are adapted from [9,17] as 3.7 and 4.5 kWh/m^3, respectively. Hence;

$$P_B(t) = \mathrm{QB}(t) \times \mathrm{SEC} \quad (23)$$

For a zero brine discharge, the brine from the RO unit, when passed through the ED unit, produces some quantities of freshwater (33.3333% of the brine, in this study) and a more concentrated brine, which is further passed into the crystallizer. The also produced some quantities of freshwater (in this case, 16.6667% of the total brine from the RO unit), and the remaining amounts of brine are crystallized salt and other compounds. Thus, the total freshwater produced from the combine RO-ED-CRY system is given as:

$$\mathrm{TQW}(t) = \mathrm{QW_{RO}}(t) + \mathrm{QW_{ED}}(t) + \mathrm{QW_{CRY}}(t) \quad (24)$$

2.6. TOU demand response load and cost model

The maximum allowable demand variation (increase/decrease) per hour is assumed 30% of total demand at that hour. The demand response load is an optimize variable expressed as:

$$-\Delta\mathrm{L}^{\max}(t) \le \Delta\mathrm{L}(t) \le \Delta\mathrm{L}^{\max}(t) \quad (25)$$

where

$$\Delta\mathrm{L}^{\max}(t) = 0.3 \times \left[P_{\mathrm{WD}}(t) + P_B(t)\right] \quad (26)$$

Also, for even distribution of load shift, cut of demand at certain hours of the day equals an increase of demand at other hours of the day expressed as:

$$\sum_{t=1}^{24} \Delta\mathrm{L}(t) = 0 \quad (27)$$

The application of TOU demand response optimally shifts loads from peak hours when the price of demand is highest to either standard or off-peak hours yet, allow the demand at every hour to be met. The cost of demand response is the difference between the cost of power demand before and after load variation due to demand responses. It is expressed as [18].

$$\Delta\mathrm{LC} = \sum \begin{bmatrix} \left(P_{\mathrm{WD}}(t) + P_B(t)\right) \times \lambda(t) - \\ \left(\left(P_{\mathrm{WD}}(t) + P_B(t)\right) - \Delta\mathrm{L}(t)\right) \times \lambda(t) \end{bmatrix} \quad (28)$$
$$t = 1,2,3,\ldots 8760$$

2.7. Carbon emission cost and global warming impact of energy source

The global warming impact (GWI, in other words, carbon emission of fossil-fuel energy source, could be due to construction or operation of the plant, with the impact due to operation exceeding that due to construction by multiple orders [4]. Thus, this study considered the impact due to operation as adopted by Baumgärtner et al. [4]. The authors define GWI as the summation of input power $P_{j,t}$ of every fossil-fuel units j in every time step $t \in T$ multiplied by specific operational emission factor $\mathrm{SEF}_{j,t}$ and the period Δt_t of time step represented as:

$$\mathrm{GWI}_g = \sum_{t \in T} \left[\Delta t_t \sum_j \mathrm{SEF}_{j,t} \times P_{j,t}\right] \quad (29)$$

where

$$\mathrm{SEF}_{j,t} = \frac{\text{emission due to electrical energ genarated}}{\text{electrical energ genarated}} \quad (30)$$

In other to estimate carbon emission cost, the formulated model given by Molinos-Senante and González [3] Kesieme et al. [19] was adopted as:

$$\mathrm{CE}\left(\frac{\$}{\mathrm{m}^3}\right) = \text{Energy supply}\left(\frac{\mathrm{kwh}}{\mathrm{m}^3}\right) \times \text{Emission factor}\left(\frac{\mathrm{kgCO_{2-e}}}{\mathrm{kwh}}\right) \times \text{Carbon tax}\left(\frac{\$}{\mathrm{kgCO_{2-e}}}\right) \quad (31)$$

The grid specific emission factor and carbon tax depend on the country of location of the plant. This study adopted the calculated emission factor for South Africa by Brander et al. [20]. The value of the emission factor is 1.069 kg CO_2/kWh. The new South Africa carbon tax rate is ranged from R6-R48 (0.40 $–3.17 $) [21]. The lowest value of 0.41 $ is considered in this study.

2.8. Optimization problem formulation

In this study, the annualized system cost matrix is used for the economic evaluation of the RO desalination system powered by a grid and RES to determine the cost of freshwater and the LCOE. The annualized cost of the system (ACS) involves the capital recovery factor (CRF) and the total system cost which includes, total initial cost (TICC), total maintenance and operation cost (TMC) of all the components that makes up the system [22–24]. Also included in the ACS is demand response cost (ΔLC) and total carbon emission cost (EC).

$$\text{TICC} = \text{IC}_{\text{PV}} + \text{IC}_{\text{WT}} + \text{IC}_{\text{RO}} + \text{IC}_{\text{ED}} + \text{IC}_{\text{CRY}} + \text{ICW}_{\text{TK}} \tag{32}$$

$$\text{TMC} = \text{AMC}_{\text{PV}} + \text{AMC}_{\text{WT}} + \text{AMC}_{\text{RO}} + \text{AMC}_{\text{ED}} + \text{AMC}_{\text{CRY}} \tag{33}$$

$$\text{ACS} = \text{TICC} \times \text{CRF} + \text{TMC} + \text{AC}_{\text{MR}} \times \text{CRF} + \text{AC}_{\text{CH}} + \text{CGP} + \Delta\text{LC} + \text{EC} \tag{34}$$

where

$$\text{CRF} = \frac{i(1+i)^n}{(1+i)^n - 1} \qquad n = 1\ldots19 \tag{35}$$

n is the number of years in the lifetime of the system of which interest rate i is considered.

$$\text{COP} = \frac{\text{ACS}}{\sum \text{TQW}(t)} + \text{Saltp} \tag{36}$$

$$\text{LCOE} = \frac{\text{ACS} + P_{\text{WD}}(t) + P_B(t)}{\sum P_{\text{PV}}(t) + W_p(t) + \text{GP}_i(t)} \tag{37}$$

$$P_{\text{PV}}(t) + W_p(t) + \text{GP}_i(t)$$

The optimization problem is formulated as a multi-objective linear programming problem as expressed in Eq. (34) with the objective of minimizing the ACS and carbon emission while maximizing the quantity of freshwater production subject to constraints expressed by Eqs. (35)–(39). The weighting factors (W_1, W_2, W_3 and W_4) were allocated based on the preference of significant concern, with GWI of emission rank highest, then ACS and quantity of water produce rank lowest since meeting water demand is paramount to having excess water production. This multi-optimization problem is solved using COMPLEX solver of the advanced interactive multidimensional modeling system (AIMMS).

Objective function:

$$\min\left[w_1 \times \text{ACS} + w_2 \times \sum \text{GWI} + w_3 \times \sum \text{QB}(t) - w_4 \times \sum \text{TQW}(t)\right] \tag{38}$$

S.t.

$$P_{\text{PV}}(\text{t}) + W_p(t) + \text{GP}_i(t) = P_{\text{WD}}(t) + P_B(t) + \Delta\text{L}(t) + \text{GP}_e(t) \tag{39}$$

$$\text{TQW}(t) \geq \text{WD}(t) \tag{40}$$

$$\text{QW}^{\min} \leq \text{QW}_{\text{RO}}(t) \leq \text{QW}^{\max} \tag{41}$$

$$P_{\text{WD}}^{\min} \leq P_{\text{WD}}(t) \leq P_{\text{WD}}^{\max} \tag{42}$$

$$\forall t = 1,2,3\ldots8760$$

$$\text{APV} \geq 0 \tag{43}$$

$$\text{AWT} \geq 0 \tag{44}$$

Eq. (39) expresses the power balance that ensures power supply from PV, wind generator and the grid at any time t equals the total demand by the RO desalination and brine treatment unit and the power exported to the grid at the same time t. Eq. (40) is a water balance that ensures the total water produces at any hour t, equals, or in excess of water demand at that hour t, while Eq. (41) ensures water produce per hour remains in a boundary of the required limit. Eq. (42) is the limit of power required by RO to produce water at any time t, and Eq. (43) expresses the limit of the area of PV while Eq. (44) limits the area of the WT. Other Eqs. (1)–(3) and (25), which express the limit of grid imported power, the limit of grid exported power, maximum allowable transfer power and limit of demand response load respectively. Also, Eq. (27) ensures even distribution of load shift.

3. Case study

In this study, the metrological data from Stellenbosch University, Western Cape Province of South Africa is used. The hourly solar irradiation and wind speed, as represented in Figs. 2 and 3, were collected from the Southern African Universities Radiometric (SAURAN). Also, the TOU energy price (in US$) for South Africa gotten from the Eskom schedule of the standard price for Eskom tariffs 2019/2020 [25] is also implemented for the demand response program. Fig. 4 represents the TOU price per hour of a day.

The choice of Western Cape Province of South Africa is based on its proximity to the coast of the Atlantic Ocean and the existing water scarcity problem in the area. The study has shown that the RO desalination technology is the most suited for South Africa for several reasons, as reflected by Swartz et al. [26]. Nonetheless, the west-coast water is usually frigid and high salinity in nature (on average 3.5 g/L), thus requires high operating pressure and low membrane fluxes and in turn, high energy requirement [26]. These challenges

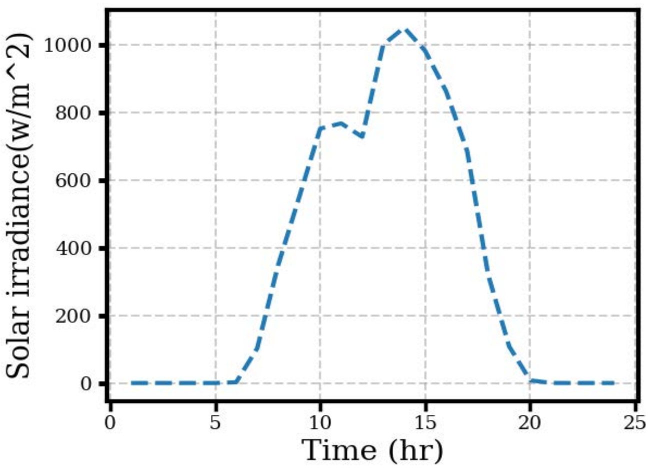

Fig. 2. Hourly solar irradiance.

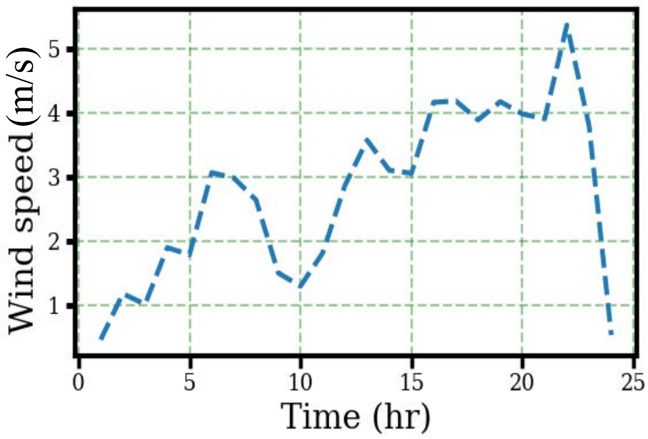

Fig. 3. Hourly wind speed.

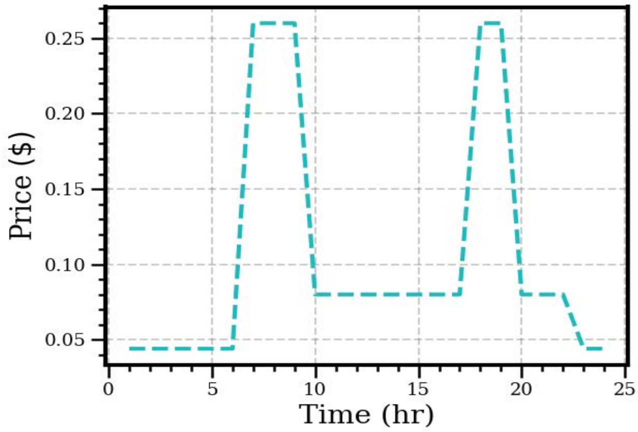

Fig. 4. Hourly price of grid power.

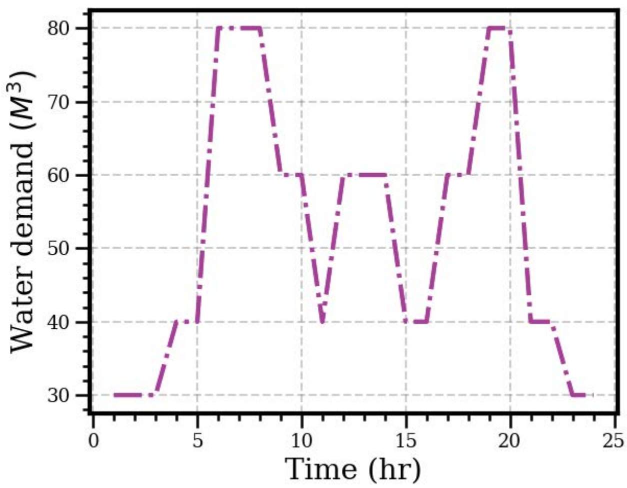

Fig. 5. Hourly water demand.

make freshwater production using desalination quite expensive, albeit still the preferred option for freshwater sustainability. There are several already existing desalination plants operating in South Africa, with the largest been situated in Mossel Bay with a capacity of 15,000,000 L/d [27]. Despite the several existing temporally desalination plants in operation, recent studies shown that the region is still in dare need of about 150,000,000 L/d of freshwater to meet demand and a continuous increase of over 30,000,000 L per annual to achieve about 350,000,000 L/d to guarantee sustainability in the nearest future [28]. While there is a good propose solution of building a more permanent seawater desalination plant of capacity above 150,000,000 L/d, this study proposes the optimization of existing modular desalination plants as well, by incorporating RES and demand response program to increase freshwater production capacity at reduce LCOE and hence minimize the cost of freshwater. An assumed hourly water demand curve based on expected behavioral water usage at different hours of the day, as represented in Fig. 5, is used in this study. Other data used especially for components cost evaluation are taken from Abdelshafy et al. [15] and Wu et al. [16].

4. Results, discussion and sensitive analysis

4.1. Results

Fig. 6 shows the hourly power supply and sold back to the grid, the power from the wind generator and the power output of the PV generator. An average day simulation is used for purposes of simplicity. Fig. 7 depicts the hourly volume of freshwater produced from the three units, RO, ED and CRY. Fig. 8 represents the hourly volume of brine, freshwater and salt produced, while Table 1 is the summary results of the other optimized parameter.

4.2. Discussion and sensitivity analysis

The result represented in Fig. 6 shows the impact of TOU demand response in shifting load from peak hours to off-peak and standard hours for energy cost-effective management. The selection of the energy sources and the subsequent power output depending on the cost and the carbon emission of the energy source, hence the resulting low power output from the grid, which depends mainly on fossil fuel generators. The carbon emitted from the grid generator

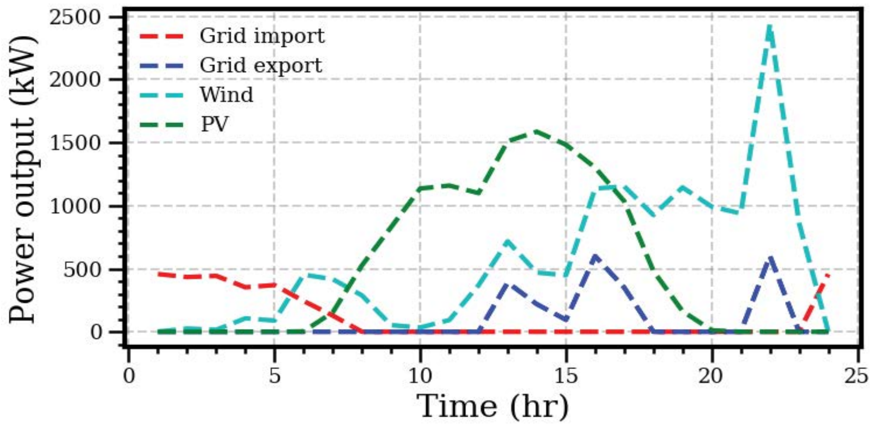

Fig. 6. Hourly energy dispensed.

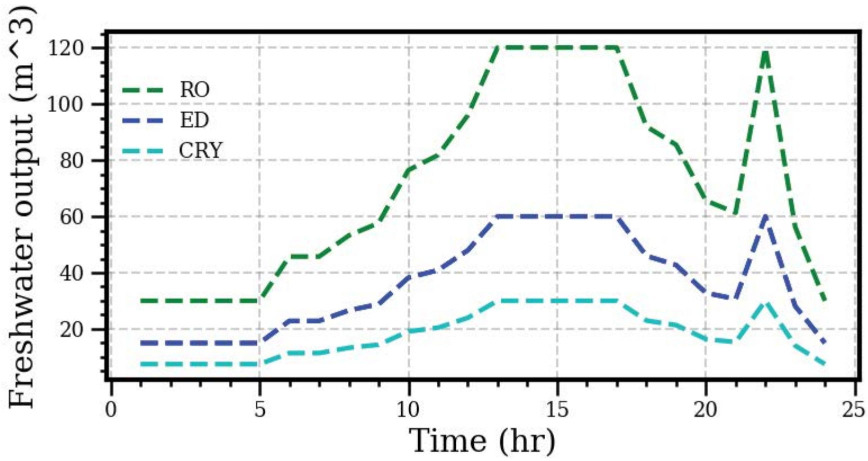

Fig. 7. Hourly freshwater dispensed.

Table 1
Input parameters [15,16]

Parameters	Value	Parameters	Value	Parameters	Value
Project time	20 y	C_{PV}	285 $/m^3	WT rated power	1 kW
Interest rate	5%	$ή_w$	85%	C_{RO}	532 $/m^3/d
Discount rate	3%	ρ_{air}	1.23 kg m^3	Plant maintenance cost	0.2 $/m^3
Emission factor	1.07	C_p	0.59	Chemical cost	0.06 $/m^3
Emission tax	0.41 $	MC_{PV}	35 $/y	C_{MR}	0.06 $/m^3
PV rated power	1 kW	C_{WT}	1,804 $	CW_{TK}	255 $/m^3
PV efficiency (ή)	16%	MC_{PV}	100 $/y		

comes with a cost (261,460 $/y), therefore increasing the cost of grid power supply. This gives the advantage to the RES (wind and PV generators), hence the high power output from the two sources.

The hourly volume of freshwater produce from the three units (RO, ED and CRY) as depicted in Fig. 7 shows that the RO unit, which is the main desalination unit, produces the highest quantity of freshwater and then the ED unit. The crystallization unit produces only a small volume of freshwater since the larger volume of brine passed into it has a high concentration of salt. The crystallization process is, therefore, the main brine treatment unit producing soluble salts and a small volume of freshwater, leaving a zero brine discharge.

The total potable water produced from RO-ED-CRY at every hour of the day alongside the hourly brine production from the RO unit, as well as the salt produced from the brine, is shown in Fig. 8. This result indicates that a large volume of the feed water is converted into freshwater while the remainder crystallized into salts. Furthermore,

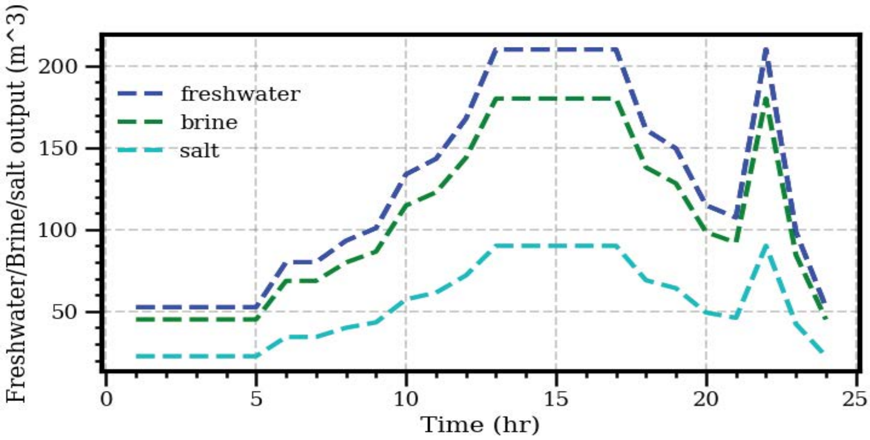

Fig. 8. Hourly freshwater, brine and salt produced.

the volume of freshwater produced (3,005 m^3/d) from this combined model of desalination and brine treatment, as shown in Table 2, is higher than the volume produced by standalone RO unit previously presented by Okampo and Nwulu [29] with similar input parameters which are also the expected desalination capacity to meet the baseline daily water demand (1,250 m^3/d). Also, this study presents the unit cost of freshwater and salt as a single unit cost of production, since it is difficult to separate the cost of production of freshwater and salt because the system is design as a single unit with the same components cost, energy sources and their costs. The unit cost of production of freshwater and salt (0.89 $) is within the range of cost of water for standalone desalination units presented in literature which range from 0.5–2.39 $ [15,16,29]. Furthermore, most standalone RO desalination systems do not account for carbon emission cost and brine treatment, therefore, use less energy, less treatment chemicals and required fewer membrane replacement than a combined model that produces freshwater and treats brine with zero discharge. Hence, the unit cost of production of this combined model is relatively low considering the economic and environmental factors. On the other hand, the LCOE of this model (1.06 $) is within the average value of those of standalone RO desalination systems which usually range between 0.5–1.2 $, suggesting a similar cost of energy for a standalone desalination unit and a combine desalination-brine treatment unit. This is because the components cost of similar energy sources used for a standalone unit is the same for a combined unit and depends largely on the size of the system and the volume of production.

Sensitivity analysis was performed to evaluate the impacts of the percentage increase of water demand on three cost matrices (ACS, LCOE and cost of products, COP) as depicted in Figs. 9–11, respectively.

The results of the sensitivity analysis show a proportional increase in ACS, a moderate increase in LCOE and a decrease in the cost of products against the percentage increase in water demand. This implies that an increase in water demand results in a rise in ACS and LCOE but the unit cost of production of water and salt is reduced with more freshwater production to meet the increased water demand.

Table 2
Summary results of optimized parameters

ACS ($)	1,401,367
Emission (kgCO_{2-e})	637,708
Emission cost ($)	261,460
Daily water produced (m^3)	3,005
Daily salt produced (m^3)	1,288
LCOE ($/kW)	0.89
Unit cost of production of freshwater and salt ($/$m^3$)	1.056
APV (m^2)	9,431
AWT (m^2)	50,891

5. Conclusion

This study presents efficient energy and brine management in the production of freshwater using the integration of RO, ED and crystallization methods. The objective of this study is to minimize LCOE and brine production whilst maximizing freshwater and salt production at a minimal cost. The proposed design is such that the feed water (saline water) is passed through the RO unit for desalination; the brine produced from the RO unit is further desalinated by the ED method, leaving a very high concentration to be crystallized into soluble salts thereby achieving a zero brine production. Furthermore, for energy-efficient management, optimal sizing of energy sources, which include grid power, wind power and solar power, was carried out considering mitigation of carbon emission and its cost and the intermittent limitation of the RES. This integrated design ensures that the internal and external costs of desalination are evaluated and minimized. The results show the impact of emission and its cost on the energy cost, increasing the cost of grid energy supply, making RES more cost-effective as well as environmentally friendly. Also, the LCOE is within the average value of those of standalone desalination units suggesting a similar cost of energy for a standalone desalination unit and a combined desalination-brine treatment unit. This is because the components cost of similar energy sources used for a standalone unit is the same for a combined

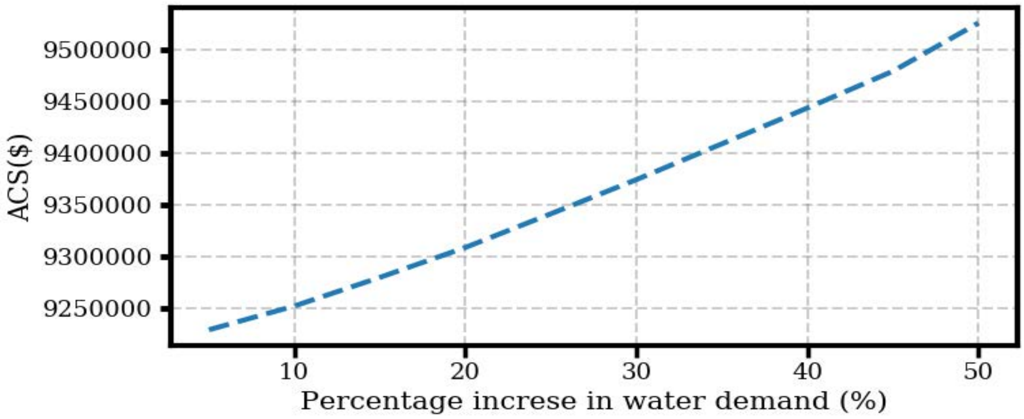

Fig. 9. Impacts of percentage increased on the annual cost of the system.

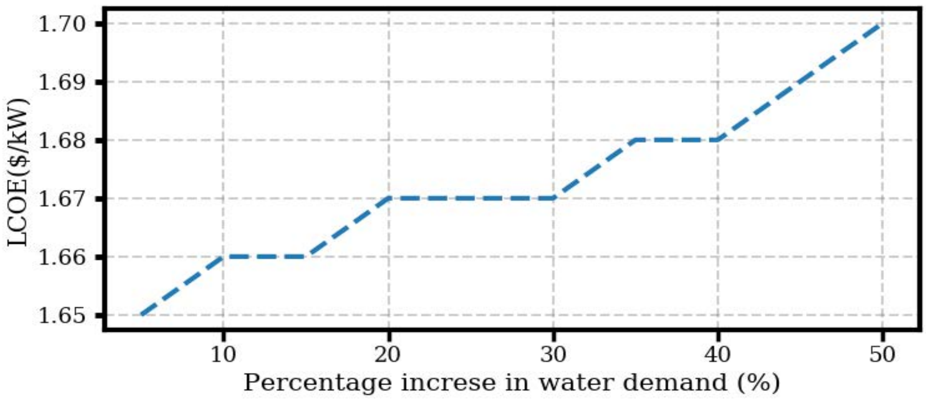

Fig. 10. Impacts of percentage increased on levelized cost of energy.

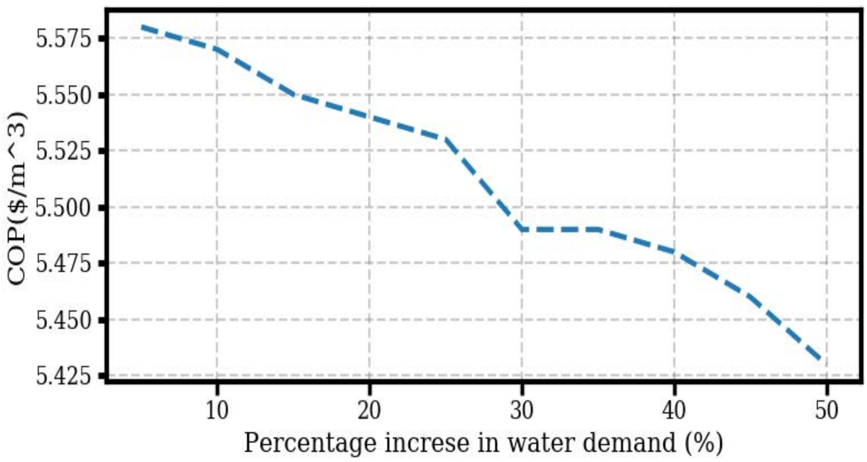

Fig. 11. Impacts of percentage increased on the cost of water and salt.

unit and depends largely on the size of the system and the volume of production. Further study can investigate the cost of salt-based on location as it is expected that the salt produced if further treated can be added advantage of the combined model of desalination and brine treatment as it can be of use. Also, the annual carbon emission (637,708 $kgCO_{2-e}$) is still very high, a further reduction can be achieved with the integration of the storage system to supplement the inconsistency of the RESs. This will reduce the dependence on grid power but might increase the cost of production.

Set

t — Time, h

Parameters

I — Interest rate
r — Discount rate
$ή$ — PV efficiency
$ή_w$ — Wind turbine efficiency
ρ_{air} — Air density
C_p — Power coefficient
α — Power law exponent
$\lambda(t)$ — Marginal price of energy, $/kWh
AC_{CH} — Annual cost of RO treatment chemicals, $
AC_{MR} – Annual cost of RO membrane replacement, $
AMC_{PV} — Annual maintenance cost of PV, $
AMC_{RO} — RO annual maintenance cost, $
AMC_{WT} — Annual maintenance cost of the wind generator, $
CRF — Capital recovery factor
$CGP_i(t)$ — Cost of grid power imported, $/kW
$CGP_e(t)$ — Cost of grid power exported, $/kW
CGP — Total cost of grid transferable power, $
C_{WT} – Wind turbine cost, $
C_{PV} — PV panel cost, $/m^2
C_{RO} — RO cost, $/m^3
CW_{TK} — Water tank cost, $/m^3
GP_i^{max} — Maximum imported grid power, kW
GP_e^{max} — Maximum exported grid power, kW
h — Projected height of wind turbine, m
h_R — Reference height of wind turbine, m
IC_{PV} — Initial capital cost of PV, $
IC_{RO} — Initial capital cost of RO Plant, $/m^3/d
ICW_{TK} — Initial capital cost of the water tank, $
IC_{WT} — Initial capital cost of the wind generator, $
ΔL^{max} — Maximum allowable change in demand, kW
ΔLC — Cost of demand response load curtails, $
MC_{WT} – Cost of maintenance of a wind turbine, $
MC_{PV} — Cost of maintenance of a PV panel, $
$P(t)$ — Price of grid power, $/kWh
P_ω^{min} — Minimum power demand, kW
P_{WD}^{max} — Maximum power demand, kW
QB — Quantity of brine produced, m^3
QF — Quantity of feed water, m^3
Q_w — Quantity of freshwater produced, m^3
QW^{min} — Minimum RO water produce, m^3
QW^{max} — Maximum RO water produce, m^3
RR — Freshwater recovery ratio
SEC — Specific energy consumption, kWh/m^3
SI(t) — Solar irradiation, W/m^2
TICC — Total initial capital cost of system, $
TMC — Total maintenance and operational cost, $
$V(t)$ — Wind speed, m/s
V_R — Reference wind speed, m/s
WD(t) — Hourly water demand, m^3

Variables

ACS — Annualized cost of system, $
APV — Area of photovoltaic, m
AWT — Area of wind turbine, m
CE_{DG} — DG carbon emission cost, $
CE_g — Grid carbon emission cost, $
COP — Cost of products (water and salt), $/m^3
$GP_i(t)$ — Grid power imported, kW
$GP_e(t)$ — Grid power exported, kW
GWI — Global warming impact, kgCO$_{2-e}$
LCOE — Levelized cost of energy, $
$\Delta L(t)$ — Demand response load curtail, kW
$P_B(t)$ — Hourly power demand for brine treatment, kW
$P_{PV}(t)$ — Hourly power output of PV, kW
$P_{WD}(t)$ — Hourly power demand by RO Plant, kW
$QW_{RO}(t)$ — RO hourly volume of water produce, m^3
Saltp — Volume of salt produce, m^3
SEF_{DG} — DG specific emission factor, kg/L
$SEF_{j,t}$ — Grid specific emission factor, kgCO$_{2-e}$/kWh
TEC — Total carbon emission cost, $
$W_p(t)$ — Wind generator power output, kW

Abbreviations

DR — Demand response
PV — Photovoltaic
RES — Renewable energy sources

References

[1] A. Giwa, V. Dufour, F. Al Marzooqi, M. Al Kaabi, S.W. Hasan, Brine management methods: recent innovations and current status, Desalination, 407 (2017) 1–23.
[2] E. Jones, M. Qadir, M.T.H. van Vliet, V. Smakhtin, S.-m. Kang, The state of desalination and brine production: a global outlook, Sci. Total Environ., 657 (2019) 1343–1356.
[3] M. Molinos-Senante, D. González, Evaluation of the economics of desalination by integrating greenhouse gas emission costs: an empirical application for Chile, Renewable Energy, 133 (2019) 1327–1337.
[4] N. Baumgärtner, R. Delorme, M. Hennen, A. Bardow, Design of low-carbon utility systems: exploiting time-dependent grid emissions for climate-friendly demand-side management, Appl. Energy, 247 (2019) 755–765.
[5] A. Hossam-Eldin, A.M. El-Nashar, A. Ismaiel, Investigation into economical desalination using optimized hybrid renewable energy system, Int. J. Electr. Power Energy Syst., 43 (2012) 1393–1400.
[6] E. Koutroulis, D. Kolokotsa, Design optimization of desalination systems power-supplied by PV and W/G energy sources, Desalination, 258 (2010) 171–181.
[7] A. Subramani, J.G. Jacangelo, Treatment technologies for reverse osmosis concentrate volume minimization: a review, Sep. Purif. Technol., 122 (2014) 472–489.
[8] A. Panagopoulos, K.-J. Haralambous, M. Loizidou, Desalination brine disposal methods and treatment technologies – a review, Sci. Total Environ., 693 (2019) 133545.
[9] K.G. Nayar, J. Fernandes, R.K. McGovern, B.S. Al-Anzi, J.H. Lienhard V, Cost and energy needs of RO-ED-crystallizer systems for zero brine discharge seawater desalination, Desalination, 457 (2019) 115–132.
[10] N.I. Nwulu, X.H. Xia, Optimal dispatch for a microgrid incorporating renewables and demand response, Renewable Energy, 101 (2017) 16–28.
[11] U. Damisa, N.I. Nwulu, Y.X. Sun, Microgrid energy and reserve management incorporating prosumer behind-the-meter resources, IET Renewable Power Gener., 12 (2018) 910–919.
[12] B.S. Borowy, Z.M. Salameh, Methodology for optimally sizing the combination of a battery bank and PV array in a wind/PV hybrid system, IEEE Trans. Energy Convers., 11 (1996) 367–375.

[13] A. Maleki, M.G. Khajeh, M.A. Rosen, Weather forecasting for optimization of a hybrid solar-wind–powered reverse osmosis water desalination system using a novel optimizer approach, Energy, 114 (2016) 1120–1134.
[14] W.X. Peng, A. Maleki, M.A. Rosen, P. Azarikhah, Optimization of a hybrid system for solar-wind-based water desalination by reverse osmosis: comparison of approaches, Desalination, 442 (2018) 16–31.
[15] A.M. Abdelshafy, H. Hassan, J. Jurasz, Optimal design of a grid-connected desalination plant powered by renewable energy resources using a hybrid PSO–GWO approach, Energy Convers. Manage., 173 (2018) 331–347.
[16] B.J. Wu, A. Maleki, F. Pourfayaz, M.A. Rosen, Optimal design of stand-alone reverse osmosis desalination driven by a photovoltaic and diesel generator hybrid system, Sol. Energy, 163 (2018) 91–103.
[17] K.G. Nayar, J. Fernandes, R.K. McGovern, K.P. Dominguez, A. McCance, B.S. Al-Anzi, J.H. Lienhard V, Cost and energy requirements of hybrid RO and ED brine concentration systems for salt production, Desalination, 456 (2019) 97–120.
[18] E. Dehnavi, H. Abdi, Optimal pricing in time of use demand response by integrating with dynamic economic dispatch problem, Energy, 109 (2016) 1086–1094.
[19] U.K. Kesieme, N. Milne, H. Aral, C.Y. Cheng, M. Duke, Economic analysis of desalination technologies in the context of carbon pricing, and opportunities for membrane distillation, Desalination, 323 (2013) 66–74.
[20] M. Brander, A. Sood, C. Wylie, A. Haughton, J. Lovell, Electricity-Specific Emission Factors for Grid Electricity, Ecometrica, 2011, pp. 1–22. Available at: https://ecometrica.com/assets/Electricity-specific-emission-factors-for-grid-electricity.pdf
[21] National Treasury, Republic of South Africa: Media Statement Publication of the 2019 Carbon Tax Act, 2019, pp. 10–13 Available at: http://www.treasury.gov.za.
[22] L.G. Acuña, M. Lake, R.V. Padilla, Y.Y. Lim, E.G. Ponzón, Y.C. Soo Too, Modelling autonomous hybrid photovoltaic-wind energy systems under a new reliability approach, Energy Convers. Manage., 172 (2018) 357–369.
[23] M.A. Al-Obaidi, G. Filippini, F. Manenti, I.M. Mujtaba, Cost evaluation and optimisation of hybrid multi effect distillation and reverse osmosis system for seawater desalination, Desalination, 456 (2019) 136–149.
[24] C. Koroneos, A. Dompros, G. Roumbas, Renewable energy driven desalination systems modelling, J. Cleaner Prod., 15 (2007) 449–464.
[25] Eskom, Schedule of Standard Prices for Eskom Tariffs 1 April 2019 to 31 March 2020 for Non-Local Authority Supplies, and 1 July 2019 to 30 June 2020 for Local Authority Supplies, 2019, pp. 1–48. Available at: http://www.eskom.co.za/CustomerCare/TariffsAndCharges/Documents/Eskom%20schedule%20of%20standard%20prices%202019_20%20Rev00%20%28full%20version%20excl%20Transflex%29.pdf
[26] C.D. Swartz, J.A. Du Plessis, A.J. Burger, G. Offringa, A desalination guide for South African municipal engineers, Water SA, 3 (2006) 641–647.
[27] T. Goga, E. Friedrich, C.A. Buckley, A LCA (Life Cycle Assessment) Comparison of Wastewater Reclamation and Desalination for the Ethekwini Municipality – A Theoretical Study, 2015. Available at: http://prg.ukzn.ac.za/docs/default-source/projects/wisa_2016-paper_taahira.pdf?sfvrsn=2
[28] Water and Sanitation Department City of Cape Town, Water Outlook 2018 Report, 2018, pp. 1–5. Available at: https://resource.capetown.gov.za/documentcentre/Documents/City%20research%20reports%20and%20review/Water%20Outlook%202018%20-%20Summary.pdf
[29] E.J. Okampo, N.I. Nwulu, Optimal energy mix for a reverse osmosis desalination unit considering demand response, J. Eng. Des. Technol., (2020) 1726–0531, doi: 10.1108/JEDT-01-2020-0025.