

Feasibility design of an optimized desalinator assisted only by solar energy. Case: Saudi Arabia

J. A. Biain*

Centro de Aplicaciones Informáticas y Modelado en Ingeniería (CAIMI), Universidad Tecnológica Nacional, Facultad Regional Rosario (UTN, FRRO), Zeballos 1346, S2000BQA Rosario, Argentina

Abstract

Desalinators are traditionally driven by fossil-fuels but in order to avoid greenhouse emissions, renewable energy must be used. In this paper, a coupling between multi-stage flash distillation apparatus and a parabolic trough solar collector is analyzed. The purpose of this study is to determine the economic feasibility of the system, considering four cities of Saudi Arabia and three different potable water productions. To avoid solar energy intermittency and unavailability at night, thermal storage is implemented. Whereas other researchers made parametric analyses, in this paper, the authors developed a mathematical program which was optimized with the help of GAMS software, where the capital cost of the plant was the objective function. After that, a life cycle cost analysis was carried out for each scenario. Depending on the region and water production, the costs of drinking water vary from 2.26 to 3.93 $US\$/m^3$, and from 7440 to 23825 tons of carbon dioxide emissions are avoided. As a consequence of the approach used, low costs are obtained; even though no auxiliary heater is implemented and the lowest irradiance conditions are considered. The results of this study reflect that the proposed process is competitive with respect to the traditional one.

Keywords: Economic, MSF process, Optimization formulation, Parabolic trough collector, Solar desalination.

1. Introduction

Industrialization and population fast growth has increased water demand. The problem is even greater if rivers and lakes pollution by industries and residual waste is considered. The only inexhaustible sources of water are the oceans. Their major drawback, however, is their high salinity. Taking into account fossil-fuel depletion and climate change, desalination powered by renewable energy is a necessity. In particular, solar desalination has applicability in arid regions where fresh water scarcity, solar resource abundance, and saline water availability coincide. This is the case in the Middle Eastern and North African region. Specifically, Saudi Arabia is the world's leading seawater desalinator, this is due both to the scarcity of freshwater sources and its abundant fossil energy resources. Solar-assisted desalination is attractive as a means of fossil resource conservation and limiting the carbon footprint of desalination.

Considering the drawbacks of solar desalination (such as high capital and maintenance costs, low production, and high amounts of terrain necessity), it is most suitable for small-scale production, especially in remote arid areas and islands where the supply of conventional energy is scarce; or in decentralized applications.

The idea of a desalination plant powered by solar energy is not new. The first large solar distillation plant was built in 1872 in Las Salinas, Chile [1]. It consisted of solar stills and it produced 22.70 m^3 of freshwater per day. Even though the total worldwide renewable energy desalination installations capacity is less than 1% of that of conventional fossil-fueled desalination plants [2], solar desalination plants coupled with conventional desalination systems have been installed in various locations of the world. Most of these plants are of experimental or demonstration scale. For example, [3] reports the performance of a 10 m^3/day solar MSF desalination system tested in Kuwait; [4] gives details

*Corresponding author

Email address: jbiain@frro.utn.edu.ar (J. A. Biain)

of an MES installed in Abu Dhabi, United Arab Emirates, where maximum daily distillate production corresponding to the optimum operating conditions was found to be $120 \text{ m}^3/\text{day}$, which can be obtained for 8 months of the year; and an MSF coupled with steam generating parabolic troughs which generates 48 kW to produce 450 L/day in three stages, with about 45 m^2 of collectors, and which water costs is $7.90 \text{ US}\$/\text{m}^3$ is presented in [5]. An example of feasibility analysis can be seen in [6], where an economic analysis of a solar-assisted desalination system, located in Cyprus, is made. Four types of application were considered, two domestic, a hotel, and a village. But, the presence of an auxiliary heater (fed by fossil fuel) is included, which is not the case in this work.

It is well known that the exclusion of an auxiliary heater is not economically advisable; even though, the author proposed here a 100% energetic sustainable approach, which motivation is to avoid greenhouse gases emission. Then, instead of an auxiliary heater driven by fossil fuels, thermal storage is implemented. It allows 24-hours operation and avoids solar energy intermittencies (which can cause operational inefficiencies). This feature allows us to use an MSF desalinator, which is the most extended desalination technology.

PTC technology was chosen because of its higher efficiency at higher working temperatures with respect to other collectors. For example, at $100 \text{ }^\circ\text{C}$ PTCs work at an efficiency of about 62%, CPCs at about 32%, and the FPC at about 10%. Moreover, the cost per unit area of the solar collecting surface is less in a PTC than that of a Flat-plate collector.

The novelty of the approach used here is that a model is optimized using mathematical program techniques, instead of using a sensitivity analysis.

The aim of this paper is to examine the economic feasibility of a multi-stage flash once through (MSF - OT) desalinator assisted only by a parabolic trough solar collector (PTC) for the case of four cities of Saudi Arabia.

The paper is organized as follows: Section 2 presents a description of the mathematical model used; then, in Section 3, availability of the solar resource is determined and optimal costs are obtained; in Section 4, the significance of these results are analyzed and a comparison with previous works is carried out; finally, conclusions are presented in Section 5.

2. Mathematical model

The system is modeled as a series of interconnected boundaries that include the operative and design equations that predict the behavior of their components. Then, the first block allows us to test the solar resource availability (determination of useful solar radiation hour by hour received by the collector in a known location and along the entire time horizon); a second block describes the optical-geometric-thermodynamic design of the collector; the third block refers to the thermal storage tank, which includes the time-dependent equipment model, where its dynamic relies on energy storage amount, storage temperature and fluid thermodynamic properties; a fourth block represents the heat exchanger which couples the solar caption and energy conservation system with the desalinator; finally, the fifth block is dedicated to designing and operating the desalinator (see Figure 1).

The main hypothesis assumed here include: a) no auxiliary heater, b) clear-sky model, c) stationary process, d) no heat loss in pipes, e) PTC modeled by Hottel-Whillier-Bliss (HWB) equation, f) PTC fixed N-S axis with E-W tracking, g) type M plant cost estimation, h) thermal energy storage (TES) fluid and heat transfer fluid (HTF) is water at 10 bar, i) perfectly mixed tank, k) MSF - OT.

With respect to the PTC, the author is interested mainly in its area, and that is why only one collector is considered. The Hottel-Whillier-Bliss equation used here is not affected by the number of pieces of equipment in parallel nor by the number of pieces of equipment in series.

For the first, second, and third boundaries the equations described by [7] were used; the specific correlations for Saudi Arabia needed in the first block were taken from [8]; the last two blocks were designed as described in [9]. Next, the main equations of each boundary are going to be mentioned.

2.1. 1st Boundary

$$G_{Bn} = A e^{\left(\frac{-P}{P_0}\right)\left(\frac{B}{\sin(\alpha)}\right)} \quad (1)$$

Where G_{Bn} refers to normal direct irradiance (W/m^2), A and B are correlation parameters (W/m^2 and dimensionless, respectively), P/P_0 refers to the ratio between local pressure and standard pressure ($P_0 = 101325 \text{ Pa}$) and α refers to solar altitude angle (rad).

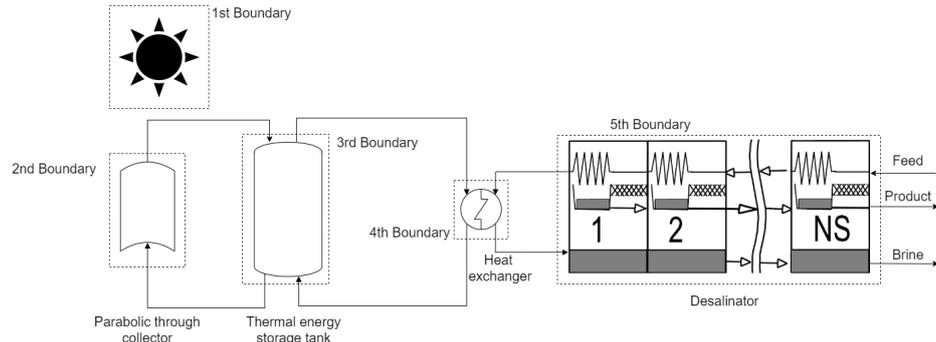


Figure 1: Equipment coupling

2.2. 2nd Boundary

$$Q_u = FR[G_B \eta_o A_a - A_r U_L (T_i - T_a)] \quad (2)$$

Where Q_u refers to useful energy delivered from a concentrator (W), FR refers to heat removal factor (dimensionless), G_B refers to direct irradiance (W/m^2), η_o refers to optical efficiency (dimensionless), A_a refers to the PTC's aperture area (m^2), A_r refers to the external area of the receiver cover (m^2), U_L refers to loss coefficient ($W/(m^2K)$), T_i refers to the inlet HTF temperature (K) and T_a refers to ambient temperature (K).

2.3. 3rd Boundary

$$T_{s-n} = T_s + \frac{\Delta t}{m_s c_{p_s}} [Q_u - Q_L - (UA)_s (T_s - T_a)] \quad (3)$$

Where T_{s-n} refers to the new TES fluid temperature (K), T_s refers to the previous TES fluid temperature (K), Δt refers to time interval (s), m_s refers to mass of the TES fluid (kg), c_{p_s} refers to specific heat capacity of the TES fluid ($J/(kgK)$), Q_L refers to heat load (W) and $(UA)_s$ refers to the TES tank conductance-area (W/K).

2.4. 4th Boundary

$$Q_L = U_{HX} A_{HX} \Delta T' \quad (4)$$

Where U_{HX} refers to the heat exchanger (HX) global heat transfer coefficient ($Kcal/(m^2Kh)$), A_{HX} refers to the HX heat transfer area (m^2) and $\Delta T'$ refers to the temperature difference between HX streams (K) (it is assumed that the driving force is constant through the HX),

2.5. 5th Boundary

$$A_t = \frac{FF C_{p_m}}{U_d} NS \log\left(\frac{\Delta T - BPE}{\Delta T_e}\right) \quad (5)$$

Where A_t refers to the heat transfer area of the desalinator (m^2), FF refers to the seawater feed (kg/h), C_{p_m} refers to the specific heat capacity of the seawater ($kcal/(kgK)$), U_d refers to desalinator global heat transfer coefficient ($Kcal/(m^2Kh)$), NS refers to the ideal number of flashing stages (dimensionless), ΔT refers to seawater temperature increase at HX (K), BPE refers to brackish boiling point elevation (K) and ΔT_e refers to effective temperature difference in each stage for heat recovery (K).

Parameter	Value adopted
interest rate	0.02 [19]
inflation rate	0.022 [19]
discount rate	0.045 [19]
project length	20 years [6]

Table 1: Economical Parameters

Parameter	Value adopted
Reflectance of PTC's mirror [dimensionless]	0.9 [20]
Transmittance of PTC's glass cover [dimensionless]	0.97 [20]
Absorptance of PTC's receiver [dimensionless]	0.98 [20]
Emissivity of PTC's glass cover [dimensionless]	0.86 [20]
TES tank conductance-area [W/K]	11 [7]
Temperature difference between HX streams [K]	10
Brackish boiling point elevation [K]	2 [21]
Desalinator global heat transfer coefficient [$Kcal/(m^2 Kh)$]	1719.69 [21]

Table 2: Main parameters

2.6. Algorithm implementation

For the system established in Figure 1, a trade-off between PTC's area and desalinator's area shows up, that is, as desalinator's area increases, the amount of heat needed in the HX decreases, and in consequence PTC's area also decreases. Then, the question that arises is, which is best? To answer it, a cost function is formulated (see equation 6) which takes into account PTC's aperture area (A_a , in m^2), desalinator's chamber area (AS , in m^2), desalinator's heat transfer area (A_t , in m^2), HX area (A_{HX} , in m^2) and TES volume (v_{tk} , in m^3). The following references were consulted [10–13].

$$Cost = 150A_a^{0.95} + 50(A_t + 20 AS) + 1.95 \cdot 10^{2.1138+0.9658\log_{10}(A_{HX})} + (5700 + 700v_{tk}^{0.7}) \quad (6)$$

The collection of equations 1 - 5 and those not mentioned here, constitute the equality, $h(x)$, and inequality, $g(x)$, equations of the mathematical program proposed, which is solved by GAMS software with CONOPT solver [14].

Minimize Cost

$$\text{subject to } \begin{cases} h(x) = 0 \\ g(x) \leq 0 \end{cases}$$

2.7. Life Cost Cycle Analysis

After the optimal design is obtained, Life Cost Cycle Analysis (LCCA) is performed. To do this, first, the following costs must be computed: installed equipment costs, process piping, instrumentation, building and site development, auxiliaries, outside lines, engineering and construction, contingencies, and size factor; as established in method 3 (estimated type M) from [15]. The maintenance is analyzed in two parts; for tracking collector, maintenance is assumed to be 2% of the initial investment, inflated 1% per year of system operation [16]; and for the other pieces of equipment, maintenance is assumed to be 10% of the fixed capital cost, as stated in [17]. It is also estimated that the system is sold at the end of its life at 30% of the initial cost (i.e. its resale value) [18].

The discounted cash flow (DCF) is computed with the present worth factor (PWF) and the net cash flow for each year. The aim is to adjust the unitary cost so that the summation of every DCF is equal to zero. Several parameters were used (see tables 1, 2 and 3).

Parameter	City			
	Dhahran	Jizan	Yanbu	Jeddah
Ambient temperature [K] [22]	300	303	300	302
Sea water temperature [K] [22]	303	303	300	300
Sea water concentration [ppm] [21, 23]	42000	42070	42070	42070
Local altitude above sea level [m]	45	40	10	12
Latitude [°]	26.3	16.89	24.029	21.48
Wind speed [m/s] [22]	4.4	3.3	3.9	4.1

Table 3: Location parameters

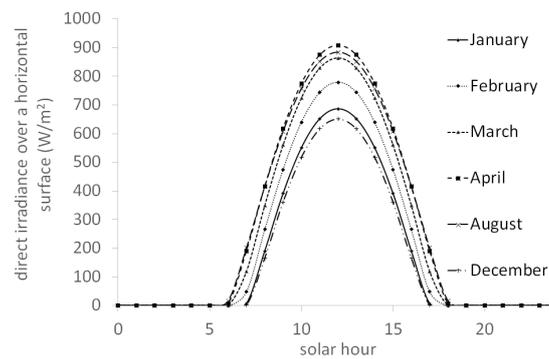


Figure 2: Monthly irradiance at Dhahran, Saudi Arabia

3. Results

3.1. Monthly irradiance

From the equations developed in the 1st block, the direct irradiance over a horizontal surface is calculated for every region and a typical day of every month of the year; as an example, in Figure 2, Dhahran city levels are shown (for greater clearness only representative months are shown). The other cities have similar graphs. There, it can be seen that the least monthly irradiance value corresponds to December (this result is valid for all regions). Given that a completely sustainable approach is here proposed, the design is developed for this month.

3.2. Optimization as function of water production

Next, main results of different production levels are shown (see Tables 4, 5, 6 and 7). To perform the calculations shown there, the following parameters were used: for utility avoided calculation, a 7.78 US\$/GJ cost was used, which corresponds to a low pressure service (160 °C) [24]; for CO₂ emission avoided calculation, a replacement of the PTC by a natural gas boiler was supposed, with a Lower Heating Value (LHV) equal to 8750 kcal/m³ [25]; for the drinking water production calculation, a value of 235 L/(m²day) of water consumption was used [26].

4. Discussion

Despite locations being different, a comparison with other works is presented below. In Zarza et al. [27, 28], a 14-effect MEB plant with a nominal output of 72 m³/day coupled with 2672 m² of PTCs was reported. The system is installed at the Plataforma Solar de Almeria in southern Spain. It also incorporates a 155 m³ thermozone thermal storage tank. The circulated fluid through the solar collectors is a synthetic oil heat transfer fluid. Interpolating for 72 m³/day in Jizan, an aperture area of 1979 m² (26% less) and a tank volume of 78.59 m³ (49% less) is got. In Kalogirou [18] the following results are reported: aperture area of 2160 m² and (worst month) production of 0.37 m³/day. Interpolating in Jizan for an aperture area of 2160 m², a production of 82.426 m³/day (222.7 times greater) is got. Costs, on the other hand, are very similar, his reported cost (solar only) is 2.28 US\$/m³, meanwhile, this

Variable	Population [people]		
	250	550	950
Production [m^3/day]	58.8	129	223.2
TES volume [m^3]	61	136	213
Delivered equipment cost [US\$]	478467	791308	1200985
Total plant or fixed capital cost [US\$]	1388751	2296771	3485860
Water cost [US\$/ m^3]	3.81	2.88	2.52
Heat transferred [W]	215835	426583	612774
Avoided utility [US\$]	1059104	2093246	3006885
Avoided CO_2 [ton]	8039	15889	22825
HX transfer area [m^2]	11	21	31
MSF heat transfer area [m^2]	151	414	855
MSF chamber area [m^2]	255	367	591
PTC aperture area [m^2]	1895	3739	5372
$L/(m^2 day)$	31.0	34.5	41.5

Table 4: Dhahran

Variable	Population [people]		
	250	550	950
Production [m^3/day]	58.8	129	223.2
TES volume [m^3]	69	120	196
Delivered equipment cost [US\$]	434633	727877	1074384
Total plant or fixed capital cost [US\$]	1261523	2112662	3118399
Water cost [US\$/ m^3]	3.46	2.64	2.26
Heat transferred [W]	249224	424151	639623
Avoided utility [US\$]	1222941	2081308	3138631
Avoided CO_2 [ton]	9283	15799	23825
HX transfer area [m^2]	12	21	32
MSF heat transfer area [m^2]	133	384	787
MSF chamber area [m^2]	225	379	552
PTC aperture area [m^2]	1748	2976	4488
$L/(m^2 day)$	33.6	43.4	49.7

Table 5: Jizan

Variable	Population [people]		
	250	550	950
Production [m^3/day]	58.8	129	223.2
TES volume [m^3]	85	241	530
Delivered equipment cost [US\$]	493490	861766	1274196
Total plant or fixed capital cost [US\$]	1432355	2501275	3698353
Water cost [US\$/ m^3]	3.93	3.13	2.68
Heat transferred [W]	199743	390298	591802
Avoided utility [US\$]	980137	1915195	2903973
Avoided CO_2 [ton]	7440	14538	22044
HX transfer area [m^2]	10	20	30
MSF heat transfer area [m^2]	155	420	875
MSF chamber area [m^2]	269	437	626
PTC aperture area [m^2]	1873	3630	5490
$L/(m^2 day)$	31.4	35.5	40.7

Table 6: Yanbu

Variable	Population [people]		
	250	550	950
Production [m^3/day]	58.8	129	223.2
TES volume [m^3]	60	120	195
Delivered equipment cost [US\$]	463541	790528	1157166
Total plant or fixed capital cost [US\$]	1345426	2294507	3358675
Water cost [$US\$/m^3$]	3.69	2.87	2.43
Heat transferred [W]	214285	403372	611700
Avoided utility [US\$]	1051499	1979345	3001611
Avoided CO_2 [ton]	7982	15025	22785
HX transfer area [m^2]	11	20	31
MSF heat transfer area [m^2]	144	398	816
MSF chamber area [m^2]	251	403	574
PTC aperture area [m^2]	1796	3379	5129
$L/(m^2day)$	32.7	38.2	43.5

Table 7: Jeddah

work best cost is $2.26 US\$/m^3$. In El-Nashar and Samad [29] an analysis of solar desalination plant in Abu Dhabi is made. The plant was designed for yearly average fresh water production of $80 m^3/day$ using seawater having a design salinity of 55,000 ppm. A bank of evacuated tube, flat plate collectors having a total absorber area of $1862 m^2$ is used to provide the thermal energy required by a multiple effect stack-type (MES) desalination unit. A thermally stratified heat accumulator with a capacity of $300 m^3$ is incorporated. Interpolating in Jizan for a productivity of $80 m^3/day$, an aperture area of $2118.86 m^2$ (14% more) and a tank volume of $84.4 m^3$ (72% less) is got. Notice that El-Nashar and Samad used FPCs and a thermally stratified tank. In Fiorenza et al. [30] water production cost for seawater desalination by MED powered by a solar thermal field has been estimated. The results obtained for plants of capacity varying between 500 and $5000 m^3/day$ have shown that the cost of water produced can be reduced by increasing the plant capacity; i.e. $3.2 US\$/m^3$ for the $500 m^3/day$ plant capacity and $2 US\$/m^3$ for the $5000 m^3/day$ plant capacity. These costs are similar to the ones obtained in this work.

The advantage of the mathematical programming approach here considered is exposed when the parameter $L/(m^2day)$ is observed, taking into account that the worst condition was assumed. Parameter $L/(m^2day)$ values generally oscillates from 6 to 60, here varies from 31.4 to 49.7.

Taking into account the environmental friendliness of this approach (7440 to 23825 tons of carbon dioxide emissions are avoided) and that water prices are like analogous approaches, the authors considered these results encouraging.

Even though MES is the best suitable technology to be coupled with solar energy, [29] reported that their analyzed evaporator has experienced a substantial drop in performance compared to its initial performance after 13 years of use.

It worth mentioning that for Jizan's case, the fixed capital costs are very similar to utility costs avoided. In other regions, fixed capital costs represent an excess of between 12% and 46% with respect to utility cost avoided.

As price reference, in [31] it can be observed that for Persian Gulf, desalinated water cost is $0.84 US\$/m^3$ if MSF is used, 1.21 to $1.34 US\$/m^3$ if MEB is used and 1.23 to $1.36 US\$/m^3$ if RO is used. Although the author's approach is not enough to compete with current costs (the costs of drinking water vary from 2.26 to $3.93 US\$/m^3$), it is still worth for remote zones or for consideration of a subsidy.

5. Conclusion

In this work, a coupling between a parabolic trough solar collector with a system which includes a heat storage tank, a heat exchanger, and a multi-stage flash desalinators is proposed, with the objective of making desalination sustainable. After solar availability was analyzed in four regions, optimization of the system, considering different production levels of drinking water, was carried out. From the results obtained it is concluded that the lowest optimized

price in the scenarios here adopted, doubled the current price from the traditional desalination process. Nevertheless, the project here proposed is completely energy sustainable which is a priceless feature. It is expected that in the future the lack of fossil fuels will increase its price, and then this approach will be more economically interesting.

Acknowledgements

The author gratefully acknowledges the financial support given by the Universidad Tecnológica Nacional (UTN).

References

- [1] J. Harding, Apparatus for solar distillation, Minutes of the Proceedings of the Institution of Civil Engineers 73 (1883) (1883) 284–288. doi:10.1680/imotp.1883.21702.
- [2] E. Delyannis, Historic background of desalination and renewable energies, Solar energy 75 (5) (2003) 357–366. doi:10.1016/j.solener.2003.08.002.
- [3] S. Moustafa, D. Jarrar, H. El-Mansy, Performance of a self-regulating solar multistage flash desalination system, Solar Energy 35 (4) (1985) 333–340. doi:10.1016/0038-092X(85)90141-0.
- [4] A. El-Nashar, Optimizing the operating parameters of a solar desalination plant, Solar energy 48 (4) (1992) 207–213. doi:10.1016/0038-092X(92)90092-0.
- [5] W. Teplitz-Sembitzky, The use of renewable energies for seawater desalination-a brief assessment, Gate Technical Information W10e (2000) 1–8.
- [6] S. Kalogirou, Economic analysis of a solar assisted desalination system, Renewable energy 12 (4) (1997) 351–367. doi:10.1016/S0960-1481(97)00063-3.
- [7] S. A. Kalogirou, Solar Energy Engineering (Second Edition), Amsterdam: Academic Press, 2014.
- [8] M. Abouhashish, Applicability of ashrae clear-sky model based on solar-radiation measurements in saudi arabia, AIP Conference Proceedings 1850 (1) (2017) 140001. doi:10.1063/1.4984509.
- [9] N. Rodriguez, Síntesis de procesos complejos minimizando el impacto ambiental. aplicación a procesos de cogeneración de vapor y energía eléctrica y sistemas de desalación de aguas acoplados a uno de generación eléctrica, Ph.D. thesis, Universidad Tecnológica Nacional Facultad Regional Córdoba (2015).
- [10] N. Voros, C. Kiranoudis, Z. Maroulis, Solar energy exploitation for reverse osmosis desalination plants, Desalination 115 (1) (1998) 83–101. doi:10.1016/S0011-9164(98)00029-0.
- [11] N. Scenna, S. Mussati, Msf design taken into account availability, Desalination 222 (1-3) (2008) 673–681. doi:10.1016/j.desal.2007.01.195.
- [12] C. A. Henao Uribe, Simulación y evaluación de procesos químicos, Universidad Pontificia Bolivariana, 2012.
- [13] G. Towler, R. Sinnott, Chemical engineering design: principles, practice and economics of plant and process design, Elsevier, 2012.
- [14] A. Drud, Conopt solver manual, ARKI Consulting and Development, Bagsvaerd, Denmark.
- [15] F. C. Vilbrandt, C. E. Dryden, Chemical Engineering Design (Fourth Edition), McGraw-Hill, 1959.
- [16] S. Kalogirou, The potential of solar industrial process heat applications, Applied Energy 76 (4) (2003) 337–361. doi:10.1016/S0306-2619(02)00176-9.
- [17] R. S. Aries, R. D. Newton, Chemical engineering cost estimation, McGraw-Hill, 1955.
- [18] S. Kalogirou, Use of parabolic trough solar energy collectors for sea-water desalination, Applied Energy 60 (2) (1998) 65–88. doi:10.1016/S0306-2619(98)00018-X.
- [19] A. Almarshoud, Technical and economic performance of 1 mw grid-connected pv system in saudi arabia, International Journal of Engineering Research and Application 7 (4,(Part- 1) (2017) 09–17. doi:10.9790/9622-0704010917.
- [20] R. Forristall, Heat transfer analysis and modeling of a parabolic trough solar receiver implemented in engineering equation solver, Tech. rep., National Renewable Energy Lab., Golden, CO.(US) (2003). doi:10.2172/15004820.
- [21] H. El-Dessouky, I. Alatiqi, H. Ettouney, Process synthesis: the multi-stage flash desalination system, Desalination 115 (2) (1998) 155–179. doi:10.1016/S0011-9164(98)00035-6.
- [22] Weather spark: The typical weather anywhere on earth, <https://weatherspark.com>, accessed: 2020-05-28 (2020).
- [23] E. Abdel-Aal, M. Farid, F. S. Hassan, A. E. Mohamed, Desalination of red sea water using both electro dialysis and reverse osmosis as complementary methods, Egyptian Journal of Petroleum 24 (1) (2015) 71–75. doi:10.1016/j.ejpe.2015.02.007.
- [24] W. L. Luyben, Principles and Case Studies of Simultaneous Design, John Wiley & Sons, Inc., 2011.
- [25] C. J. Cleveland, C. G. Morris, Handbook of Energy: Diagrams, Charts, and Tables (Vol. 1), Elsevier Science, 2013.
- [26] W. A. Abderrahman, Water management in arriyadh, Water Resources Development 22 (2) (2006) 277–289. doi:10.1080/07900620600654785.
- [27] E. Zarza, J. Ajona, J. León, A. Gregorzewski, K. Genthner, Solar thermal desalination project at the plataforma solar de almeria, In: Proceedings of the Biennial Congress of the International Solar Energy Society 1 (part II) (1991) 2270–2275.
- [28] E. Zarza, J. I. Ajona, J. Leon, K. Genthner, A. Gregorzewski, G. Alefeld, R. Kahn, A. Hablerle, J. Gunzbourg, J. Scharfe, C. Cord'homme, Solar thermal desalination project at the plataforma solar de almeria, in: Proceedings of the New Technologies for the Use of Renewable Energy Sources in Water Desalination, no. sec. III, 1991, pp. 62–81.
- [29] A. M. El-Nashar, M. Samad, The solar desalination plant in abu dhabi: 13 years of performance and operation history, Renewable energy 14 (1-4) (1998) 263–274. doi:10.1016/S0960-1481(98)00076-7.
- [30] G. Fiorenza, V. Sharma, G. Braccio, Techno-economic evaluation of a solar powered water desalination plant, Energy conversion and management 44 (14) (2003) 2217–2240. doi:10.1016/S0196-8904(02)00247-9.

[31] M. Fichtner, Regional water outlook. part 2, Desalination Using Renewable Energy Final Report.