International Journal of Smart Grid and Clean Energy

Optimum design of PV-RO system solar-powered sea water desalination without storage in Saudi Arabia (Case study)

Khalid Al-Shail[a], Javier Ordoñez[b]

[a]*Saline Water Conversion Corporation, Desalination Technologies Research Institute, KSA*
[b]*Department of Construction & Engineering Projects, University of Granada, Spain*

Abstract

Bad effects associated with drinking water are a serious problem in regions with low freshwater supplies and high frequency of droughts, just like Saudi Arabia. Desalination of water is an excellent solution to this issue, but this process uses a great deal of energy, which mainly comes from fossil fuels. Power provided by photovoltaic cells for desalination provides a cleaner and cost-effective substitute. The focus of this survey is to find means to run reverse osmosis desalination plants by the electricity generated by solar cells without storage to find the cost per unit electricity (kWh), and to estimate the highest energy percentage, which can be generated by solar panels in the day time. That is the reason why a reverse osmosis plant was selected for the case study. The data for solar power produced and consumed for desalination of brackish water into potable water is based on actual measurements acquired from the direct observation of a reverse osmosis desalination facility located in Saudi Arabia. It was observed that during summer months, a larger amount of solar energy are produced compared to the winter months because of greater daylight hours in summer. It was found that the maximum electrical power generated at midday by the photovoltaic solar plant lies within the range of 9.15 MWh to 17.95 MWh. By studying the results of the chosen plant as a case study, it was found that the percentage of non-usable energy is less than 2% in a plant whose size is 20 MW. In this case, 20 percent of total consumed energy could be provided at a price of around 0.025 €/kwh. The expenses for power produced exceeds 0.043 €/kwh when the plant is greater than 60 MWp.

Keywords: Resource monitoring and mapping program, reverse osmosis, desalination, photo voltaic cell, renewable energy

1. Introduction

1.1. Water availability issues around the world

Water shortage has emerged as a crucial problem in many parts of the globe. Two major key players are there to intensify this problem; the first one is the climate change in the world, and the second one is the excessive use of fresh water. It is estimated that global temperature will rise from 1.4 to 5.8 Celsius until 2100 [1]. The water cycle is closely associated with these variations and, consequently, the quality of water is being affected significantly. The Middle East region, in general, and the Gulf Cooperation Council (GCC) countries (including Saudi Arabia), in specific, are badly exposed to intense shortage of water, mainly by significant growth in population, fast expansion in industry and ever-increasing droughts [2]. Saudi Arabia, ranked 13th in the world, is enjoying the status of the biggest state in the Arabian Peninsula. The mean naturally occurring water resources per person is 6000 m3 across the globe, while the estimated figure for Saudi Arabia is 84.8 m3 per person [1]. On the other hand, the total intake of

* Manuscript received December 6, 2020; revised June 17, 2021.
Corresponding author. *E-mail address*: kalshail13@gmail.com
doi: 10.12720/sgce.10.3.224-233

water per person is 250 L in Saudi Arabia, which is the third-highest in the world, and it is estimated to rise by 30% by 2035. [3]. It is predicted that if the country continues to withdraw the freshwater resources at the current rate, aquifer reserves will satisfy the current needs for only three more decades at best [3]. Under the prevailing situation, water desalination is the best strategic choice for resolving the water shortage issues.

1.2. Desalination is Saudi Arabia

In 1907, the first large capacity plant for water desalination was constructed in Saudi Arabia. In 1928, a multistage flash plant for water desalination, with the ability to produce 227 m3 per day, was built in Al-wajh & Doha. In 2010, Saudi Arabia used 6% of the water needs with desalinated processed water, 2.2 % through reused wastewater, and 33.5% using surface water in 2010 [4]. The situation was improved in 2014, and Saudi Arabia produced 60% of its entire water needs through desalinated water [5]. In 2016, desalinated water supplies enhanced by 827 million m^3 in 2 thousand to 1377 million m^3 and consequently touched 18 hundred million m^3 in 2018 [6,7]. In accordance with this situation, plants for desalination in diverse sizes and implementing different technologies were designed and developed by the corporation for saline water conversion in Saudi Arabia. These plants have a capacity of 44,000 - 947,890 m^3/ day. Table I provides data about the desalination plants presently working with their starting time, the technology employed, and lifetime duration. It can be observed that with strict quality control and operation, and with proper maintenance, several plants have exceeded their expected lifetime.

The technologies used for desalination of water are subdivided into two types: phase and non-phase change processes. Multi-effect distillation (MED), Multi-stage flash (MSF), and mechanical vapor compression (MVC) are considered phase change processes, while reverse osmosis is considered a non-phase change process. The most frequently used technique for water desalination is reverse osmosis. It is used in 63% of desalination plants across the globe, while MSF is the second most used technology, which is applied in more than 23% of desalination plants around the world [8]. MSF and MED are particularly suited for integration into cogeneration plants, where they can utilize the waste thermal energy, leaving the turbine to produce fresh water [9]. Due to its ability to integrate into cogeneration plants and their large capacities, MSF makes 87% of total desalination plants in Saudi Arabia, as Fig. 1 shows [7]. Water desalination is a highly energy-intensive process. Today, Saudi Arabia consumes 25% of its total gas and oil resources for desalination plants. This ratio is likely to reach a level of 50% in 2030 [4].

All types of desalination technologies need some form of energy. In reverse osmosis, electrical energy is utilized to keep the pressure constant at a value more than the relative osmotic pressure. On the other hand, MED and MSF, which are known as thermal desalination technologies, need thermal energy for the vaporization of feed water. Fossil fuel is being used in most plants for desalination in the present day, and fuel cost is a major portion of the total production cost of desalination plants. 20-25% of entire energy resources are being used by plants for desalination in Saudi Arabia. This consumption has risen by eighty-four percent, starting from 1980 to 2010 [10,11]. Table II presents consumption data of the energy used by prominent technologies for water desalination. [12]. The minimum energy uptake by reverse osmosis process is observed in the form of electricity. The natural osmotic process uses a special type of membrane for separation of water, but in reverse osmosis, a totally different effect is achieved. A new type of chemical potential of water is used on both sides to convert water with larger salt contents to a solution possessing lower salt contents.

Table I. Plants for desalination presently in service in the Kingdom of Saudi Arabia (2018) [7].

No. [a]	Service Area	Location	Technology used	Year of Commission	End of Life	Export Design[b]	Water Production[b]
1	Tabuk	**Haql-II**	**RO**	**1990** (27)	**2015** (+2)	**4954**	**5,760**
2		**Duba-III**	**RO**	**1989** (28)	**2014** (+3)	**4954**	**5,760**
3		Al-Wajih-III	MED	2009	2034	7740	9,000
4		**Umlujj-II**	**RO**	**1986** (31)	**2011** (+6)	**3784**	**4,400**

5		Umlujj-III	MED	2009	2034	7740	9,000
6	Makkah	Rabigh-II	MED	2009	2034	15480	18,000
7		Al-azizia	MED	1987 (30)	2012 (+5)	3870	4,500
8		Laith	MED	2009	2034	7740	9,000
9		Al-qunfudah	MED	2008	2033	7740	9,000
10	Jizan	Farasan-II	MED	2009	2034	7740	9,000
11	Makkah	Jeddah-IV	MSF	1982 (37)	2007 (+10)	190,555	221,575
12		Jeddah-I	RO	1989 (28)	2014 (+3)	48,848	56,800
13		Jeddah-II	RO	1994	2019	48,848	56,800
14		**Jeddah-III**	**RO**	**2013**	**2038**	**206,400**	**240,000**
15	Makkah	Shoaiba-I	MSF	1989 (28)	2014 (+3)	191,780	223,000
16	Al-baha	Shoaiba-II	MSF	2001	2026	391,300	455,000
17	Makkah	Yanbu-I	MSF	1981 (38)	2006 (+11)	86,688	100,800
18		Yanbu-II	MSF	1998	2023	123,675	143,808
19		**Yanbu**	**RO**	**1998**	**2023**	**109,908**	**127,800**
20	Al-madinah	Yanbu-Exp	MED	2013	2038	58,643	68,190
21 22	Asier Jizan	Shoqaiq	MSF	1989 (28)	2014 (+3)	83,432	97,014
23	Al-sharqiah	Al-Jubail-I	MSF	1982 (37)	2007 (+10)	118,447	137,729
24	Al-Riyadh	Al-Jubail-II	MSF	1983 (36)	2008 (+9)	815,185	947,890
25	Al-qasim	**Al-Jubail-III**	**RO**	**2000**	**2025**	**78,182**	**90,909**
26	Al-sharqiah	Al-Khobar-II	MSF	1983 (36)	2008 (+9)	191,780	223,000
27		Al-Khobar-III	MSF	2000	2025	240,800	280,000
28		**Ras-Al-Khair**	**RO**	**2014**	**2039**	**307,500**	**310,656**
29	Al-Riyadh	Ras-Al-Khair	MSF	2040	2015	717,500	740,656
30	Al-sharqiah	Al-Khfji	MSF	1986 (31)	2011 (+6)	19,682	22,886

a. 1-10 West Coast (Satellite Plant), 11-122 West Coast (Large Plant), 23-30 East Coast (Large Plant)
b. (m3/day)

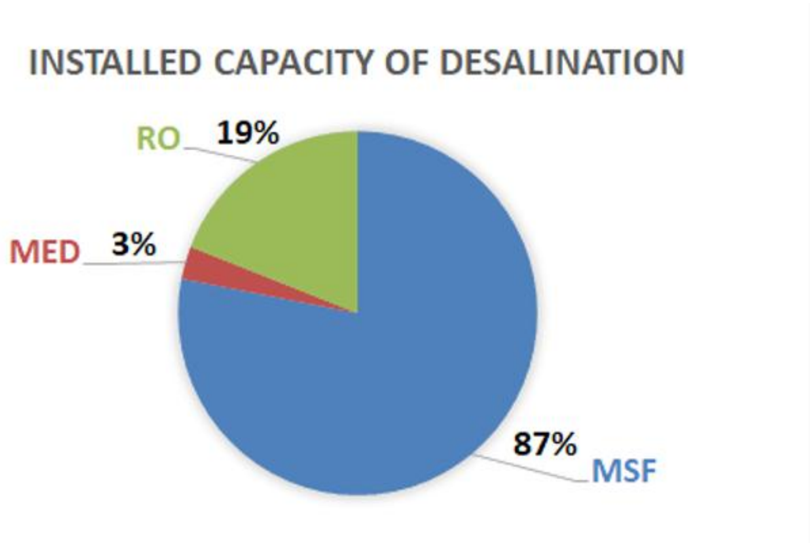

Fig. 1. Capacity of installed desalination plants in KSA by desalination technology types.

Table 2. Desalination technologies and their energy requirements

Technology	Heat utilized (kJ/kg)	Electrical energy (kWh/m^3)
Vapor compression (VC)	-	8-15
Multiple stage flash (MSF)	250-330	3-5
Reverse Osmosis (RO)	-	2.5-7
Multi effect desalination (MSD)	145-39	1.5- 2.5

2. Motivation

Vision 2030 is a program declared by Saudi Arabia in April 2016. The motive behind this vision is to switch over Saudi Arabian financial resources from exports of oil and related goods, which are to be diminished in future, to any other sustainable alternatives. To start with, a plan was launched for the production of renewable energy resources figured at 9.5 GW by 2030. On one side, this plan is forecast to give a boost to the economy of the country along with the reduction of fossil fuel consumption plus having a good impact on the ecological system [13, 14]. The earth's surface receives great amounts of solar energy, and has no match among other sources of energy available. Whether solar energy is harnessed by concentrating solar power (CSP) or using photovoltaic (PV) panels, there is plenty of potential for solar energy in Saudi Arabia.

Fig. 2 represents the direct normal irradiation (DNI) and global horizontal irradiation (GHI) in Saudi Arabia [15], while Fig. 3 shows those two indicators, in addition to a third indicator, which is the diffuse horizontal irradiation (DHI) [16].

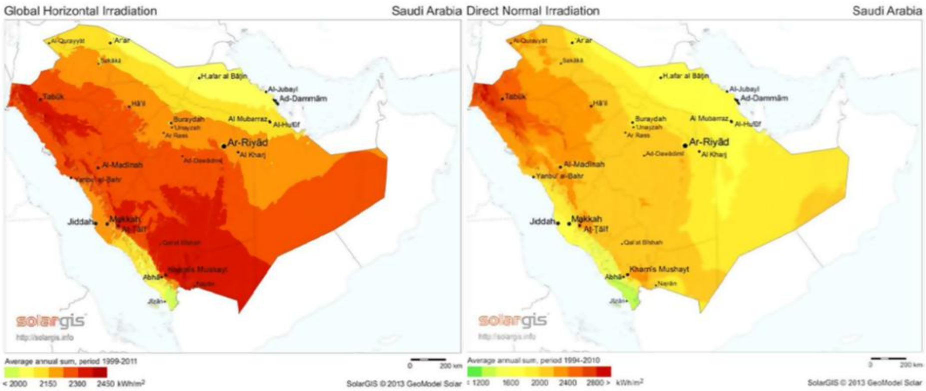

Fig. 2. Global direct normal irradiation & horizontal irradiation GHI in KSA from 1999 to 2011.

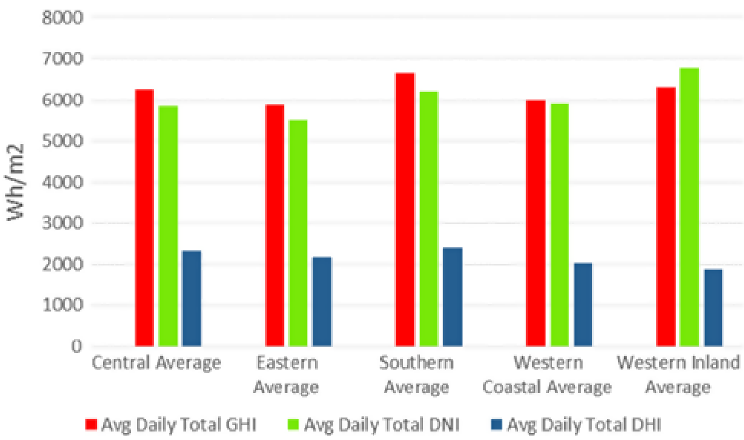

Fig. 3. A review from October 2013 to September 2014 for solar irradiance by region in Saudi Arabia.

The main objective of this study is to explore the feasibility of integrating reverse osmosis desalination with PV panels without using batteries for the purification of water in Saudi Arabia. For the identification of potential, an economic study was carried out with the aim of finding the per unit (KWh) cost for solar energy. In addition, the optimum energy ratio which could be extracted through a PV plant in a day span is also investigated. For the purpose of this case study, the reverse osmosis plant was selected to be in Saudi Arabia on the coast of the Arabian Gulf. The figures showing energy utilization are based on a one-year actual data from the selected reverse osmosis plant. Solar radiation data from Saudi Arabia's renewable resources monitoring and mapping program was acquired, and it was used to calculate the energy generated by the PV panels and the cost per kWh, as well as the percentage of electrical energy consumption that can be generated by PV [17]. In the end, for the purpose of analysis of feasibility integration between reverse osmosis desalination and solar energy, the energy requirement for the purification plant which could be provided by PV panels, was investigated.

3. Method Applied

To achieve the stated objective, the study was carried out in accordance with the guidelines provided in Modi and Stodola, 2009 [18]. To conduct the research, data of hourly energy consumption in an existing desalination plant situated in Ras Al Khair, Saudi Arabia was acquired. The location of the plant is 27 °32' 12.12" North and 49 °8' 20.4" East, and it is located 90 kilometers north of the city of Al Jubail. The energy consumption data of this plant was examined thoroughly as a case study in order to forecast the amount of solar radiation needed based on the PV system efficiency [19, 20]. As mentioned earlier, direct and solar radiation data was obtained from Saudi Arabia's renewable resources monitoring and mapping program. To assess the feasibility of using PV panels to operate a reverse osmosis desalination plant, a solar PV plant was designed. To bridge the gap between the energy consumed by the reverse osmosis plant and the energy generated by the PV plant, we used the same plants that utilize fossil fuel as an energy source. To attain the electrical energy produced by the PV plant, we calculated the amount of solar plant generated energy on an hourly basis. Direct fraction of solar radiation (H_b), which approaches the surface of the earth without scattering or absorption by the atmosphere, is called direct beam solar radiation, while the scattered radiation which is assumed to hit the surface of the earth from all directions, is labelled as diffused radiation (H_d). The amount of H_d varies, depending upon the forecast conditions. Diffuse radiation varies from 10% of the entire radiation on a clear day to approximately a hundred percent on a cloudy day. Reflected radiation (H_r) from the surroundings and earth surface also needs to be taken into consideration [18]. The total global radiation (H) comprising of diffuse, direct, and reflected radiation, is given by:

$$H=H_r+H_d+H_b \tag{1}$$

The total amount of energy hitting the panel was determined by the incidence angle of sunlight for every point in time for each arrangement [20].

$$I_{panel}=I_{beam}\cdot\cos\theta+I_{ddiffuse}\cdot F_{ps} \tag{2}$$

where

- I_{panel} = Total radiation on the panel
- I_{beam} = Direct radiation on the panel
- θ is referred as to 90 degrees when sun raise is parallel to the panel and 0 degrees when perpendicular to panel.
- $l_{ddiffuse}$ = Diffuse radiation on the panel
- The terms F_{ps} and F_{pg} are considered as view parameters: These are the geometric terms used for the description of part of the ground or sky that is directly exposed to the panel.

Solar radiation at Ras Al-khair that affects the panels of the photovoltaic solar plant can be used for determining the amount of solar plant generation. In terms of energy, the variation of cost with the power of photovoltaics is used to obtain the curve that describes the plant power & price of produced electrical energy. Likewise, different values of the performance ratio of the plant have been assumed. The performance ratio (PR) allows to evaluate the quality of a photovoltaic installation calculated as the relationship between the real energy generated by the plant and the theoretical energy that can be generated. This ratio is independent of the orientation of a photovoltaic installation and the solar irradiation that affects it and allows to compare the operation of different facilities. The photovoltaic solar plant for each one of the peak powers was defined, and the cost of the KWh generated by each one of the plants which were calculated was examined.

To calculate the price estimation of electrical energy, to calculate the reimbursement for borrowed money on the basis of fixed payments & fixed interest ratio were obtained. Considering that the start of the period is the point when reimbursement becomes due.

$$Q=\frac{Pv}{1+(1-(1/(1+r)^{n})} \tag{3}$$

where

- Q per annum payment of borrowed money on the basis of fixed payments & fixed interest ratio.
- Pv Current evaluation. That is the total price of PV solar power plants.
- r loan interest rate.
- n twenty-five years.

To obtain the cost per kWh of electricity from the PV solar plant, it is necessary to divide Q (per annum payment of borrowed money on the basis of fixed payments & fixed interest ratio) by the usable energy.

$$P=\frac{Q}{\text{Usable energy (KWh)}} \tag{4}$$

where P = price of kWh.

4. Case Study Results

The first objective of this research work is to optimize energy from the sun, which can be used according to the energy utilization curve of the plants. From the data related to direct radiation & diffuse radiation, the sun energy produced by the plant is obtained hourly. Figure 4 shows the solar energy generated by the plant (installation) as an average time for different months. The generated solar energy is higher in summer and lower in winter logically. During winter, days are shorter compared to summer, and most days are cloudy, resulting in less solar power generated.

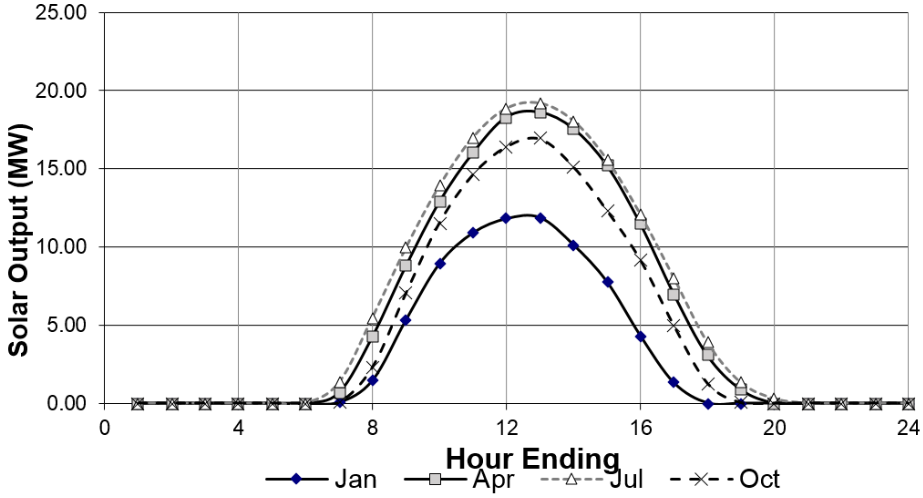

Fig. 4. Mean solar array outcome for four months in KSA.

Hourly real annual consumption data from the Ras Al-Khair plant as well the solar data from King Abdullah City for renewable energy & atomic energy have been obtained. Fig. 5 illustrates the electricity consumption curve required for the operation of the Ras Al-Khair desalination plant (in March), which is supported by the electrical grid that uses fossil fuels, and energy that can be shared by solar energy.

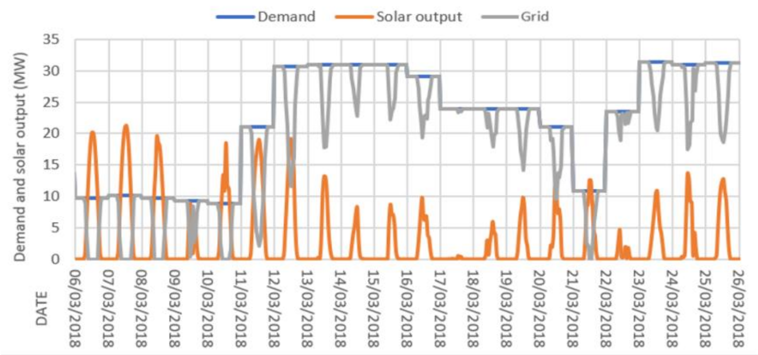

Fig. 5. Demand and solar contributions for the azimuthal tracking panel.

It is noteworthy, as shown in the graph, that during the month of April there were certain periods of time when the actual consumption of the plant decreased. These periods are related to technical stops necessary to carry out the maintenance. Fig. 6, shows the average electricity consumption required during (a day) during January and the solar-generated by cells to provide the energy needed to operate the plant during daylight hours. We notice the presence of wasted energy higher than the required energy in the afternoon.

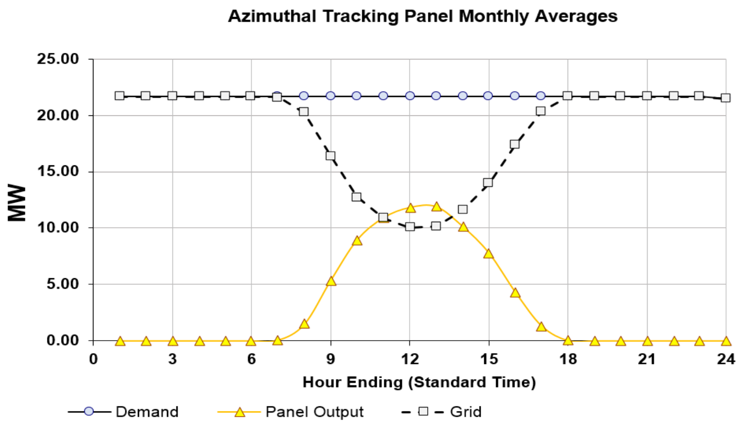

Fig. 6. Demand, PV electricity consumption and grid consumption.

These hypotheses will be carried out and summarized in the following section when the cost per kW per hour from the solar plant is estimated. So, we can establish the restrictive criterion that during the entire period of operation of the plant, the total energy generated by the solar plant is utilized for its consumption in the desalination plant. This alternative is conditioned by the low consumption that occurs during technical halts. Another hypothesis would be to allow the energy generated by the solar plant to exceed consumption in certain periods as described above. In order to do so, we will set a maximum percentage of generated energy that will not be used by the installation and could be discharged to the national grid electricity at a sale price equal to zero. With the actual consumption data of the plant and the energy produced from solar the photovoltaic plant, the amount of energy that can be consumed in the desalination plant (Usable energy) is obtained. A higher rating of the solar power plant would inevitably lead to surplus generation at times. The surplus energy generated during certain periods cannot be effectively utilized by the RO plant, leading to wastage and, thereby, increased the overall cost of production. It is assumed as a hypothesis that this energy is either sent to the network at a price equal to zero euros or the solar plant is disconnected during those periods in case it could not be connected to the network, in order to analyze the feasibility of the use of desalination plants without storage.

4.1. Financial study

The financial study of the solar plant, which can be employed to estimate the price for electrical energy produced from the photovoltaic solar power plant and assessment for the feasibility of solar plant is carried out. In order to do so, first, the size of the plant is defined. The calculations have been made for the following cases: 1, 2, 3, 4, 5 MWp; and 10, 20, 40, 60, 80, 100 MWp.

For each case, the following parameters of the plant are considered:

- Efficiency of panels 12%
- Performance Ratio (PR): 100%, 90% and 80%.
- Plant cost: 0.835 € / KWp
- Life cycle of the PV plants; 25 years

Besides, it is also considered: that the interest rate for the loan (*r*) is 4%, and the costs of operation and maintenance are 0.1 €/watt. The price of the electricity generated by each of the facilities studied is calculated as indicated equation no. 4.

4.2. Total investment

Fig. 7 shows that the optimal design of the capacity of the solar plant found that the best design of the capacity of the plant is about 20 megawatts; therefore, the wasted energy will be about 20%. In this case, the price of production cost for the solar plant is 0.025 euros per kWh. This price is less than the current tariff price of the kilowatt of electricity in Saudi Arabia, which is estimated at 0.036 euros. In the following graph (Fig. 8), it can be seen that, the amount of solar energy generated in the photovoltaic solar plant is exponentially related to the size of plant. By increasing the size of the plant, the amount of solar energy generated in the photovoltaic solar plant increases and cannot be used to cover the energy consumption of Ras Al-Khair, as shown in Fig. 6. The gray area is the ideal area to design the capacity. In the case of design for capacity greater than 60 megawatts, the price of kilowatts per hour will exceed the tariff of electricity consumption in Saudi Arabia. In the following graph, Fig. 8 confirms that the higher design of capacity for the solar power plant increases the waste of energy produced. Thus, they are not utilized in Ras Al-Khair plant as indicated in Fig. 6. The gray area is the ideal area design the capacity. In the case of design for a capacity greater than 60 megawatts, the price of kilowatts per hour will exceeded the tariff of electricity consumption in Saudi Arabia.

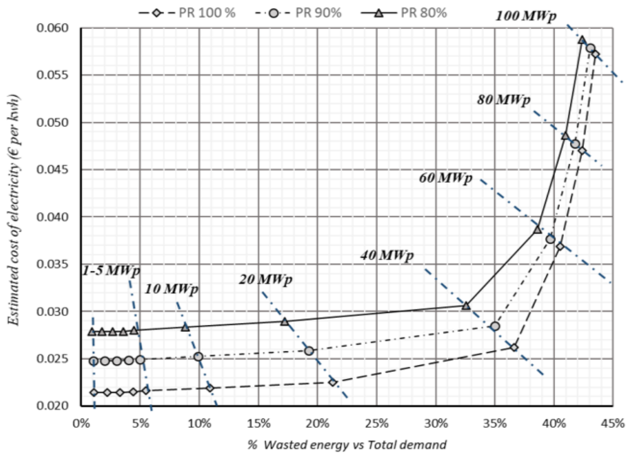

Fig. 7. Estimated cost of electricity over the percentage of wasted energy.

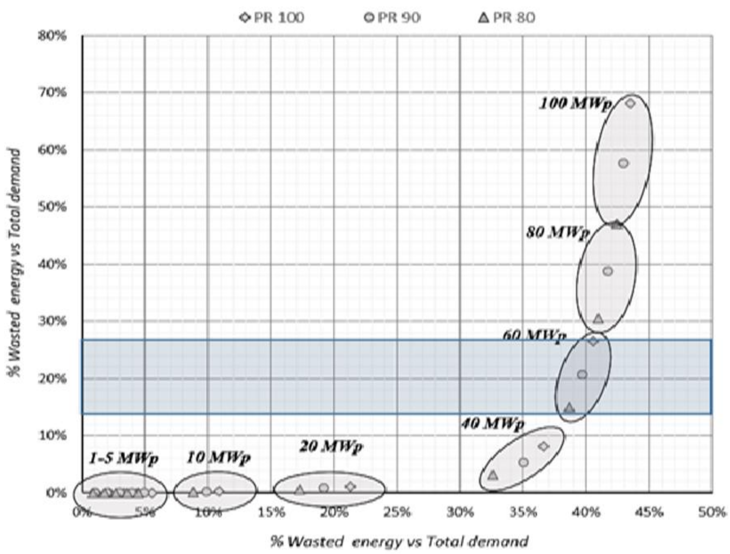

Fig. 8. Wasted energy generated in relation to size of plant.

5. Conclusions and Recommendations

In recent years, the cost of solar panels and the installation cost has been drastically decreased. Due to the decrease in the overall cost of solar panels, the generation of electrical energy from solar energy has become an economically viable alternative, especially in countries like Saudi Arabia, where there is a large number of sunny hours during the year, which accounts for higher electricity generation from solar panels. The availability of potable water and usable energy are two fundamental pillars for the development of any society. Desalination technologies, which are used for the treatment of the saline water of the sea for conversion into potable water, consume a great amount of energy. The use of solar energy to fulfill the power requirements of the desalination unit is a viable alternative, and it also reduces the CO2 emissions, which are usually generated by the use of fossil fuels. The case study examined by the authors focuses on the use of photovoltaic solar plants to supply energy without storage, and the surplus energy can then be sold to a centralized grid available. From the gathered data, established for certain sizes of plants, the costs of electricity generated by photovoltaic cells are even lower than the cost of electricity generated by fossil fuels.

Conflict of Interest

The authors whose names are listed immediately below certify that they have NO affiliations with or involvement in any organization or entity with any financial interest (such as honoraria; educational grants; participation in speakers' bureaus; membership, employment, consultancies, stock ownership, or other equity interest; and expert testimony or patent-licensing arrangements), or non-financial interest (such as personal or professional relationships, affiliations, knowledge or beliefs) in the subject matter or materials discussed in this manuscript.

Author Contributions

a, b conducted the research; b, Analyzed the data; a, wrote the paper; a, improve figures and tables; b, made the final review of the paper. all authors had approved the final version.

Acknowledgements

The authors would like to express their deepest appreciation to the King Abdulaziz City for Science and Technology (KACST) and King Abdullah City for Atomic and Renewable Energy (K.A.CARE) for their technical assistance and support in this research.

References

[1] DeNicola E, Aburizaiza OS, Siddique A, Khwaja H, Carpenter DO. Climate change and water scarcity: the case of Saudi Arabia. *Annals of Global Health*, 2015; 81: 342–353.

[2] Mokheimer EMA, Sahin AZ, Al-Sharafi A, Ali AI. Modeling and optimization of hybrid wind--solar-powered reverse osmosis water desalination system in Saudi Arabia. *Energy Conversion and Management*, 2013; 75: 86–97.

[3] Drewes JE, Garduño CPR, Amy GL. Water reuse in the Kingdom of Saudi Arabia-status, prospects and research needs. *Water Science & Technology: Water Supply*, 2012; 12: 926–936.

[4] Caldera U, Bogdanov D, Afanasyeva S, Breyer C. Role of seawater desalination in the management of an integrated water and 100% renewable energy based power sector in Saudi Arabia. *Water*, 2018; 10(32): 32.

[5] Global Water Intelligence. Top Market Opportunities Saudi Arabia. In: *Global Water Market 2017: Meeting the World's Water and Wastewater Needs until 2020; Middle East and Africa*, Oxford: Media Analytics Publication; 2016; 1379–1400.

[6] Al-Ghalib E. (January 2018). Saudi desalination capacity sets global record at 5 million cubic meters a day. [Online]. Available: https://www.businesswire.com/news/home/20180125006048/en/Saudi-Water-Desalination-Capacity-Sets-Global-Record

[7] Saline Water Conversion Corporation (January 2019). [Online]. Available: http://www.swcc.gov.sa/Arabic/Pages/Home.aspx

[8] Gude VG. Desalination and sustainability - an appraisal and current perspective. *Water Research*, 2016; 89: 87–106.

[9] Fthenakis V, Atia AA, Morin O, Bkayrat R, Sinha P. New prospects for PV powered water desalination plants: Case studies in Saudi Arabia. *Progress in Photovoltaics: Research & Applications*, 2016; 24: 543–550.

[10] Rambo KA, Warsinger DM, Shanbhogue SJ, Lienhard V JH, Ghoniem AF. Water-energy nexus in Saudi Arabia. *Energy Procedia*, 2017; 105: 3837–3843.

[11] Taher N, Hajjar B. *Energy and Environment in Saudi Arabia: Concerns and Opportunities*. Switzerland: Springer International Publishing; 2014.

[12] Trieb F. Concentrating solar power for seawater desalination. Research Report. German Aerospace Center (DLR) & Federal Ministry for the Environment Nat. Conserv. Nucl. Safety, Germany, 2007.

[13] Saudi Arabia Vision 2030 (January 2019). [Online]. Available: http://vision 2030.gov.sa

[14] Jurgenson S, Bayyari FM, Parker J. A comprehensive renewable energy program for Saudi Vision 2030. *Renewable Energy Focus*, 2016; 17(5): 182-183.

[15] Solar GIS (January 2019). [Online]. Available: solargis.com

[16] Zell E, Gasim S, Wilcox S, Katamoura S, Stoffel T, Shibli H et al. Assessment of solar radiation resources in Saudi Arabia. *Solar Energy*, 2015; 119: 422-438.

[17] KA CARE Renewable Resource Atlas (May 2020). [Online]. Available: https://rratlas.energy.gov.sa/RRMMDataPortal/en/MapTool

[18] Stodola N, Modi V. Penetration of solar power without storage. *Energy Policy*, 2009: 37: 4730–4736.

[19] King DL, Boyson WE, Kratochvil JA. Analysis of factors influencing the annual energy production of photovoltaic systems. Presented at 2002 Conference Record of the Twenty-Ninth IEEE Photovoltaic Specialists Conference, pp 1356–1361.

[20] Duffie JA, Beckman WA. *Solar Engineering of Thermal Processes*, 2nd ed. New York: Wiley Interscience; 1991.