

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

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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 a 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 day time. That is why 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 reverse osmosis desalination facility located in Saudi Arabia. It was observed that during summer months, larger amount of solar energy is produced as compared to the winter months because of greater day 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 per cent of totally consumed energy could be provided at the price around 0.025 €/kwh. The expenses for power produced exceeds 0.036 €/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 across 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 is the climatic change in the world and the second is 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 to these variations and, consequently, 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 a 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 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 [3]. On the other hand, the total intake of 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 present degree, aquifer reserves can satisfy current needs for only three more decades at best [4]. Under the prevailing situation, water desalination is the best strategic choice for resolving the water shortage issues.

1.2 Desalination in 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 by desalinated processed water, 2.2% through reused wastewater and 33.5% using surface water in 2010 [5]. The situation was improved in 2014 and Saudi Arabia produced 60% of its entire water needs through desalinated water [6]. In 2016 desalinated water supplies enhanced by 827 million

m³ in 2 thousand to 1377 million m³ and consequently touched the figure of 18 hundred million m³ in 2018 [5,7]. 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 m³/ day. Table 1 provides data about desalination plants presently working with their starting time, technology employed, and lifetime duration. It can be observed that with strict quality control and operation, and with proper maintenance, several plants exceeded their expected lifetime.

Table 1. Plants for desalination presently in service in 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	Shoaiiba-I	MSF	1989 (28)	2014 (+3)	191,780	223,000
16	Al-baha	Shoaiiba-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	Asier						
22	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-kair	RO	2014	2039	307,500	310,656
29	Al-Riyadh	Ras-Al-kair	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)

The technologies used for desalination of water are subdivided into two types that are 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 as 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 and it is applied in more than 23% of desalination plants around the world [9]. MSF and MED are particularly suited for integration into cogeneration plans, where they can utilize the waste thermal energy leaving the turbine to produce fresh water [10]. 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 [11]. 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 the level of 50% in 2030 [5].

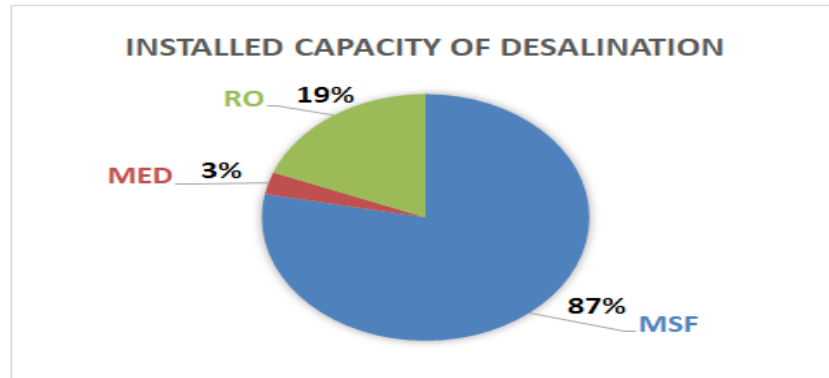


Fig. 1: Capacity of installed desalination plants in KSA by desalination technology types [11]

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 majority of the plants for desalination at 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 [12,13]. Table 2 presents consumption data of energy used by prominent technologies for water desalination. [14]. Minimum energy uptake by reverse osmosis process is observed in the form of electrical. 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 the water with larger salt contents to a solution possessing lower salt contents.

Table 2. Desalination technologies and their energy requirements [14]

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 alternates. 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 forecasted to give a boost to the country's economy along with reduction of fossil fuel consumption plus putting a good impact on the ecological system [15,16]. 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.

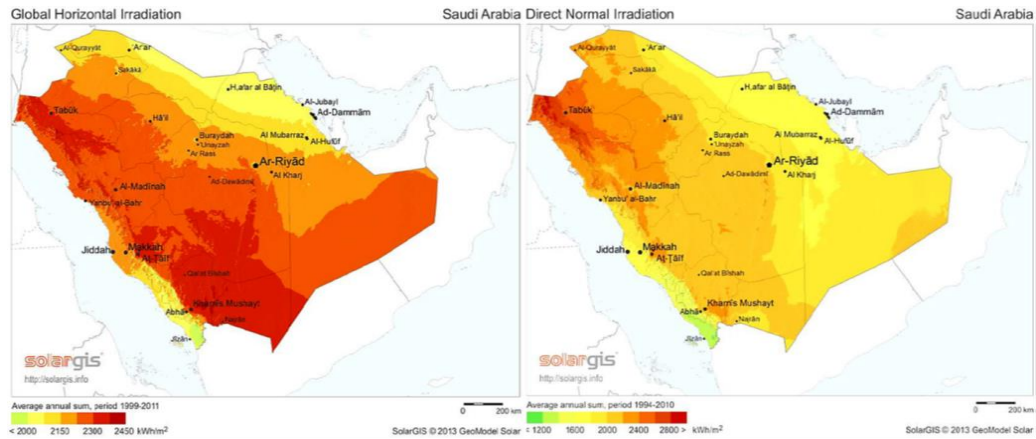


Fig. 2: Global direct normal irradiation & horizontal irradiation GHI in KSA from 1999 to 2011.

Figure 2 represents the direct normal irradiation (DNI) and global horizontal irradiation (GHI) in Saudi Arabia [17], while Figure 3 shows those two indicators, in addition to a third indicator which is the diffuse horizontal irradiation (DHI) [18].

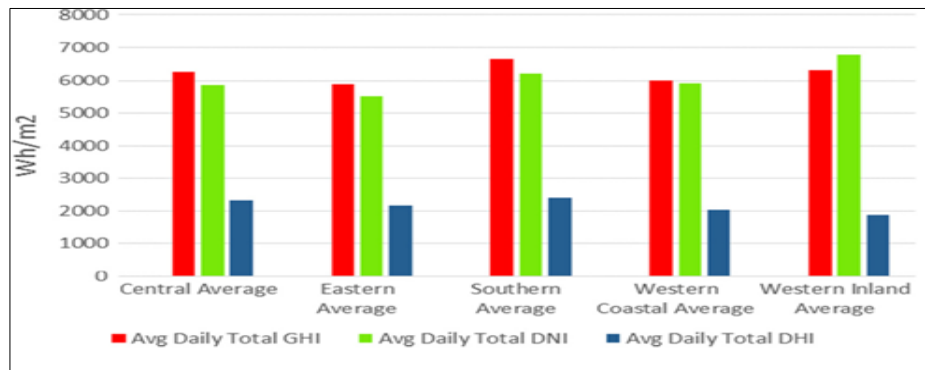


Fig. 3: A review from OCT 13. To Sep. 2014 for solar irradiance by region in Saudi Arabia [18]

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 objective to find 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 [19]. At the end, for the purpose of analysis of feasibility of integration between reverse osmosis desalination and solar energy, the energy requirement for 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 [20]. 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. 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 [21,22]. 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 hourly basis. Direct fraction of solar radiation (H_b) which approaches the surface of 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 earth from all directions is labeled as diffused radiation (H_d). Amount of H_d varies depending upon the forecast conditions. Diffuse radiation varies from 10% of entire radiation on a clear day to approximately hundred percent on a cloudy day. Reflected radiation (H_r) from surroundings and earth surface also needs to be taken into consideration [20]. Total global radiation (H) comprising of diffuse, direct, and reflected radiation, is given by:

$$H = H_r + H_d + H_b \quad (\text{eq. 1})$$

Total amount of energy hitting the panel was determined by incidence angle of sunlight, for every point in time for each arrangement. [22].

$$I_{\text{panel}} = I_{\text{beam}} \times \cos\theta + I_{\text{diffuse}} \times F_{\text{ps}} \quad (\text{eq. 2})$$

Where,

- I_{panel} = Total radiation on the panel
- I_{beam} = Direct radiation on the panel
- θ is referred as 90 degree when sun raise is parallel to panel, and 0 degree when perpendicular to panel.
- I_{diffuse} = 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 ground or sky that is directly exposed to panel.

Solar radiation at Ras Al-khair that affects the panels of the photovoltaic solar plant can be used for determining amount of solar plant generation in terms of energy. A wide range of powers of the dissipated photovoltaic solar plants is defined that allow to obtain curve that describes 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 which 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 examined the cost of the KWh generated by each one of the plants which was calculated.

For the calculation of price estimation of electrical energy, to calculate the imbursement for borrowed money on the basis of fixed payments & a fixed interest ratio were obtained. Considering that start of the period is the point when imbursement become due.

$$Q = PV / (1 + (1 - (1/(1+r)^n))) \quad (\text{eq. 3})$$

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 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.

$$P = Q / \text{Usable energy (KWh)} \quad (\text{eq. 4})$$

where, P = price of kwh

4 Case Study Results

Prime objective for this research work is to optimize energy from sun which can be used in accordance with energy utilization curve of plants. From the data relating to direct radiation & diffuse radiation, sun energy produced by plant is obtained hourly. Fig.4 shows the solar energy generated by the installation as an average time for different months. Solar power generated is higher in summer and lower in winter. During winter, days are shorter as compared to the summers and forecast gets cloudy which also accounts for less solar power generated.

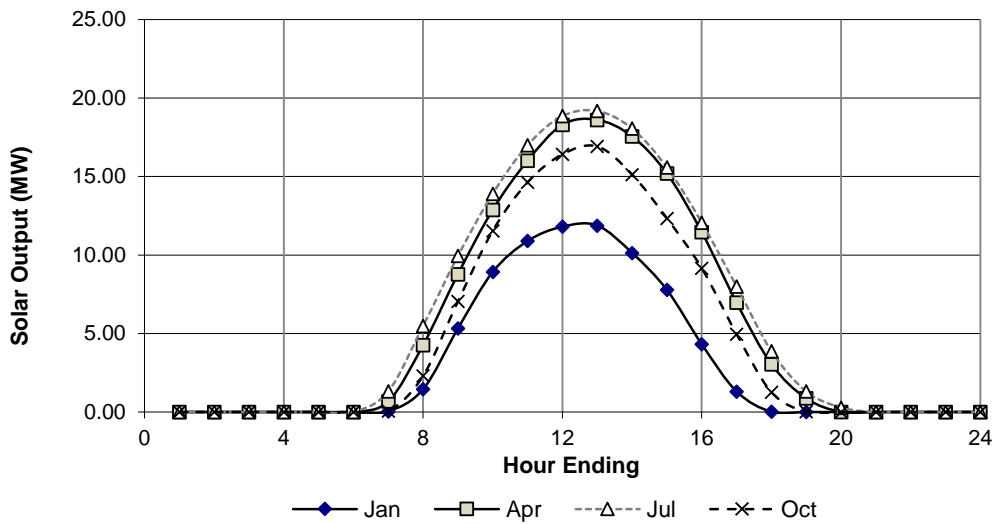


Fig. 4: Mean solar array outcome for four months in KSA

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. Figure.5 shows the electricity consumption curve required for the operation of the Ras Al Khair desalination plant (for the case of March), which is supported by the electrical grid that uses fossil fuels, and energy that can be shared by solar energy.

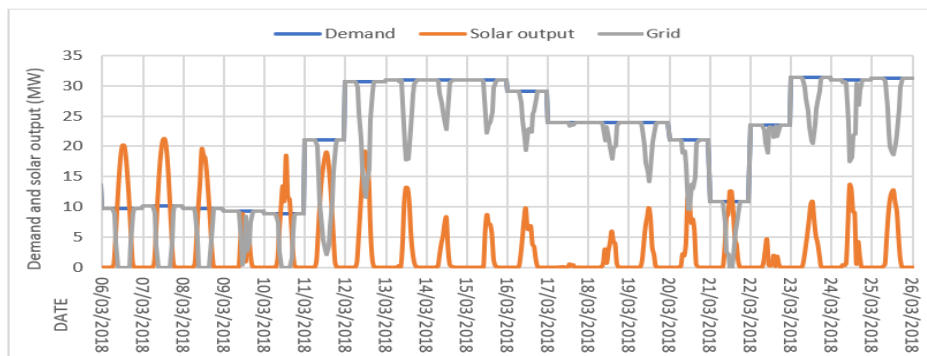


Fig. 5: Demand and Solar Contributions for Azimuthal Tracking Panel

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. In Fig.6, shows the average electricity consumption required during (days) 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.

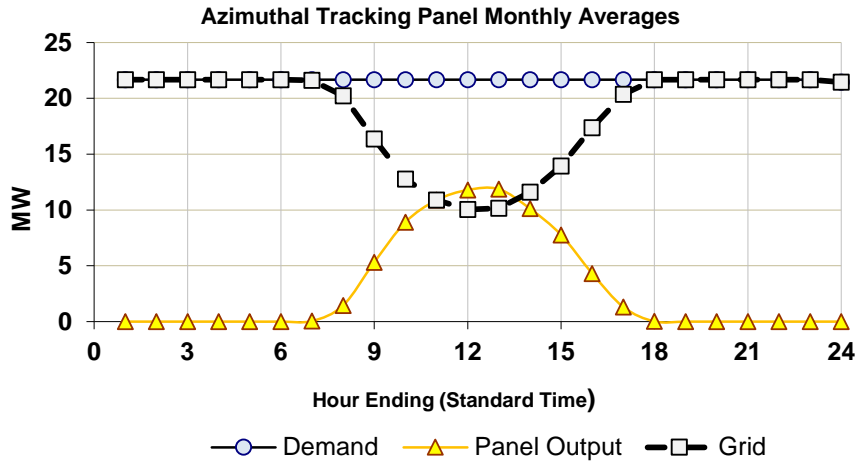


Fig.6: Demand, PV electricity consumption and grid consumption

These hypotheses will be carried out and summarized in the following section when we estimate the cost of one generating of kw per hour from the solar plant. 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 photo voltaic plant, amount of energy that can be consumed in the desalination plant (Usable energy) is obtained. The energy generated and that would not be used (not usable energy) is due to the fact that in certain periods the energy generated by the solar plant is higher than the energy consumed by the desalination plant. 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 feasibility of solar plant is carried out. In order to do so, first 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 of the cases, 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

Also, it is considered: that the interested rate for the loan (r) is 4% and the costs of operation and maintenance 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 was 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 is estimated at 0.036 euros.

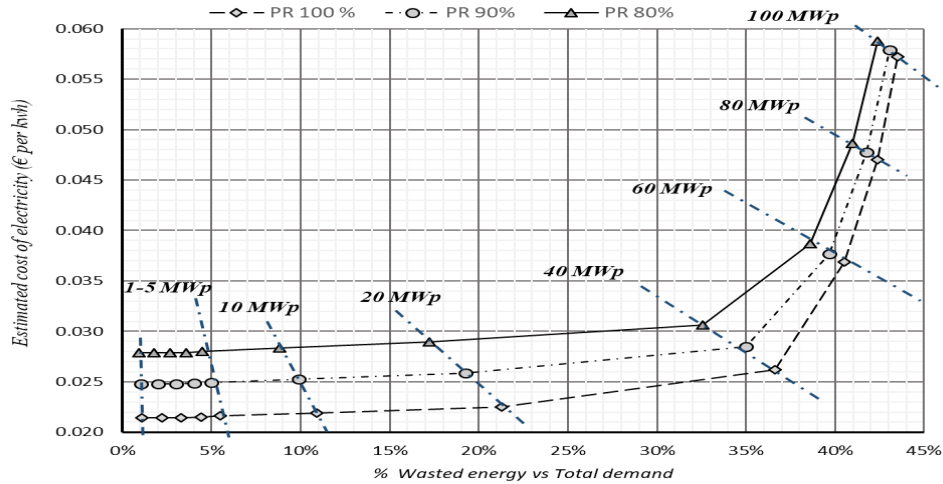
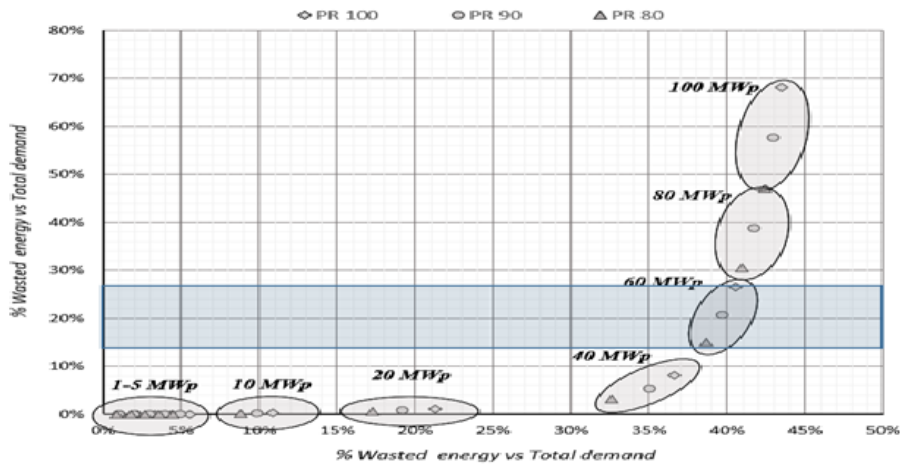


Fig. 7: Estimated cost of electricity over the percentage of wasted energy

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, cannot utilized to cover the energy consumption of Ras Al-khair as indicated in Fig 6. The gray area is the ideal area 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.



5 Conclusion and recommendation

In recent years, the cost of solar panels and installation cost has been drastically decreased. Owing to the decrease in 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 that have a large number of sunny hours during the year which accounts for higher electricity generation from solar panels. Availability of potable water and usable energy are two fundamental pillars for the development of any society. The desalination technologies which are used for the treatment of the saline water of the sea for conversion into potable consume a great amount of energy. The use of solar energy to meet power requirements of desalination unit is a viable alternative and also helps in

reduction the CO₂ emissions which are usually generated by the use of solid fuels. The case study examined by authors focuses on the use of photovoltaic solar plants to supply energy without storage, and the surplus energy if generated is transferred to the network could be sold. From the gather data it has been established for certain sizes of plants, the costs of electricity generated by photo voltaic cells are even lower than the cost of electricity generated by fossil fuels.

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