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Solar energy to optimize the cost of RO desalination plant case study: Deir Elbalah SWRO plant in Gaza strip

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Abstract—Seawater desalination by reverse osmosis (SWRO) is currently considered as one of the most widely used and reliable technology in providing additional water supply for areas suffering from water scarcity. High energy consumption of Reverse Osmosis plants is one of the biggest challenges, particularly in developing countries such as Palestine. The future demand for fresh water and thus, energy, triggers researchers to find methods to integrate the use of renewable energy for the desalination process. Palestine has a high solar energy potential, where the average of solar radiation intensity on horizontal surface is 5.31kWh/m2 per day. In this research, the possibilities of using solar energy to optimize the cost of the desalination process in Gaza were studied. The research focused on the optimal use of solar energy and selection of the most economically feasible configuration of utilizing this source either fully or partially in the SWRO process. Internal Rate of Return (IRR) was used as an economic indicator to analyze the feasibility of establishing a SWRO desalination plant with a capacity of 600m3/d in Gaza based on the optimal energy sources. The available options of energy sources were Traditional System, Off Grid and On Grid Solar systems. The results for the economic study found that the IRR was 6.6%, 3.80%, and 7.64% for the first, second, and third options respectively. The higher the IRR, the more attractive is the option for the investment. The IRR should be more than the market interest rate by a comfortable margin (6.43% in Palestine). Based on the results, the On Grid Solar System has the ability to balance the system production and Plant power requirements, which is about 105kwh. Considering the On-Grid system, the unit cost for desalinated water was reduced from 1.08$/m3 (Electric utility as a baseline) to 0.89$/m3 which is about 17% saving.

Index Terms—Optimization, Desalination, Solar Energy and IRR.

I INTRODUCTION

The problem of scarcity of fresh water has been faced by most countries because of increasing consumption and population growth. Gaza Strip, in particular, has a problem in terms of water quantity and quality due to depletion of ground water aquifer and intensive land use exploitation.

In Gaza Strip, the main source of fresh water comes from the coastal aquifer (shallow aquifer). Where Gaza Strip lies on the seashore with Coastal length of approximately 42 km, so most of the water pumped from water wells has high salinity due to seawater intrusion and does not meet the World Health Organization (WHO) drinking water guidelines and Palestinian Water Authority (PWA) standards. Therefore, the PWA believes that desalination is a strategic option for Gaza Strip [1].

In desalination by Reverse Osmosis (RO), which is found to be the most economically feasible technique in Gaza strip [2], Energy cost in RO desalination plants comprises about 30% to 50% of the total cost of the produced water based on the type of energy used [2] Therefore, the total cost of desalination can be reduced significantly by reducing the energy consumption.

Under the current energy crisis in Gaza Strip, The Gaza strip's energy resources are controlled by Israel, which employs policies to restrict the electrical production capacity of the Palestinian territories, so from the point view of the sustainable, it is recommended to utilize the renewable energy sources for desalination purposes. More studies show that solar energy is the most feasible among all types of renewable energy for the region climate (Middle East) [3].

Palestine has a high solar energy potential, where the average solar energy varies between 2.63 kWh/m2 per day in December to 8.5 kWh/m2 per day in June, and the daily average of solar radiation intensity on horizontal surface is 5.31 kWh/m2 per day while the total annual sunshine hours are about 3000 hours [3].

All previous studies that depended on the solar system especially in water field in Gaza were for environmental purposes only, but this study has three essential dimensions for a desalination process. The first is an environmental dimension by using the solar energy system. The second is an economical dimension by using the Internal Rate of Return (IRR) method as economic indicator for feasibility study, and the third is a technical dimension by using the RO technique that was recommended in previous studies.

II METHODOLOGY

A Research Concept

The research focused on the optimal use of solar energy and selection of the most economically feasible configuration of utilizing this source either fully or partially in the Seawater Reverse Osmosis (SWRO) process. Methodology of the research consisted of three main stages, Research data were collected as a first stage, the second stage was modeling of three main scenarios of energy to establish a SWRO desalination plant with a capacity of 600 m3/d in Gaza based on the optimal energy sources that are represented in figure (1), The sources are by Electricity Energy System (EES), Solar Energy System (SES), and Combined Energy System (CES). In the third stage, Internal Rate of Return (IRR) was used as an economic indicator to analyze the feasibility of energy system size that fits the adequate voltage and current ratings for each component of the photovoltaic system to meet the electric demand at the facility.

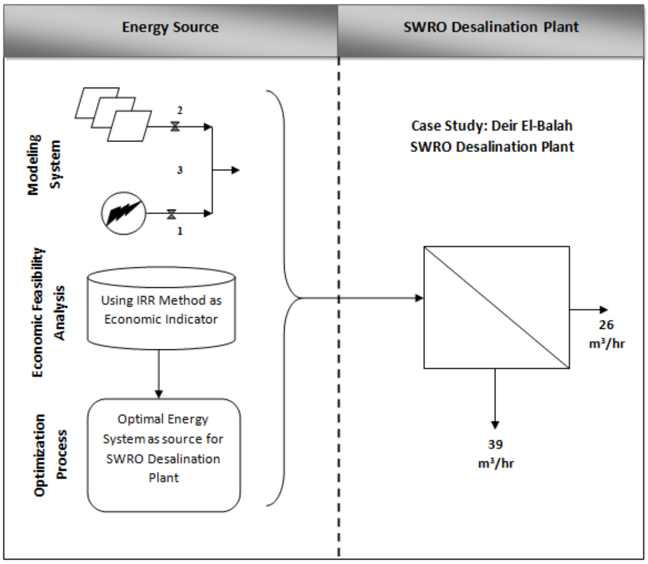

Figure 1 Research framework

In general, the aim of this research is to optimize the cost of desalination using the solar energy as a complementary source of energy.

Studying the best configuration to introduce the following specific objectives was pursued in order to achieve the aim above:

- System modeling of energy consumption processes in Deir El-Balah desalination plant.
- Economic feasibility analysis of energy alternatives
- Sizing optimal solar system for optimal energy cost.

B Case Study: SWRO Desalination Plant-Technical Description

At present, Gaza Strip has three desalination seawater plant (under construction), and existing one (under operation) in Deir Elbalah City that was the case study in this research as illustrated in figure (2).

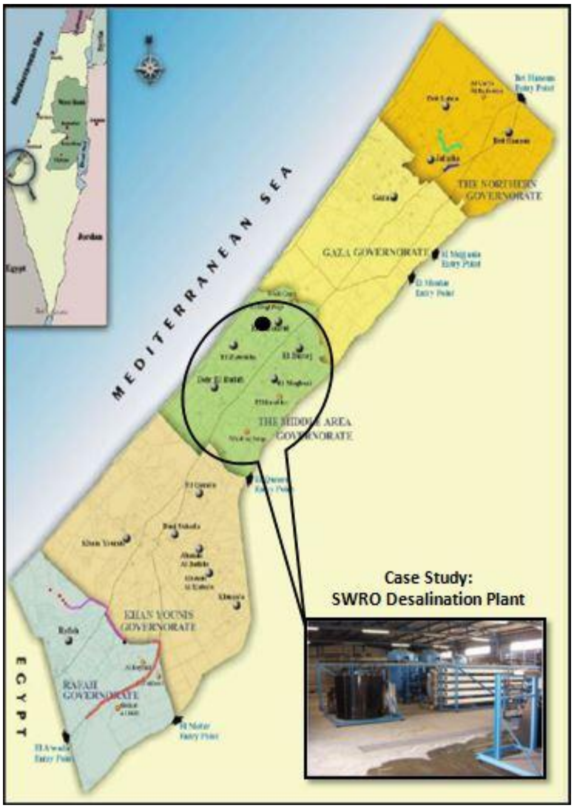

Figure 2 Location of SWRO desalination plant in Gaza Strip

The plant consists in general of the following process units [4]:

- Seawater intake (beach wells),
- Seawater pretreatment plant,
- Reverse Osmosis Desalination Plant,
- Post treatment Plant, and
- Potable water storage and distribution.

The source of seawater comes from two beach wells close to the shore, and the wells have been constructed for the delivery of 65 m³/h raw water (maximum quantity 1.500 m³/d), and the pumps and the electromechanical equipment will also be designed for 75 m³/h raw water per well. After the water has passed the cartridge filters (5 micron) that is equipped with a difference pressure transmitter maximum 1.5 bar, the high-pressure pump pressurizes the pretreated seawater to a required operation pressure of 65 to 70 bar and feeds the seawater into the RO unit. The RO unit is equipped with spiral wound Thin Film Composite RO membrane elements of 8-inch diameter and 40-inch length. Six pieces of these RO membrane elements may be installed in the pressure vessels.

In our case, the feed water flow rate to the RO unit is 65 m^3/hr, the permeate flow rate is 26 m3/h and the brine flow rate is 39 m^3/h, the water recovery is therefore 40 % and the remaining 60 % brine stream is discharged to the sea [5]. An automatic flushing of the pressure vessel, the RO elements, high-pressure pump and pipe work is performed at every plant stop with permeate with flushing pump. The high-pressure feed pump system consists of the pumps connected in series. The first pump is connected with a pelton turbine to recover the energy from the high-pressure brine stream. The second pump is equipped with a speed controlled electric motor to increase the pressure to the above-mentioned operation pressure.

III MATERIALS AND METHODS

A First Stage: Data Collection

There were three main types of collected data to model energy source scenarios in the SWRO plant, power consumption data of the SWRO desalination plant, a new energy source data that was solar energy system and investment costs to establish this plant.

- **Power Consumption Data of SWRO Desalination Plant**

The design capacity of the SWRO desalination plant is to produce 600 m3/day. So the mechanical and electromechanical equipment of the reverse osmosis unit itself was designed for a maximum capacity of 600 m^3/d potable water. The calculated power consumption was based on seawater with a feed TDS of 40,000 ppm and a plant recovery of 40 %. The total power load required to operate the RO during 24 hours was calculated 2,520 KW/day, 90 KWh/day for High-pressure unit and 15 KWh/day for other units in desalination plant as shown in the following table (1) [5].

Table 1

Power Consumption of the SWRO Plant

Description	Required unit operation power	Specific power consumption
Well pumps for water supply	14 kWh/h	0,65 kWh/m3
Pretreatment and RO Plant	105 kWh/h	4 kWh/m3
Water filling and distribution station	27 kWh/h max.	0,50 kWh/m3

- **Solar Energy Data**

Palestine has a high solar energy potential, where the average solar energy is between 2.63 kWh/m2 per day in December to 8.5 kWh/m2 per day in June, and the daily average of solar radiation intensity on horizontal surface, peak sunshine hour PSSH, is 5.31 kWh/m2 per day while the total annual sun shine hours are about 3,000 hour. The annual average temperature amounts to 22 Co while it exceeds 30 Co during summer months [6], these figures were very encouraging to use Photovoltaic generators for SWRO desalination plant. The solar radiation data had a great effect on the performance of photovoltaic (PV) systems. Table (2) shows the history data for monthly values of solar energy [6].

Table 2

Average of PSSH in Palestine

Month	Mean of PSSH KWh/m2/day (1989-2002)
Jan	3.36
Feb	3.97
Mar	4.33
Apr	5.19
May	6.46
Jun	7.78
Jul	7.40
Aug	6.76
Sep	5.88
Oct	4.73
Nov	4.31
Dec	3.53
Mean	5.31
Standard deviation	1.5

Figure (3) shows the average monthly solar energy on horizontal surface (kw/m2-d) plotted from data of table (2).

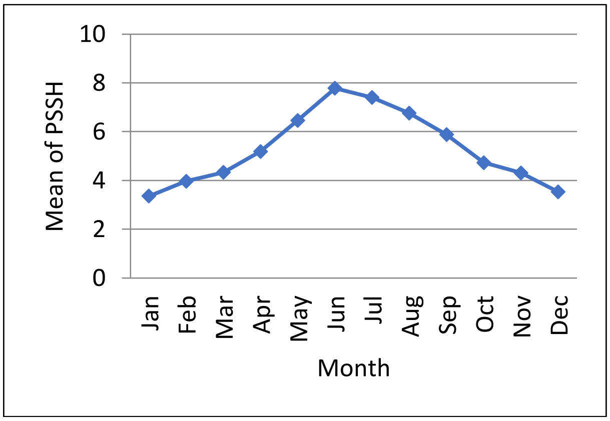

Figure 3 Average monthly solar energy on horizontal surface

Based on the illustrated power data for the SWRO desalination plant (105 kwh), When we used any type of solar system, the produced power (Ac Energy) was calculated as the following figure (4) for each month that illustrates the variation in the monthly daily average in total insolation on horizontal surface that depends on PSSH for each month, which is up to higher value during summer season.

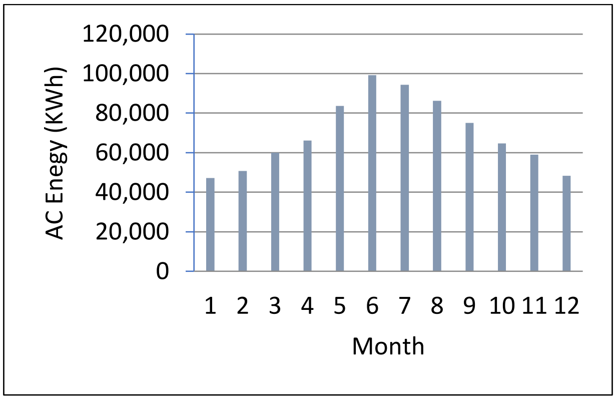

Figure 4 Produced Monthly Energy

- **SWRO Desalination Plant Investment Cost**

SWRO Desalination Plant Investment Cost Unit product cost calculations depend on the plant capacity, site characteristics, and design features. Plant capacity specifies sizes for various process equipment, pumping units, and membrane area. Site characteristics have a strong effect on the type of pretreatment and post-treatment equipment, and consumption rates of chemicals. In addition, design features of the process affect consumption of energy power and chemicals. Desalination plant implementation costs can be categorized as capital costs (fixed costs) and operation and maintenance costs (variables costs). These costs were prepared by referring to the experts in the Coastal Municipalities Water Utility (CMWU), Palestinian Water Authority (PWA), Palestine Energy & Natural Resources Authority (PENRA), Palestine Land Authority (PLA) and other companies.

The annual cash flow of SWRO plant with series time (lifespan) that is 22 years is as the same age as any Solar System age. The investment costs were calculated as presented in figure (5). Some costs were the same in different scenarios such as the costs of the plant establishment and land costs. But the profits of the project were estimated based on the sale price and production unit of the plant ($ per one cubic meter of desalted water), that is 1.7 $/m3.

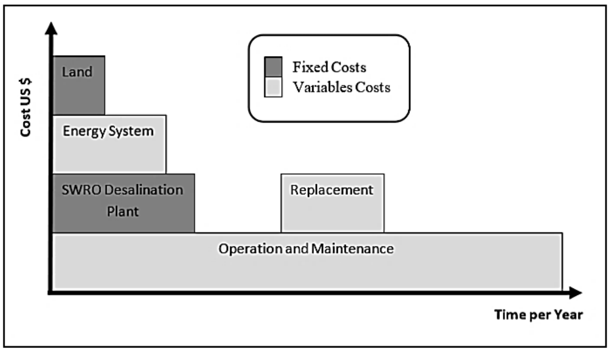

Figure 5 Types of Plant costs with time

B Second Stage: Modeling Energy Source Systems

To model the solar energy systems, we used a solar photovoltaic calculator which was originally developed by (Abualtayef, 2015) and modified by the researchers [7] as the following figure (6).

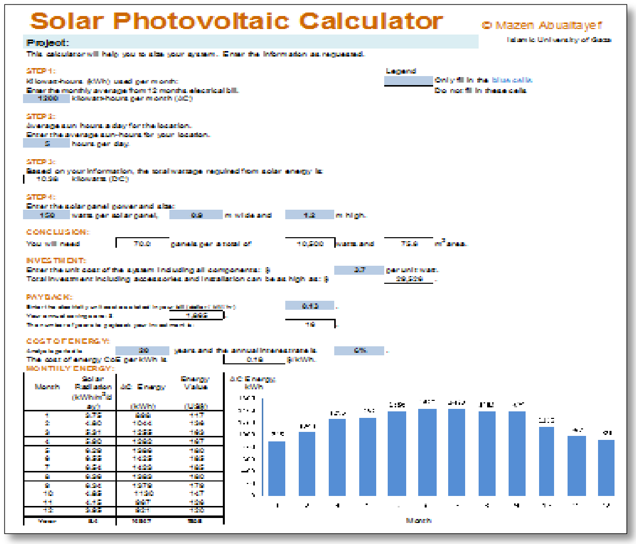

Figure 6 Solar photovoltaic calculator

The model was built using Microsoft Excel as an analysis tool to determine Sizing of the photovoltaic generator and system costs that are dependent on some of energy and economic parameters in Gaza. The energy sources were Electricity Energy System, Solar Energy System, and Combined Energy System.

- **Electricity Energy System (EES)**

Figure (7), represents the first scenario of the proposed plant, which depended on local electricity network. The required energy of the desalination plant was 105 kwh, while the commercial price of one kilowatt of electricity was estimated to be 0.172 $/kwh.

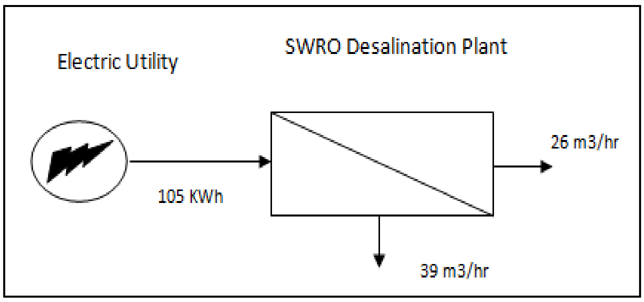

Figure 7 SWRO Plant depends on Electricity Source

- **Solar Energy System (SES)**

Figure (8), represents the Second scenario of the proposed plant, that depended on Solar Energy System only that is known as (Off Grid System). Off-grid systems are not connected to the electricity grid. The output of the off-grid system is entirely dependent upon the intensity of the sun [8]. The more intense the sun exposure, the greater the output.

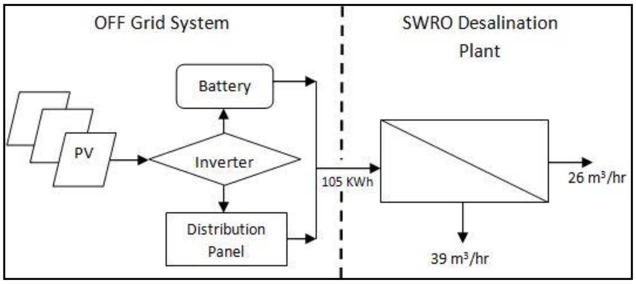

Figure 8 SWRO Plant depends on Off Grid System

- **Combined Energy System (CES)**

Figure (9), represents the third scenario of the proposed plant, that depended on solar energy system combined with the traditional source that is known as (On Grid System) [9]. The prime advantage of this type of systems is the ability to balance the system production and plant power requirements. When a grid inter-tied system produces more power than the Plant consumes, the excess can be sold back to the utility in a practice known as net metering. When the system does not produce sufficient power, the Plant can draw power back from the utility grid.

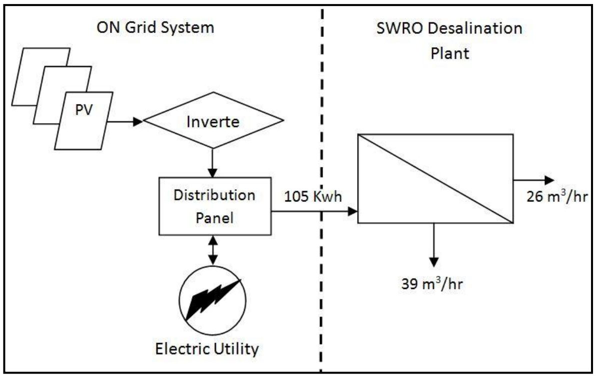

Figure 9 SWRO Plant depends on On Grid System

C Third Stage: Economic Feasibility Analysis

Proposed capital projects can be evaluated by economic feasibility study that may also include an economic analysis of the project. The purpose of economic analysis is to determine whether there is an economic case for the investment decision. In this Study, Internal Rate of Return (IRR) method was used as an economic indicator to compare the feasibility of establishing a SWRO desalination plant with a capacity of 600 m3/d in Gaza based on the best energy sources. This method refers to the percentage rate of return implicit in the flows of benefits and costs of projects. A margin defines the internal rate of return IRR as "the discount rate at which the present value of return minus costs is zero". Thus, IRR is the discounted rate which equates the present value of cash inflows that represent the fixed annual profits with the present value of cash outflows that represent direct and indirect costs of the project as shown in figure (10). IRR is also based on discount technique like Net Present Value NPV method. Under this technique, the future cash inflows are discounted in such a way that their total present value is just equal to the present value of total cash outflows.. IRR can be measured by the following equations [10]:

$$IRR = \frac{A_1}{(1+r)^{\wedge 1}} + \frac{A_2}{(1+r)^{\wedge 2}} \ldots\ldots + \frac{A_n}{(1+r)^{\wedge n}} - C = 0$$

Where, A1, A2 are the cash inflows at the end of the first and second years respectively. And the rate of return is computed as follows.

$$C = \frac{A_1}{(1+r)^{\wedge n}}$$

Where, 1 is the cash outflow or initial capital investment, A1 is the cash inflow at the end of first year, r is the rate of return from investment.

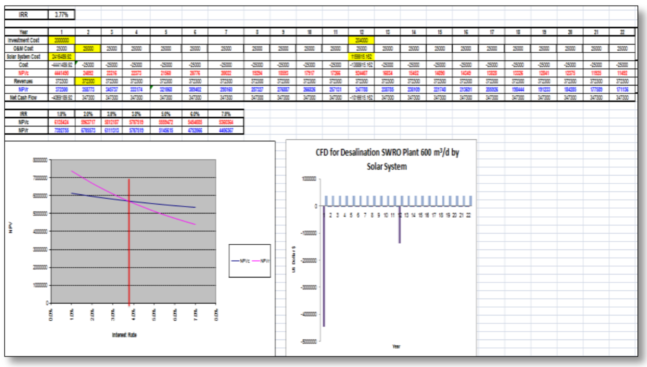

Figure 10 IRR Function at Microsoft Excel

In Palestine, with the absence of a national currency, IRR is calculated from the debit and credit interest rates on major currencies in circulation in Palestine: Jordanian dinar, the U.S. dollar and the Israeli shekel, periodically depending on data supplied by banks to the Palestine Monetary Authority PMA on the basis of the mean weighted average.

For economic analysis of this project which has taken interest rate 6.43 % as mean value of last three years for US dollars. The IRR function, which is available as a financial function within Excel tools, can be used to build the economic feasibility model for the three scenarios. As shown in previous figure (10).

IV RESULTS AND DISCUSSIONS

A comparison between the three scenarios will be discussed as regard to the cost and the saving values and its reflections on the specific cost of desalinated water.

A Energy System Cost

Investment cost of the SWRO Desalination Plant that depended on the Combined System (On Grid Solar System) as energy source was the lowest cost between other scenarios which was up to 0.13 $/KWh. This was reflected positively according to the economic indicator (IRR value), and we can note there is an inverse relationship between the IRR and the energy system cost as shown in table (3).

Table 3

Comparison of Energy Systems Cost

Energy System	IRR	$/KWh
Solar Energy System (Off Grid)	3.8%	0.27
Electricity Energy System (Electric Utility)	6.6%	0.17
Combined Energy System (On Grid)	7.64%	0.13

The Interest rate in Palestine is 6.43 % so the IRR value should be higher than the local interest rate to consider the project as a cost effective project from the standpoint of investors, see following figure (11) to recognize the differences.

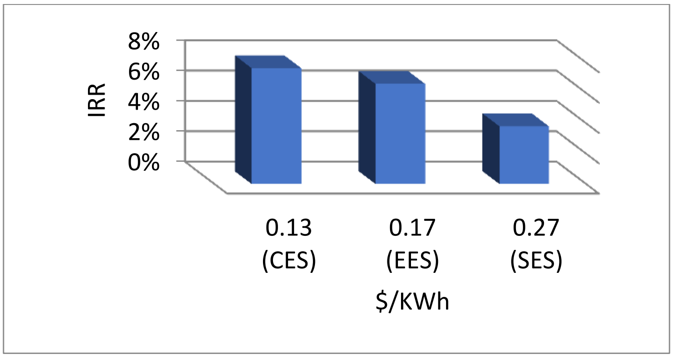

Figure 11 Relationship between IRR and Energy system cost

B Analysis of Combined System Costs

On Grid solar system was able to balance the system production and plant power requirements. In May, June, July and August, the grid inter-tied system produced more power than the Plant consumed, the excess could be sold back to the utility which was up to 61,046 kwh/year from the plant. When the system did not produce sufficient power, the Plant could draw power back from the utility grid which was estimated to be 133,719 kwh/year for the plant as shown in table (4).

Table 4

Saving Cost of Combined System by Net Metering System

Mon.	PSSH	AC Energy	Electricity Cost	Energy Value	Req. Energy	Net Energy	Net Cost
	(kWh/m2/day)	(kWh)	(US$)	(US$)	(kWh)/m	(kWh)	(US$)
1	3.36	47,206		8,119		-28,394	-4,884
2	3.97	50,688		8,718		-24,912	-4,285
3	4.33	60,033		10,326		-15,567	-2,677
4	5.19	66,200		11,386		-9,400	-1,617
5	6.46	83,594		14,378		7,994	1,375
6	7.78	99,237	0.17	17,069	75600	23,637	4,065
7	7.40	94,390		16,235		18,790	3,232
8	6.76	86,226		14,831		10,626	1,828
9	5.88	75,001		12,900		-599	-103
10	4.73	64,705		11,129		-10,895	-1,874
11	4.31	58,959		10,141		-16,641	-2,862
12	3.53	48,289		8,306		-27,311	-4,697
-	5.31	834,527	0.17	143,539	75600	-72,673	-12,500

So it would be reading of net meter with each year which was up to 72,673 kwh/year that was estimated to be 12,500 $/year as Shown in figure (12).

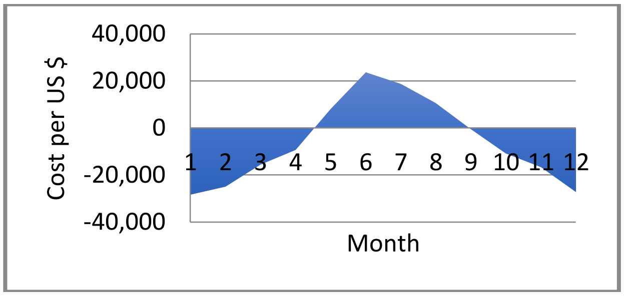

Figure 12 Net Cost of On Grid Solar System

C Saving Values of Optimal System

To estimate the saving value, we should take the traditional power as a baseline value. The cost of Electricity system during the lifespan of the project was higher than the investment cost of the On Grid Solar System. The Net Metering process increased the Solar Systems Efficiency and could save more values, which was up to 17 % as saving value by On Grid Solar System compared with other systems as shown in table (5) and figure (13).

Table 5

Comparison of the saving value for energy systems

Energy System	SES	EES	CES
IRR Value %	3.8	6.60	7.64
Energy Cost $/KW	0.27	0.17	0.13
Saving Value %	- 30	0.00*	17

* The traditional power is the baseline to calculate the saving value
Knowing that the net saving value (17%) was enough to the operating cost during 7.5 year for the SWRO Desalination Plant.

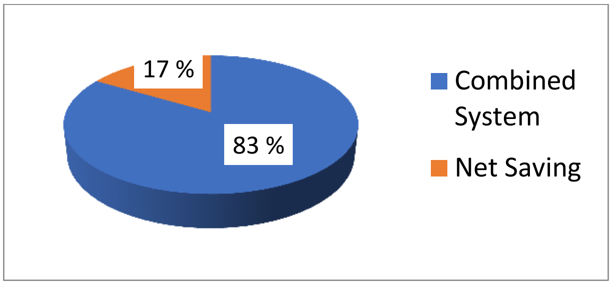

Figure 13 Saving Value of Combined System

There are many desalination plants in Gaza strip that desalinate brackish water (BW) from water wells by using Reverse Osmosis (RO) technique that depends on the traditional energy (electric utility) as an energy source. As it is known, the total cost of RO plants that desalinate the brackish water (BWRO) is lower than the seawater desalination plants (SWRO) as regard to the TDS and plant recovery, and that will be reflected on the used energy costs. So, the saving value that has been calculated increases when we desalinate fully or partially the brackish water by RO. So, the study chose seawater desalination as it is the worst case in energy consumption, so the results will have an effect on decision makers.

D Specific Cost Reduction of Desalinated Water

When reduction of operation and maintenance cost in the plant happened, that would decrease the production cost of desalinated water per cubic meter (m3). See the following figure (14).

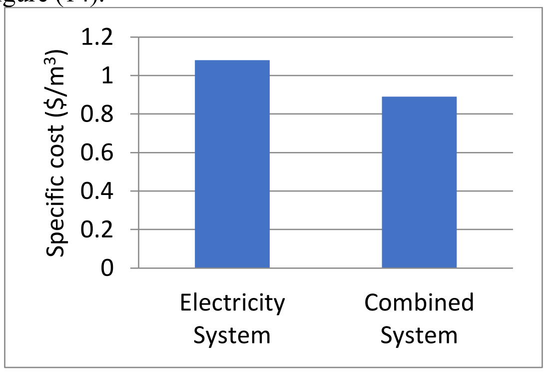

Figure 14 Specific Cost of Desalinated Water

E Cost Reduction of PV Modules

There is a big potential for further reductions of PV system costs. Less expensive materials would allow to cut significantly the costs of PV modules. Even if it is still uncertain how fast and to what extent this potential could be tapped by the PV industry, in the research there was enough evidence to indicate that PV systems in grid-connected building-integrated applications would be able to reach the break-even price and then compete without incentives with electricity [11].

V CONCLUSION

The third scenario (combined system-On Grid System) was selected as the best economic option to optimize the cost of the desalination plant in Gaza. Considering the On-Grid system, the unit cost for desalinated water will be reduced from 1.08 $/m3 to 0.89 $/m3 (Electric utility as a baseline) which is about 17% saving that is enough for the operating cost during 7.5 years for the SWRO desalination plant. This study was as an optimal method in Palestine to plan strategic water projects that are dependent on an energy source for operational purposes specially desalination plants projects that its structural design should include all specific details of solar energy system such as plant site, roof areas, storage locations, etc. Finally, using On Grid solar energy system as the energy source in desalination plants in Gaza decreases the treated water cost that will be more decreased in future surely when we support the solar industry of all types in our region.

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