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Feasibility study for different configurations of PV Panels Coupled with RO Desalination Systems

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Abstract: In the presence of overpopulation in Egypt, it was necessary to establish new cities. Hence, these new cities need water, where the Nile water budget is 55.5x10^9 m^3/ year in Egypt and this budget is fixed. So the only option needed to manage our resources efficiently is by searching and developing other resources, like using seawater desalination. This paper aims to compare the feasibility of using the three suggested configurations of the integrated solar photovoltaic into a reverse osmosis desalination system (with a capacity of 254,000 m^3/ day). Within the framework of this paper, a simplified approach has been elaborated, which allows a quick but relatively precise assessment of the investment as well as of the operational cost of solar desalination plants. In addition, the results show the sensitivity of the Levelised Cost of Water as a function of selected key parameters. The designs have been carried out according to the manufacturer‘s recommended specifications using a commercially available simulation tool (IMSDesign software program and PVsyst software program). The best configuration (The integrated solar photovoltaic into reverse osmosis desalination system with solar photovoltaic and electricity grid) was selected because it has the lowest cost of a cubic meter of water (0.892 USD/ m^3)**.**

Keywords: *Planning of water projects; The integrated solar photovoltaic into reverse osmosis desalination system (PV-RO)*

1. INTRODUCTION

In the presence of overpopulation in Egypt in the last decades, it was necessary to establish and expand new cities to accommodate this overcrowding. Hence, these new cities need water, where the Nile water budget is 55.5x10^9 m^3/ year in Egypt and this budget is fixed. So the only option needed to manage our resources efficiently is by searching and developing other resources, like using seawater desalination and reuse the tertiary treated wastewater to reduce the depletion of water resource-limited for future generations. Energy and freshwater production are heavily interconnected; the integration of renewable energy into water desalination systems has become increasingly attractive due to the growing demand for water and energy. Solar energy is the most readily applicable source of renewable energy to be integrated with desalination technology [1]**.**

The new city of Burj Al Arab is a sample of the new (residential and industrial) cities that have been studied in this paper. This paper aims to compare the feasibility of using the three suggested configurations of the integrated solar photovoltaic into a reverse osmosis desalination system (PV-RO) (with a capacity of 254,000 m^3/ day). The best configuration was selected to supply the new Burj Al Arab city with water to cover future needs. This is in line with the directives of the government in Egypt. There are other benefits, such as reducing dependence on Nile water to benefit from it in other landlocked areas and reducing harmful gases resulting from electricity generation by traditional methods used in seawater desalination**.** Within the framework of this paper, a simplified approach has been elaborated, which allows a quick but relatively precise assessment of the investment as well as of the operational cost of the three PV-RO systems configurations included in this report. Also, the results will show the sensitivity of the Levelised Cost of Water (LCOW) as a function of selected key parameters. After this analysis and comparison, the best alternative will be selected**.**

- **The three suggested PV-RO plant configurations as follows:**

a) PV-RO system with PV solar only: in this case, the solar photovoltaic (PV) power station is the only electricity source for the reverse osmosis (RO) desalination plant. Accordingly, the operation of the RO plant is intermittent **(Figure (1)).**

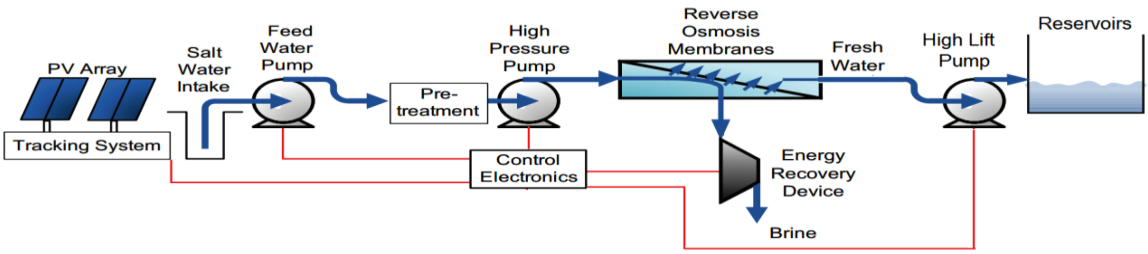

Figure (1): Schematic representations of PV-RO system with PV solar only.

b) PV-RO system with PV solar and batteries: the RO operation time is extended by batteries with three full load hour capacity. Accordingly, the operation of the RO plant is intermittent **(Figure (2)).**

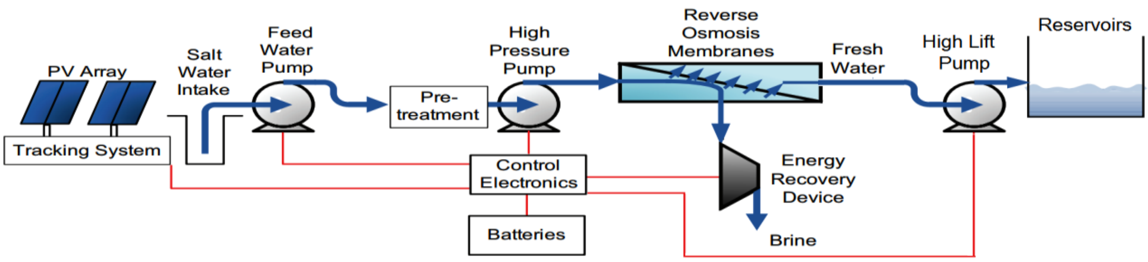

Figure (2): Schematic representations of PV-RO system with PV solar and batteries.

c) PV-RO system with PV solar and electricity grid: The PV is designed in order to cover the electricity requirements of the RO plant. The continuous operation of the RO plant is guaranteed by the backup electricity is provided by the grid **(Figure (3)).**

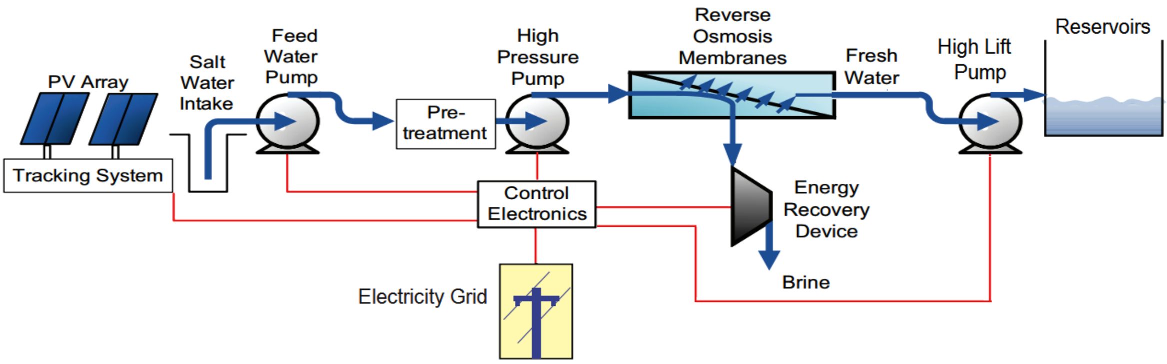

Figure (3): Schematic representations of PV-RO system with PV solar and electricity grid.

- **Study area**

The new Burj Al-Arab is a sample of existing residential and industrial new cities that studies in this paper, located just about 60 km in the direction of West Alexandria, Egypt [2]. The suggested PV-RO system location at Kilo 51 Alex -Matrouh Coastal road, with coordinates of latitude 30° 92' N and Longitude 29° 44' E, which far from New Burj Al-Arab city about 16 km and it's the elevation above the sea level by 18 meters [3].

2. METHODOLOGY

To design the proposed Seawater Reverse Osmosis plant (SWRO) powered by PV, documentary data were collected from several governmental and non-governmental organizations and institutions. Part of the data was used in the IMSDesign software program and another part was used in the PVsyst software program. IMSDesign software program was used to design a membrane-driven desalination plant [4]. PVsyst V6.86 software program was used to design, optimize, sizing PV arrays and battery banks and analyze the performance of the designed PV system [5]. In the following paragraphs, the fundamental principles of the design process will be given.

The (PV- RO) System Design Calculations

The following steps are guidelines to design the 254,000 m^3/ day reverse osmosis plant coupled to PV panels [6]; and considering the new technology based on energy recovery devices.

- **Step 1: Determine the product volume requirement**

The maximum monthly discharge is assumed be equal to (254,000 m^3/ day).

$F_{Total} = maximum\ monthly\ discharge\ +\ 7\ \%$ = (271,780 m^3/ day) (1)

Where, F_{Total} = total amount of product water to be produced by membranes (m^3/d) [7].

- **Step 2: Determine the characteristics of the feed water and maximum water recovery possible during desalination**

The design calculations presented down here are based on seawater analysis of Egypt offshore. The following parameters should be taken into considerations:

- Feedwater salinity (TDS) = 39,284 mg/l based on (Sidikerir Region, west of Alexandria, Egypt offshore sample during summer season with water temperature 25(℃)) [8].
- The product water salinity is targeted to be in the range of 500 mg/ l [9].
- Maximum Recovery Ratio (RR) = 40% [10].

- **Step 3: Consider pre-treatment requirements**

A pre-treatment system requires additional water for maintenance purposes such as backwash, etc. Therefore the feed pumps must supply an additional volume of water for the pre-treatment system and not only for the RO membranes. **Equation (2)** will give the total water supply per day (to be provided by the feed pumps) [10].

$$F_{Total\ (Feed)} = \frac{\text{maximum monthly discharge} + 7\ \%}{RR} = (679{,}450 m^3/\ day) \qquad (2)$$

Where, $F_{Total\ (Feed)}$ = Total water amount to be supplied [m^3/d]; RR = Maximum Recovery Ratio allowed, obtained from **Step 2**. **Figure (4)** shows the design flow rates of the desalination plant.

- **Step 4: Consider post-treatment and brine discharge**

i) Post-treatment

The Produced water from the RO plant needs to be stabilized and disinfected before it can be used and for these reasons the importance of the ground tanks [10].

The ground tanks will be designed as following [7]:

The fire requirements in the new Burj Al-Arab city are equal to 1944 m^3/ day [6].

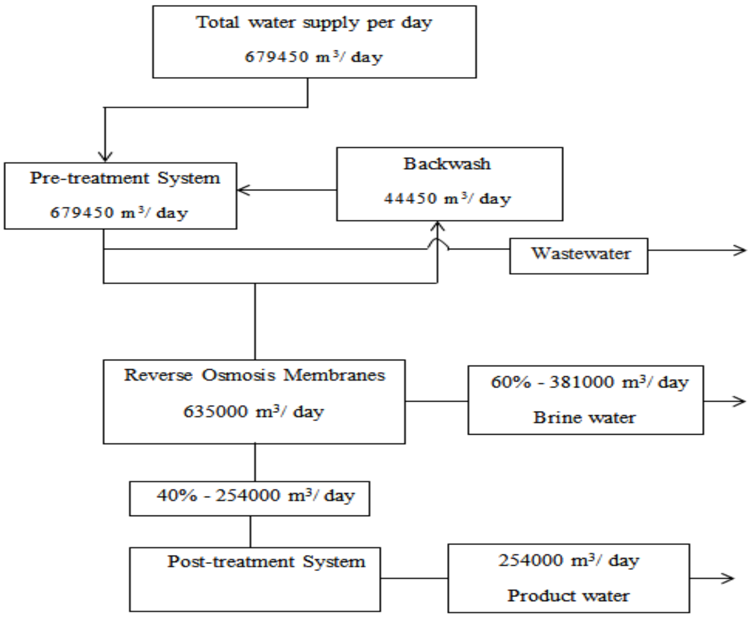

Figure (4): Flow diagram of the desalination plant.

The total ground storage requirements = (25%) From the volume of the daily production of the station + (80%) of the fire requirements = (65,055 m^3) (3)

The establishment of five ground storage reservoirs for drinking water is proposed with a capacity of 15,000 m^3/ tank with a total capacity of about 75,000 m^3**.**

ii) Brine Discharge

The brine water will be released into the sea. This outfall technique should be investigated by a specialist to determine if any damage to the environment may accrue [10]**.**

❖ Step 5: Calculate the feed pressure requirement and the number of membranes required

Integrated Membrane Solutions Design (IMSDesign) software was used to design, optimize and analyze the performance of the designed plant and testing the configuration according to seawater analysis. Elements are selected according to feed water salinity, feed water fouling tendency, required productivity, and salt rejection, as well as energy requirements, where the membranes are selected for the designed plant, is SWC6 and IMSDesign software. **Table (1)** shows the design parameters of the designed RO desalination plant, including the amount of pressure required for the desalination process [4]**.**

❖ Step 6: Estimate the energy requirements of the RO plant

a) High-pressure pumps energy requirements ($E_{desalination}$)

High-Pressure Pumps (HPP) are used to achieve this high feed pressure. However, this results in high energy demands ($E_{desalination}$) for the RO process [10]. Therefore, a high-pressure pump with Energy Recovery Devices (ERD) will be chosen to reduce the energy used in the desalination process**.**

b) Additional systems energy requirements

Apart from the desalination energy, the RO plant needs basic electricity for auxiliary systems, lighting, etc. By using a slight over-estimated pressure for the pre- & post-treatment depending on the design. The following sub-sectors will give an estimated energy requirement for these systems [10]**.**

- **Transfer pumps (Feedwater pumps) energy requirements ($E_{(\text{Transfer pumps})}$) and Lifting pumps energy requirements ($E_{(\text{Lifting pumps})}$)**

Transfer pumps are used to pump the clarified seawater to the pressure required by the pretreatment stage [10]. Lifting pumps will be used to lift water from the RO station to the ground tanks in the new Burj Al-Arab city.
The $E_{\text{desalination}}$ and other design parameters of the high-pressure feed pumps can be obtained from an IMSDesign detailed report (see **Table (2)**). **Tables (2)** also show the design parameters of the transfer Pumps and lifting pumps.

Table (1): Design parameters of the RO plant.

Design parameters	Pass 1	Total system
Company name	Hydranautics	
Design software used	IMS design	
Pressure vessels configuration	1 stage	
No. of trains		10
Permeate recovery %	40	40
Average flux, lmh	13.5	
No. of pressure vessels	318	3180
No. of membranes	1908	19080
No. of membranes per pressure vessels	6	
Nominal diameter, inch	8	
Membrane model	SWC6 MAX	
Max. operating pressure, bar	83	
Working pressure, bar	51	
Ph	8	
Temperature, °C	25	
Feed flow, m^3/ d	63500	635000
Permeate flow, m^3/ d	25400	254000
Concentrate flow, m^3/ d	38100	381000
Fouling factor, %	96	96
Concentrate salinity, mg/ l	65163	65163
Permeate salinity, mg/ l	433.86	433.86
Feed salinity, mg/ l	39284	39284

Table (2): Transfer Pumps, high-pressure pumps, and lifting Pumps design parameters.

Power Calculation (with ERD)	Transfer Pumps	High-pressure pumps	Lifting Pumps
Working pressure, bar	4.5	51	2.84
Product flow m^3/ d	679450	254000	254000
Pump flow m^3/ d	86400	63500	86400
Total number of high-pressure pumps	(8 main + 4 stand by)	(4 main + 2 stand by)	(3 main + 2 stand by)
Pump efficiency %	87	87	87
Motor efficiency %	95	95	95
Variable Frequency Drive (VFD) efficiency %	97	97	97
Total pumping power KW	4402.4	24473	1041.9
Total energy consumption of pumps KWh	105657.6	587352	25005.6
Pumping specific energy KWh/ m^3	0.42	2.31	0.1

The total power required for the RO plant can be calculated as follows [6]:

- **The first (Total Power MW(P_{Total})):**

$$P_{Total} = (P_{(desalination)} + P_{(\,transfer\ pumps)} + P_{(\,lifting\ \ pumps)}) \tag{4}$$

$$P_{Total} = (24473 + 4402.4 + 1041.9) = 29917.3\ kW \approx (30\ MW)$$

- **The second (Total Energy MWh (E_{Total})):**

$$E_{Total} = (E_{(desalination)} + E_{(\text{transfer}\ pumps)} + E_{(Lifting\ pumps)}) \tag{5}$$

$$E_{Total} = (587352 + 105657.6 + 25005.6) = 718015\ KWh \approx (720 MWh)$$

- **The third (Total specific energy kWh/m^3 *(SE Total)*):**

$$SE\ Total = \left(\frac{E_{(desalination)}}{Total\ Water\ production} + \frac{E_{(\text{transfer}\ pumps)}}{Total\ Water\ production} + \frac{E_{(Lifting\ pumps)}}{Total\ Water\ production}\right) \tag{6}$$

$Total\ specific\ energy =$ (2.31 + 0.42 + 0.1) = (2.83 kWh/ m^3**).**

❖ Step 7: The photovoltaic systems (PVs) design calculations

In this paper, PVsyst simulation tool is used to design and model the PV energy supply. PVsyst performs yearly simulations using hourly weather data which are more accurate than manual calculations using average monthly or yearly irradiation data [5]. PVsyst also performs detailed analysis on the performance of the battery bank, particularly in terms of the battery state of charge (SOC), which helps in obtaining more accurate battery sizing**.**

It is important to keep in mind that the irradiation value strongly depends on the station of the year, reaching its maximum values in summer, and minimum values in winter this is for PV system part [5]. On the other side the maximum demand for clean water in the summer and minimum demand in winter, and maximum values in feed water salinity for RO system in summer, and minimum values in winter [8]. To accomplish a correct design, one must select the summer values**.**

a) The meteorology data for design and analyze solar system

- **A Geographical site defined:**

The coordinates will be defined by the Google earth map to get the parameters of the defined site [3]. Using these parameters and entering them into a PVsyst simulation program to get monthly meteorology data on PV system site. **Figure (5)** shows the global irradiation data at the location assumed for the RO plant (30° 92' N, 29° 44' E) and the conversions on Two-axis tracking planes as estimated by the PVsyst software program**. Table (3)** lists the system parameters used in designing the PV energy supply[5]**.**

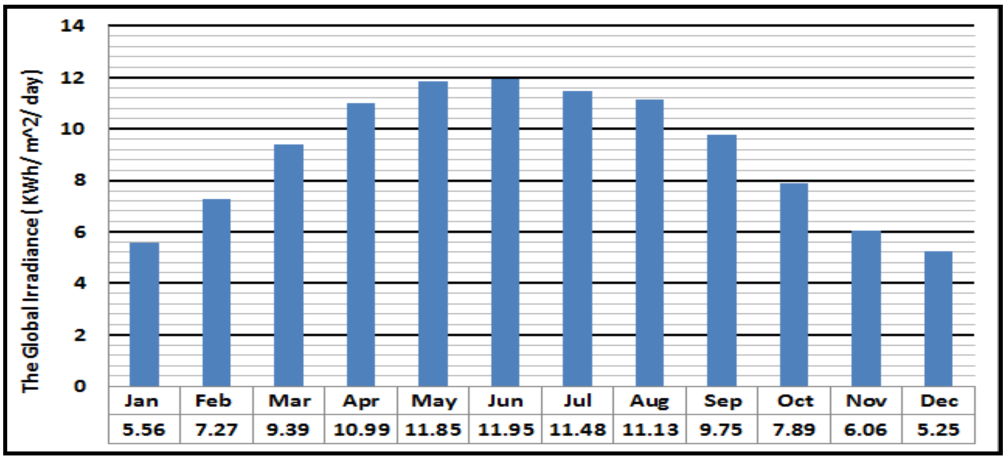

Figure (5): The irradiation section results of the simulation using PVsyst software [5].

Table (3): System parameters that are used in designing the PV energy supply [5].

Battery Specifications		Reference
Battery voltage	51.4 V	**Manufacturer, model:** LG Chem, EM048290P5B1 290Ah [9].
Battery capacity	3.81 kWh	
Coulombic efficiency	96 %	
PV Module Specifications		**Module specifications based on:** Monocrystal Technology **Manufacturer:** Talesun Solar Model: TP6H72M-440-L [9].
Vmpp (STC)	42.6 V	
Impp (STC)	10.33 A	
Pmpp (STC)	440.2	
Voc (STC)	50.8 V	
Isc (STC)	10.90 A	
Module efficiency (STC)	21.9%	
Inverter Specifications		**Manufacturer, model:** Zeversolar, Zeverlution Pro 40K-MV [9].
Nominal AC power	40 kWac	
Nominal voltage	600 V	
European average efficiency	98.2%	

b) Estimate the levelized cost of electricity of the PV system

- **Cost reviews**

In this paper, the cost data from some publications were used to develop **Table (4)** providing cost assumptions for different PV systems [11-21]**.**

- **Measuring the Cost of Renewables**

According to OECD and NEA (2018), the cost of electricity can be categorized into three different levels:

A- PV plant (PV system)-level costs;

B- Grid-level system costs;

C- External or social costs outside the electricity system.

The plant-level cost is commonly referred to as the technology cost, described as the Levelised Cost of Electricity (LCOE), which represents the lifetime costs divided by the electricity production. Grid-level system costs concern the costs at the level of the electricity system, linked through the transmission and distribution grids. The third category includes items that impact the well-being of individuals and communities outside the electricity sector [11]. Known as external or social costs, such costs include the impacts of local and regional air pollution, climate change…, etc.

There are well-established methodologies applied in any kind of industry to compare different projects involving cash flows over several years. The most commonly applied indicators used in the evaluation of investments are the "amortization factor" or the "annualized life cycle cost method" was used. The situation is similar in energy projects, where the price at which the generated electricity can be sold has to be known. In that case, the concept of the LCOE has been introduced, which is an assessment of the price at which the electricity would have to be sold for the project to break even and is calculated by dividing the discounted costs over the lifetime of the project by the discounted energy produced over the same period. **Equation (7)** is obtained for the Levelised Cost of Electricity ($\mathrm{LCOE}_{t,n}$) of PV-generated power [11, 12]**.**

$$\mathrm{LCOE}_{t,n} = \frac{\text{sum of costs over lifetime}}{\text{sum of electrical energy produced over lifetime}} = \frac{\mathrm{I}_{(PV)0} + \sum_{t=1}^{n(pv)} \frac{\mathrm{C}_{(PV)t}}{\left(1+\mathrm{i}_{(PV)}\right)^{t}}}{\sum_{t=1}^{n(pv)} \frac{\mathrm{E}_{(PV)t}}{\left(1+\mathrm{i}_{(PV)}\right)^{t}}} \tag{7}$$

where, the initial capital investment is ($\mathrm{I}_{(PV)0}$), it is assumed that every year (from year 1 to year $n(pv)$) the photovoltaic system produces exactly the same amount of energy produced in a year ($\mathrm{E}_{(PV)t}$) and has exactly the same annual cost operation and maintenance ($\mathrm{C}_{(PV)t}$), $\mathrm{i}_{(PV)}$ represents the discount rate [12]**.**

Table (6) also illustrates the costs and related assumptions of the three configurations we evaluated. It is shown that both (PV-RO system with PV solar only) and (PV-RO system with PV solar and Batteries) result in higher LCOE costs (Unit Energy Cost) than the (PV-RO system with PV solar and electricity grid)**.**

❖ **Step 8: Estimate the levelised cost of water of the RO plant**

- **Cost reviews**

In this paper, the data from some publications were used to develop **Table (5)** providing cost assumptions for RO desalination technology powered by conventional sources and renewable energy. All these papers classify costs based on technology and energy source and sometimes plant size [22-28].

Table (4): Parameters with values used for the PV system economic analysis.

Parameters	Reference	Value Used
Discount rate	[13]	5 %
PV Module Lifetime (Project lifetime)	[13, 14, 15, 16, 19]	25 Years
Inverter Lifetime	[13]	15 years
Battery Lifetime	[5]	5 years
Solar PV costs	[14, 16]	600 USD/ KW
Inverter or converter costs	[14, 16]	160 USD/ KW
Battery costs	[16, 20]	1500 USD/ kW
Mounting structure costs	[14, 16]	600 USD/ KW
Balance of system (BOS) costs	[14]	540 USD/ KW
Operation and maintenance costs	[14]	1.5 % of the capital cost
The Levelized transmission cost	[18]	3.3 USD/ MWh
Emission factor for Electricity and Carbon Tax	[21]	9.7×10^{-3} USD/ kWh
Grid selling price	[28]	0.079 USD/ kWh

Table (5): Parameters with values used for the RO system economic analysis.

Parameters	Reference	Value Used
Discount rate	[22]	5 %
The availability rates of the RO plant	[22, 23]	90% (Grid powered). 29% (PV powered).
RO Plant Lifetime (Project lifetime)	[24]	25 Years
The capital cost of a water transmission line	According to the Egypt building index at 23-4-2020	625 USD/ m/ line
The capital cost of ground storage tanks		125 USD/ m^3/ tank
The capital cost of a RO plant	[25]	1102.36 USD/ m^3
Chemicals costs	[25]	0.02 USD/ m^3
Specific costs for labor	[22, 23, 25]	0.02 USD/ m^3
Membrane replacement rate. Replacement cost.	[23, 24]	**Membrane replacement rate** = (15 %/ yr) (Grid powered). = (40 %/ yr) (PV powered). **Membrane cost** = 846.40 USD/ element.
Other maintenance costs	[23, 25]	0.02 USD/ m^3
Brine Disposal cost	[22, 23]	0.04 USD/m^3

Table (6): The data inputs and the results of the economic study (LCOE) for the three PV configurations; assumptions electricity cost from the grid in the year 2020 [11-21].

Identifier	PV solar only	PV solar and batteries	PV solar and electricity grid
PV configuration	Two-axis tracking	Two-axis tracking	Two-axis tracking
Average RO load (kW)	30000	30000	30000
Global horizontal irradiation (daily inputs) (total kWh/ m^2/ year)	3055	3055	3055
PV module dc efficiency (%)	21.9	21.9	21.9
PV system efficiency (%)	17.68	16.85	17.68
Solar Fraction (E / E_{TOTAL}) (%)	29.27 (From the PV)	61.41 (29.27 From the PV) + (32.14 From the batteries)	100 (29.27 From the PV) + (70.73 From the grid)
PV capital cost (USD/ kW)	1706.6	7504.5	1706.6
PV O&M cost (USD/ kW/ year)	25.6	112.7	25.6
PV lifetime (years)	25	25	25
Discount rate (%)	5	5	5
Grid selling price (USD/ kWh)			0.079
Levelized transmission cost and distribution grid infrastructure (USD/ kWh)			3.3×10^{-3}
Emission factor for Electricity and Carbon Tax (USD/ kWh)			9.7×10^{-3}
LCOE solar electricity (USD/ kWh)	0.1	0.21	0.1
LCOE mix electricity into RO (USD/ KWh)	0.1	0.21	0.086

- **Investment evaluation indicators**

The situation is similar in energy projects, where the price at which the generated electricity can be sold has to be known. In that case, the concept of Levelised Cost of Electricity (LCOE) has been introduced, which is an assessment of the price at which the electricity would have to be sold for the project to break even and is calculated by dividing the discounted costs over the lifetime of the project by the discounted energy produced over the same period. By adapting that concept for desalination and other water production technologies, **Equation (8)** is obtained for the Levelised Cost of Water (LCOW) [23]**.**

$$\mathrm{LCOW} = \frac{\text{sum of costs over lifetime}}{\text{sum of the amount of water produced over lifetime}} = \frac{I_0 + \sum_{t=1}^{n} \frac{C_t}{(1+i)^t}}{\sum_{t=1}^{n} \frac{p_{\text{Water}}}{(1+i)^t}} \tag{8}$$

where, the initial capital investment is (I_0), it is assumed that every year (from year 1 to year n) the desalination plant produces exactly the same amount of water produced in a year (p_{Water}) and has exactly the same annual cost operation (C_t), i represents the discount rate**.**

3. RESULTS AND DISCUSSION

As mentioned, all the three suggested PV-RO plant configurations are assumed to have the same design capacity of 254000 m³/ day. A salinity of 39,282 ppm has been assumed. See detailed design results in **Table (7).**

- The comparison of the LCOW shows that (under the given assumptions) the PV with grid backup configuration is the best-performing one because it gave the lowest cost of cubic meter production (0.892 USD/m³), which is due to the low cost of unit energy for the integration of electricity of the grid and the PV system of 0.086 USD/kWh and high RO plant availability rate of 90%). **Figure (6**) shows the breakdown of the annualized cost of the (PV-RO system with PV solar and electricity grid) configuration. The breakdown includes capital costs of the RO plant, Energy costs, net maintenance costs, and net other operating costs. In this scenario, energy accounts for 27.24% of the water production cost**.**
- The (PV+ battery) - RO delivers high LCOW (1.585 USD/m³), which is due to the intermittent operation of the desalination plant (the (PV+ battery) system covers 61% of the capacity of the RO plant). Also, the still relatively high investment, operation, and maintenance costs for the battery. This characteristic can also be appreciated in **Figure (7)**, which shows the share of capital cost, operation cost, and electricity on the LCOW**.**

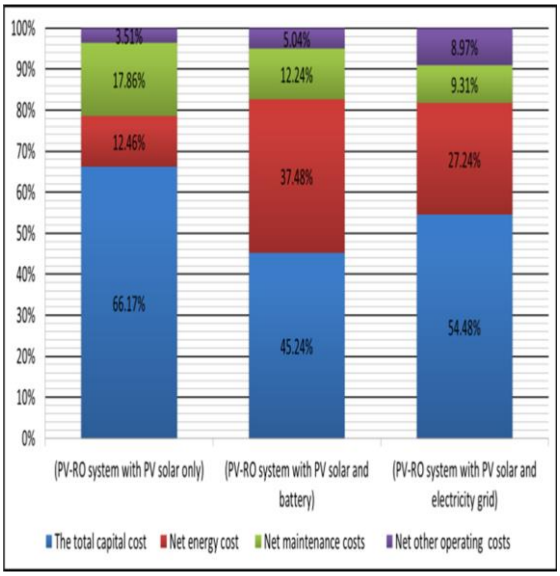

Figure (6): Water production cost breakdown for the three PV- RO configurations (in %)**.**

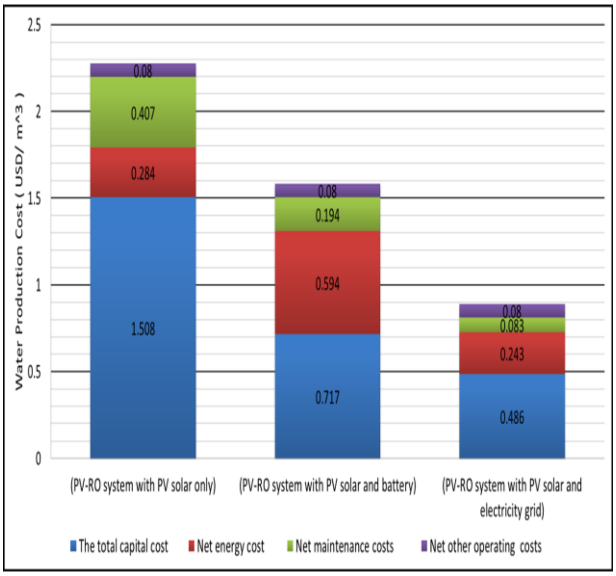

Figure (7): LCOW comparison by configuration and by cost item.

Table (7): Water production cost estimates for the three PV- RO configurations [22-28].

Identifier	Units	PV-RO system with PV solar only	PV-RO system with PV solar and battery	PV-RO system with PV solar and electricity grid
The design capacity of RO plant	m^3/d	254000	254000	254000
Working pressure	bar	51	51	51
Permeate recovery	%	40	40	40
The design capacity of PV system	MW	30	30	30
Discount Rate	%	5	5	5
RO plant lifetime	Year	25	25	25
PV System Efficiency	%	17.68	16.85	17.68
RO plant Availability rate ≈ Solar Fraction	%	29	61	90
The actual amount of water produced in a year	m^3/d	73660	154940	228600
Amount of water produced in a year	m^3/yr	26885900	56553100	83439000
Capital Expense				
RO capital cost	USD	280×10^6	280×10^6	280×10^6
The capital cost of water transmission line	USD	10×10^6	10×10^6	10×10^6
The capital cost of ground storage tanks	USD	9.375×10^6	19.375×10^6	9.375×10^6
The total capital cost	USD	299.375×10^6	299.375×10^6	299.375×10^6
Energy Expense				
Total specific energy	KWh/m^3	2.83	2.83	2.83
The unit energy cost for all PV system configurations	USD/ kWh	0.1	0.21	0.086
Energy expense	USD/m^3	0.283	0.594	0.243
Net energy cost	USD/ yr	7.61×10^6	33.59×10^6	20.28×10^6
Membrane replacement cost and Other maintenance costs				
Total elements	Number	19080	19080	19080
Membrane replacement rate	%/ yr	40	40	15
The membranes that replaced it	Number	7632	7632	2862
Replacement cost	USD/ element	846.40	846.40	846.40
Replacement cost for elements	USD/ yr	6.46×10^6	6.46×10^6	2.42×10^6
Other maintenance costs	USD/ yr	4.49×10^6	4.49×10^6	4.49×10^6
Net maintenance costs (M costs)	USD/ yr	10.95×10^6	10.95×10^6	6.91×10^6
Other operating costs				
The chemical costs	USD/m^3	0.02	0.02	0.02
The specific costs for labor	USD/m^3	0.02	0.02	0.02
Brine disposal cost	USD/m^3	0.04	0.04	0.04
The total of other operating costs	USD/m^3	0.08	0.08	0.08
Net other operating costs (O costs)	USD/ yr	2.15×10^6	4.52×10^6	6.68×10^6
The annual cost of operation and maintenance				
The annual cost of (O and M)	USD/ yr	13.1×10^6	15.47×10^6	13.59×10^6
The total annual cost of operation, maintenance, and energy				
The annual cost of (Energy, O, and M)	USD/ yr	20.71×10^6	49.06×10^6	33.87×10^6
Water Production Cost (LCOW)				
LCOW	USD/m^3	2.279	1.585	0.892

- The PV -RO solar only case delivers much higher LCOW (2.279 USD/m^3), which is due to the photovoltaic system operates only during daylight hours, which is solely used for the supply of the desalination plant (as no electricity is fed from the electricity network in these cases). Electricity generated by the photoelectric system covers 29% of the capacity of the RO plant (RO plant Availability rate ≈ Solar Fraction) and this results in less water produced, which causes the price of cubic meters produced from the water to rise.

4. CONCLUSIONS

There are three the PV-RO plant suggested configurations, available as alternatives for water supply are studied and compared to choose the best one to supply the city during the development period. These configurations are:

1- PV-RO system with PV solar only (LCOW is **2.279 USD/ m^3).**

2- PV-RO system with PV solar and Batteries (LCOW is **1.585 USD/ m^3).**

3- PV-RO system with PV solar and electricity grid (LCOW is **0.892 USD/ m^3).**

According to the results, the third configuration is the best economic configuration, because it has the lowest cost of a cubic meter of water. The PV-RO system with PV solar and the electricity grid (with 254000 m^3/ day capacity at an estimated cost of 350.573×10^6 USD) project should be implemented. This is to supply the new Burj Al Arab city with water to cover future needs. There are other benefits to the project, such as reducing dependence on Nile water to benefit from it in other landlocked areas and also reducing harmful gases resulting from electricity generation by traditional methods used in seawater desalination**.**

Symbols and Abbreviations

Abbreviations		**Symbols**	
ED	Electro-Dialysis	$C_{E,t}$	The energy-related cost for the year (t)
ERD	Energy Recovery Devices	C_t	The annual cost operation of RO plant
HPP	The High Pressure Pump	$C_{(PV)t}$	The same annual cost operation and maintenance
LCOE	The Levelised Cost of Electricity	E_{Total}	Total required energy of the RO plant
LCOW	The Levelised Cost of Water	$E_{(desalination)}$	High-pressure pumps energy requirements
MED	Multi-Effect Distillation	$E_{(Lifting\ pumps)}$	High lifting pumps energy requirements
MSF	Multi-Stage Flash	$E_{(PV)t}$	The photovoltaic system produces the same amount of energy produced in the year
O&M	operation and maintenance	$E_{(\text{transfer}\ pumps)}$	Transfer pumps energy requirements
PV	Photovoltaic	i	The discount rate of RO plant
PV-RO	The solar PhotoVoltaic panels coupled to Reverse Osmosis desalinate water system.	I_0	The initial capital investment of RO plant
RO	Reverse Osmosis	$I_{(PV)0}$	The initial capital investment of PV system
RR	The Recovery Ratio	n	The number of years.
SOC	The battery State of Charge	$n(pv)$	The PV system lifetime
STC	Standard Test Conditions	P_{Total}	Total required power of the RO plant
SWRO	Seawater Reverse Osmosis	p_{Water}	The amount of water produced in a year by RO plant
VC	Vapor Compression	$P_{(desalination)}$	Total power consumption of high-pressure pumps
TDS	Total Dissolved Solids	$Power_{(\ lifting\ \ pumps)}$	Total power consumption of high lifting pumps
USD	United States Dollar	$Power_{(transfer\ pumps)}$	Total power consumption of transfer pumps
VFD	A Variable-Frequency Drive	*SE Total*	The total specific energy of the RO plant

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