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Design and Cost Analysis of a Solar Photovoltaic Powered Reverse Osmosis Plant for Masdar Institute

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Abstract

In this study we designed a cost-effective solar photovoltaic (PV) powered reverse osmosis (RO) desalination plant for Masdar Institute of Science and Technology. The proposed system allowed us to design a RO plant that does not rely on expensive batteries or extra land and drastically decreased the government expenses to subsidize the water production cost to 84% of the current expenses. In additional, the system allowed to reduce the emission of GHG by 1,035 tCO2 annually. The equity payback time was found to be 23.3 years and the benefit-cost ratio to be 0.72. Comparing the results obtained with the conventional values, it can well be said that this system would definitely provide a much needed efficient alternative to the current method of water purification making it more sustainable and economically feasible at the same time.

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Keywords: Desalination; reverse osmosis (RO); solar photovoltaic (PV); cost analysis

1. Introduction

Masdar Institute of Science and Technology is a graduate research university located in Abu Dhabi, dedicated to the goal of sustainability, and has an on-going collaboration with MIT. The water needs for Masdar Institute are fulfilled using governmental managed thermal desalination plants that operate using fossil fuels. In order to achieve the vision of Masdar Institute in utilizing renewable energy, a desalination reverse osmosis (RO) plant powered by solar photovoltaic (PV) is proposed to satisfy the water needs of Masdar Institute.

2. Methods

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This analysis has three main components: (1) estimation of the water consumption and cost at Masdar Institute, (2) calculation of the electric power and financial cost required to run a reverse osmosis (RO) unit, (3) estimation of the area and cost associated with constructing a small-scale photovoltaic plant to supply the power requirements of RO.

The main challenge in this project is to match the required constant demand of water with the available fluctuating supply of solar energy. A variety of solutions were proposed to overcome this problem as outlined in Table 1. Using batteries to store energy is a reliable solution, but ineffective in terms of cost and technology. Producing extra water and storing it in backup tanks is a simple solution. However, it is not applicable due to limitation in land area. Another solution is to increase PV capacity and sell extra produced electricity to grid. Then import electricity from grid during periods when solar radiation is insufficient. Nevertheless, the overall system is relatively complicated. The proposed solution for this study is to supply the required power to run the RO plant directly from grid and use PV to produce the annual required energy for RO and send it directly to grid. Therefore, a constant supply of energy is guaranteed to run the RO plant without the need to buy extra expensive batteries or use more land area for additional tanks.

This RO-PV project is divided into two main plants: (1) RO plant (2) PV plant. The design, costs, and financial statistics are discussed for each plant separately in subsection 2.2 and 2.3. The results section discusses the coupling of the two plants into one project and evaluates the benefits and implications.

Table 1. Selection matrix for PV-RO project. A value of 5 resembles best whereas a value of 1 represents worst.

Technique	Cost	Technology	Reliability	Applicability	Total
Store energy using batteries	2	1	5	5	13
Store water using extra tanks	5	5	4	1	15
Increase PV capacity and sell/buy from grid when needed	4	4	5	2	15
Send produced PV electricity to grid and run RO from grid	4	4	5	4	17

2.1. Water consumption and cost

Masdar Institute is currently divided into two main blocks: 1A and 1B. Each block requires 100 m^3 of water per day. Abu Dhabi Distribution Company (ADDC) produces water at a rate of up to AED 7.35 /m^3 or \$ 2 /m^3 [1] and sells water to Masdar Institute at a rate of AED 2.2 /m^3 or \$ 0.6 /m^3 [2].

2.2. Reverse Osmosis (RO) plant design and costs

ROSA 9.0 software was used to design a small-scale RO plant. The plant is designed considering the requirement of Masdar Institute which is 200 m^3/day. The properties of seawater in Abu Dhabi were used. Table 2 lists the composition of the considered saline water [3]. The design includes a pretreatment process in which fouling elements would be removed. Conventional pretreatment was selected due to the low cost in incurs [4]. Considering the required capacity, a single stage plant was designed. The number of elements in each pressure vessel were considered to be 8 [5]. The operating temperature was chosen to be 26˚C and the final pH of water 8.0. It is worth mentioning that the lower the operating temperature is, the higher feed pressure is needed for RO. Therefore, 26˚C was selected to design for the maximum power requirement. An efficiency of 40% is considered. The RO analysis done using ROSA 9.0 software suggested that a specific energy of 6.99 kWh/m^3 would be needed.

Table 2. Seawater composition in Abu Dhabi

Element number	Element	Concentration (mg/L)
1)	Sodium	16290
2)	Chlorine	26120
3)	Magnesium	1730
4)	Calcium	520
5)	Carbonate	11.29
6)	Bicarbonate	70
7)	Silica	4020

Table 3. Inputs and outputs of RO into ROSA 9.0 software

Item	Description	Value
System water production	Permeate	56 m^3/hour
System recovery	Fresh water produced from feed	40 %
Project life	Life expectance of the project	30 years
Interest rate	-	8 %
Power cost	Cost of power required to run pumps	\$ 0.168 /kWh
Number of pressure vessels	-	12
Cost per pressure vessel	-	\$ 500
Number of elements	-	96
Cost per element	-	\$ 750
Pumping power	-	390 kW
Capital of total system	-	\$ 78,000
Operating expenses	Energy expenses + cost of membrane replacement	\$ 7,068,996
Cost of water (NPV)	-	\$ 0.49 / m^3

2.3. Photovoltaic (PV) plant design and costs

RETScreen software was used to estimate the energy production using solar PV and financial assessment of the plant. The aim is to produce energy using PV and sell it to central grid. This software was developed by Natural Resources Canada's Canmet Energy Research Center to analyze renewable energy projects. Various studies have utilized and validated the outcomes of this software [6,7]. First of all, an energy production analysis involving inputs and costs was carried out. Input values are tabulated in Table 4. The power capacity of the proposed PV system is 720 kW. The inverter capacity, the output of the inverter in AC kW, is calculated as the inverter efficiency multiplied by PV power capacity and found to be 684 kW. The capacity factor of the plant is 27.9% and the annual electricity exported to grid is 1757.8 MWh. The total solar collector area is 5038 m^2.

Table 4. Input values for RETScreen's energy model sheet.

Item	Input value
Solar tracking mode	One-axis
Slope	22°

Azimuth	0˚
PV module type	mono-Si – BP 590F (nominal operating temperature 45˚C).
Capacity of one PV unit	90 W / 0.63 m^2
Number of PV units	8000
Annual solar horizontal radiation (MWh/m^2)	NASA 22-year monthly average for Abu Dhabi International Airport
Miscellaneous losses	5% (dust and sandstorms)
Inverter efficiency (DC to AC)	95%
Inverter capacity	684 kW
Inverter losses	0%
Electricity export rate	$ 160 /MWh

Next, cost and financial analyses are carried out. The cost analysis estimates the initial, periodic, and end-of-life costs of the solar PV system. Table 5 summarizes the input values in the cost analysis. The financial analysis yields financial statistics such as net present value (NPV), simple payback period (SPP), and internal rate of return (IRR) of the project. The input values used in the financial analysis are listed in Table 5. Several references were used to provide relative estimates for the costs [8,9]. Finally, Table 6 summarizes the financial statistics of the PV plant. The net present value of the project is $ -2,896,244 and the equity payback period is 23.3 years.

Table 5. Initial, periodic, and end-of-life cost for the PV power plant.

Type of cost	$USD	% of initial costs
Feasibility study	22,466	0.22%
Development	18,382	0.18%
Engineering	16,339	0.16%
Power system (PV modules)	3,960,000	38.5%
Balance of system and miscellaneous	6,252,000	60.9%
Operation and Maintenance (O&M)	20,000	Every year
Inverter replacement costs	720,000	Every 5 years
End-of-project life	(1,021,200)	10%

Table 6. Inputs and outputs values for financial feasibility analysis of PV plant

Type of cost	$USD
Inflation rate	2.5%
Nominal discount rate	5%
Project life	30
Electricity export rate	$ 160 /MWh
Revenue of electricity exported to grid	$ 281,250
Electricity export escalation rate	4%
Net present value (NPV)	$ -2,896,244
Simple payback period	39.3 years
Equity payback	23.3 years

Benefit-cost ratio	0.72

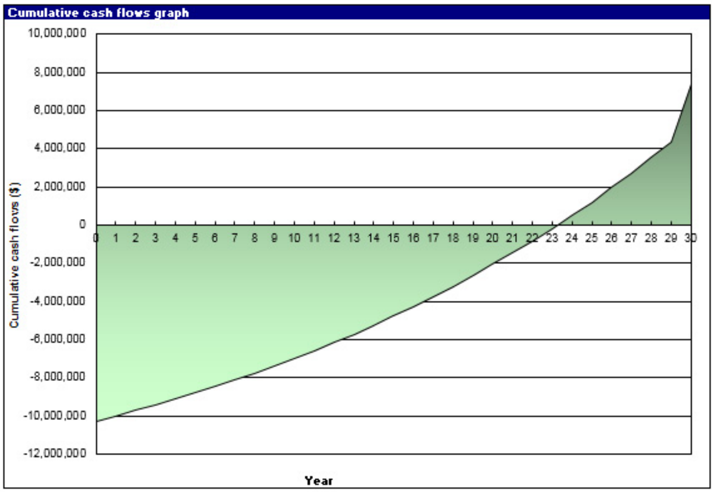

Fig. 1. (Cumulative cash flow graph for PV plant)

3. Results

In this section, we evaluate of the feasibility and benefits of the project.

To evaluate feasibility of proposed system we calculated and compared the cost of water that could be produced using this system and the cost of water purchased from ADDC, see Table 7. The proposed system gives higher water costs by \$ 0.225 /m^3. However, considering the costs of water production by ADDC and the price at which it is sold to Masdar, we conclude that the government subsidizes 70% of water cost, while using proposed system the government would need to subsidize only 26.8% of water cost. Hence, saving over \$ 17 million during the project life-time for the given water production or about 84% of the current expenses on water production subsidies.

Natural gas is the main fossil fuel used in the UAE to run the power plants. The GHG emission factor for natural gas is estimated to be 0.589 tCO2/MWh. Therefore, using PV to generate 1,758 MWh per year required to run the proposed RO plant will reduce the emission of GHG by 1,035 tCO2 annually. This is equivalent to almost 86 hectares of forest absorbing carbon.

Table 7. Financial statistics of combined PV-RO project

Total financial statistics for project life-time (30 years)	Unit
Total expenses for PV plant	\$ (13,427,987)
Total expenses for RO plant	\$ (7,146,997)
Income from PV plant energy fed to the grid	\$ 8,437,500
Total balance	\$ (12,137,484)
Water produced	14716800 m^3
Cost of produced water	\$ 0.825 /m^3
Cost of purchased water	\$ 0.6 /m^3
Government expenses to subsidize produced amount of water	\$ 20,603,520

using conventional method	
Government expenses to subsidize the project	$ 3,307,403
Government savings subsidizing the project	$ 17,296,116

4. Conclusions

In this study we designed a cost-effective solar photovoltaic (PV) powered reverse osmosis (RO) desalination plant for Masdar Institute of Science and Technology. The main challenge of fulfilling the required constant demand of water with the available fluctuating supply of solar energy was solved through supplying the required power to run the RO plant directly from grid and use PV to produce the annual required energy for RO and sell it directly to grid.

The proposed system allowed us to design a RO plant that does not rely on expensive batteries or extra land and drastically decreased the government expenses to subsidize the water production for 84% of the current expenses on water production subsidiaries. In additional, the system allows to reduce the emission of GHG by 1,035 tCO2 annually. The equity payback time is 23.3 years and the benefit-cost ratio is 0.72. Considering the high amounts spent for the desalination of water using thermal based technologies and comparing it to the results obtained, it can well be said that this system would definitely provide a much needed efficient alternative to the current method of water purification making it more sustainable and economically more feasible at the same time.

5. Copyright

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