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OPTIMIZED DESIGN OF GRID CONNECTED PHOTOVOLTAIC AND FUEL CELL HYBRID ENERGY SYSTEM FOR REVERSE OSMOSIS DESALINATION PLANT

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ABSTRACT

The main objective of the present study is to perform simulation, and modeling analysis for the optimized design of grid connected solar photovoltaic (PV) and proton-exchange membrane fuel cell (PEM FC) hybrid energy system for reverse osmosis desalination plant. The goal is to integrate renewable and clean energy technologies for seawater desalination. Grid (baseline), and grid-tied hybrid solar PV/fuel cell power systems are designed and tested. The performance of the renewable power system, the cost of energy and CO_2 emissions are determined. The simulation data show that the grid connected photovoltaic and fuel cell hybrid energy system meet the energy demand of the desalination plant without shortage. The proposed grid connected hybrid renewable power system offers the best overall performance compared to the grid: High power generation from renewable source (31%), good cost of energy (110 $/MWh - 13% cost reduction), and low CO_2 emissions (430 kg CO_2/MWh – 32% CO_2 emissions reduction).

Keywords: solar photovoltaics, PEM fuel cell, hybrid renewable power system, reverse osmosis (RO) desalination, modeling, and simulation.

1. INTRODUCTION

Desalination system consumes high amount of energy. The most significant factor on the power consumption is the feed water salinity. Desalination technologies include reverse osmosis and thermal process. The osmotic pressure must be overcome to reverse the flow during the reverse osmosis desalination process. The cost of energy to meet the electrical loads of the desalination system is about 30-60 % of the cost of water treatment.

Fossil fuel power plants are the primary source of energy for the desalination plants. The combustion of fossil fuels results on high greenhouse gas emissions (air pollution) responsible for the global warming. Fossil fuel is non-renewable fuels and is consumed at a much higher rate than the reserves (depletion of fossil resources). Sustainable power systems and new and alternative fuels need to be developed and integrated with desalination systems. Solar, wind, and biomass power systems, and biofuels (biodiesel, biogas, syngas, and bi-oil) are good alternatives to conventional power systems and fossil fuels. The development of sustainable power system is one of the key solutions for freshwater production through desalination and to meet the challenges of energy and water shortages.

Currently, the world desalination capacity is powered with less than one percent of renewable energy systems [1]. From this small amount of renewable energy systems powering desalination plants, solar PV is the most dominant renewable system (43%), followed by solar thermal and wind [1]. The problem with solar PV is the high cost of energy especially with the off-grid power system. The prospect and challenges of reverse osmosis applications are outlined in more details by Wenten [2], the cost analysis and system performance of renewable energy systems (solar and wind) for reverse osmosis (RO) desalination

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systems are summarized by Caldera et al. [3] and Sangkeum et al. [4], and the policies for desalination plants powered with RE systems are reported in Mahmoudi et al. [5] study. Heba et al. [6] investigated the integration of renewable power for RO desalination system. Solar PV, wind, and battery system; wind and battery; and an off-grid solar PV were tested. The hybrid solar PB, wind, and battery power system was the best power system with the lowest net present cost (NPC) and levelized cost of energy (LCOE). Optimal wind, photovoltaic, Diesel generator, and battery power system to operate a desalination plant was investigated by Tang et al. [7]. The best operation conditions of the micro-grid for the desalination plant were determined using theoretical analysis. CSP and photovoltaic systems were used by Darwish et al. [8] to power desalination systems. The results showed that the off-grid solar PV has the highest cost for the capital compared to the other energy systems (due to the high cost of storage device and the intermittency of the solar resources). In Ghenai et al. [9] simulation study, off-grid and grid-tied solar PV system for a desalination plant were investigated. Modeling and simulation analysis were performed to test the performance of the power systems and cost of electricity. A new grid connected photovoltaic and fuel cell hybrid energy system is proposed in this study to power the desalination plant. Fuel cell has higher efficiency than the solar PV system and the hydrogen fuel is available most of the time (solve the intermittency problem with the solar resources).

The main objective is to design an optimized hybrid renewable energy system (Solar PV/Fuel Cell) to power a reverse osmosis desalination plant in Sharjah, UAE with competitive cost of energy, high renewable fraction, and low carbon dioxide (CO_2) emissions.

2. MODELING APPROACH

2.1 Hybrid Renewable power system architecture

Two power system architectures are modeled in this study to serve the electrical load of the desalination plant (see Fig. 1). In the first configuration, the desalination plant is powered from the grid (baseline – model 1), and in the second configuration, a grid connected photovoltaic and fuel cell hybrid power system is used (model 2). The second hybrid renewable power system configuration consists of sola PV array, utility grid, PEM FC, electrolyzer, and an inverter.

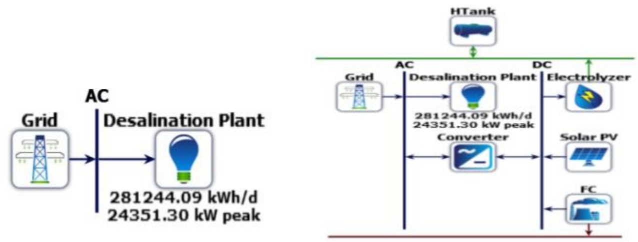

Fig. 1 Power system architectures: grid (baseline: model 1), and grid connected photovoltaic and fuel cell hybrid system (model 2)

2.2 Modeling Equations

The power output from photovoltaic array, PEM FC, and inverter; the power in for the electrolyzer and the AC power load for the desalination plant are summarized in the equations 1-5. More details about these equations can be found in Ghenai et al. [9]:

Solar PV $$P_{PV} = P_{\mathrm{STC}} DF \left(\frac{IR}{IR_{STC}}\right)\left[1 + a_P (T_{\mathrm{mod}} - T_{\mathrm{mod,STC}})\right] \quad (1)$$

Fuel Cell $$P_{FC} = U_{Stack}\, I = U_{SC}\, N_{CELLS}\, I \quad (2)$$

Electrolyzer $$P_{EZ} = \frac{\dot{m}_{H_2} HHV_{H_2}}{\eta_{EZ}} \quad (3)$$

Inverter $$P_{InvOut} = P_{InvIn}\, \eta_{Inv} \quad (4)$$

Load $$P_{Load}(k) = P_{PV}(k) + P_{FC}(k) + P_{Grid}(k) \quad (5)$$

The power from the PV depends on the solar irradiance IR, the derating factor DR (considers the losses due to the wiring, dust, and aging), the power temperature coefficient a_P, and the module temperature T_{mod} (See Eq. 1). The power out from the PEM fuel cell depends on the number of cells, and the voltage and current in each cell (See Eq. 2). For the electrolyzer, P_{EZ} represents the power consumption of the electrolyzer. The AC power load for the desalination system is provided by the photovoltaic, PEM FC, and the utility grid.

3. DESALINATION PLANT ELECTRICAL LOAD, SOLAR RADIATION, AND POWER SYSTEM COMPONENTS

The selected RO desalination plant is in the Emirate of Sharjah, UAE (see Fig. 2). The desalination treatment capacity of the plant is 90,920 m^3 of seawater treatment per day. The power consumption data for the desalination plant for 2015 is shown in Fig. 2. The monthly average solar radiation in Sharjah city is 8.30 kWh/m^2/d (See Fig. 3). There are enough solar resources in Sharjah to produce electrical power to meet the energy demand of the desalination plant.

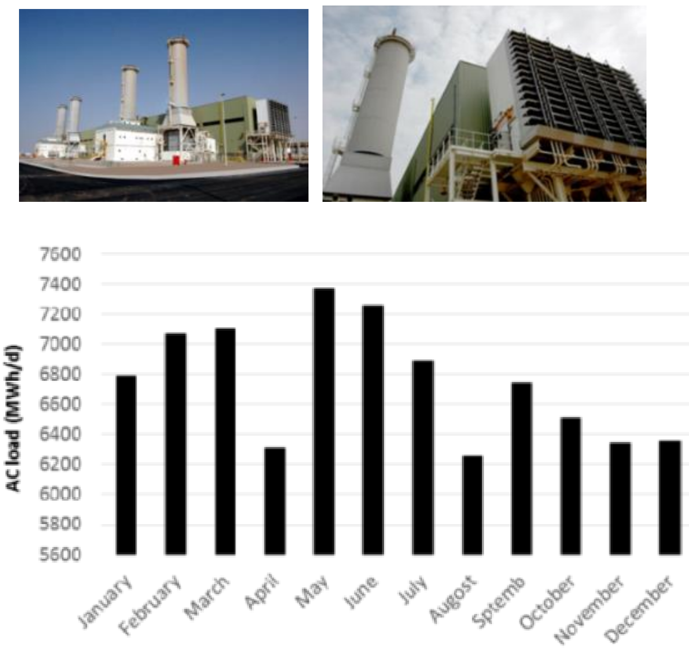

Fig. 2 Desalination plant and AC primary loads.

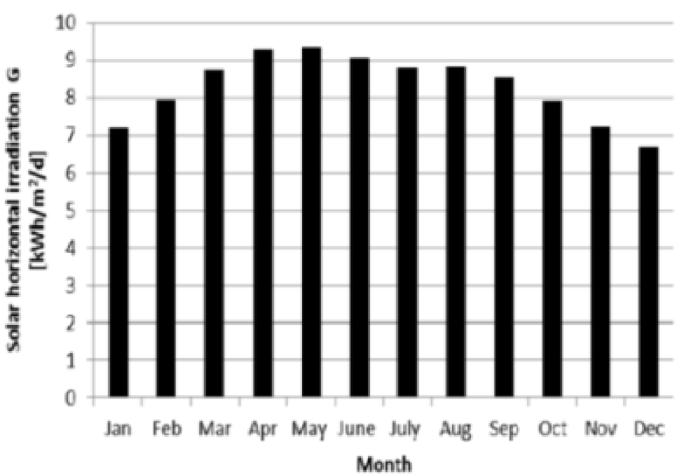

Fig. 3 Solar Irradiance – Sharjah, UAE.

Table 1 shows the hybrid photovoltaic and fuel cell power system components and the corresponding cost.

Table 1. hybrid renewable power system components

System Component	Description
Solar PV	Module: polycrystalline, Nominal Maximum Power = 330 W, Operating Voltage Vmp= 37.5 V, Operating Current Imp = 8.80 A, Open Circuit Voltage VOC = 45.9 V, Open circuit Current ISC = 9.31 A, Efficiency = 16.97%, Operating Temperature 45 °C, and Derating factor f_{PV} = 75%. Cost per 1 kW: Capital = \$1300/kW, Replacement = \$1300/kW, O&M = \$5/year Life time = 25 years
Fuel Cell	PEM Fuel Cell (DC) with electrical efficiency of 70%, Fuel: Hydrogen Cost per 1 kW: Capital = \$600, Replacement = \$600, O&M = \$0.01/hour Life time (hours)= 50,000
Electrolyzer	Electrolyzer (DC), Efficiency = 85% Cost per 1 kW: Capital = \$300, Replacement = \$300, O&M = \$8/year Life time = 15 years
Converter: Inverter	Leonics S219CPH, Voltage = 48 VDC, Efficiency = 96% Cost per 1 kW: Capital = \$40, Replacement = 40\$, O&M = 10\$/year Lifetime = 25 years

4. RESULTS

The simulation results for the optimized design of grid connected photovoltaic and fuel cell hybrid energy system for the desalination plant are presented in this section. As shown in Fig. 1 the average daily load of the desalination plant is 281244.09 kWh/day. Based on the AC primary load of the plant, the desired constraints, the best optimized system architecture for the grid connected photovoltaic and fuel cell power system is: 1 Mega Watt (MW) capacity for the fuel cell, 10 MW capacities for the solar PV system, and 10 MW power capacities for the DC to AC inverter. Figure 4 shows the monthly average electrical production from the baseline (grid only - model 1) and grid connected renewable energy system (model 2). All the energy demand of the desalination plant is met through the proposed grid-tied power system without shortage. The energy production from the photovoltaic and fuel cell power systems are respectively 22.7% and 8.03% of the total production. The grid purchases and sales are respectively 69.3% and 0.2% as shown in Fig. 5. It is noted that the photovoltaic and fuel cell capacity factors are respectively 27.4% and 97.3%. The fuel cell with high electrical efficiency (~70%) is running most of the time at maximum capacity. Figure 5 shows also that the inverter losses (DC to AC power conversion) are 9.9% and the renewable fraction is about 31%.

Table 2 summarizes a comparison of the cost of energy, CO_2 emissions and the renewable fraction of the two power systems. The grid connected hybrid photovoltaic and fuel power system is a good option for the desalination plant: the cost of energy is 110\$/MWh, the renewable fraction is 31%, and the CO_2 emissions are 430 kg CO_2/MWh (32% CO2 emission reduction compared to the grid).

Fig. 4 Monthly average electrical production – grid (model 1) and grid-tied solar PV/fuel cell power system (model 2)

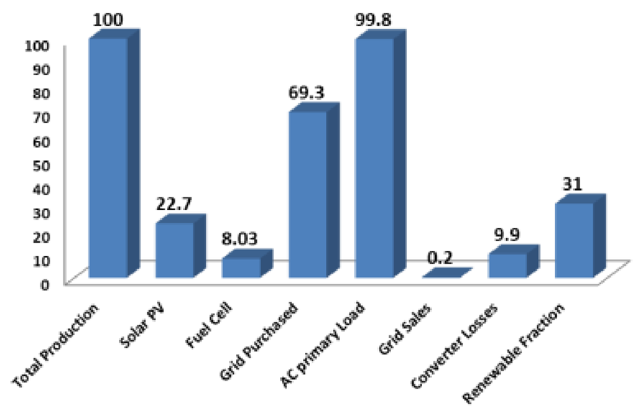

Fig. 5 Yearly performances - grid tied solar PV/fuel cell power system

Table 2. Power system architectures performance comparison

Cases	Cost of Energy $/MWh	Renewable Fraction %	CO_2 Emissions Kg CO_2/MWh
Grid – Baseline	127	0	630
Grid Tied Solar PV/Fuel Cell	110	31	430

5. CONCLUSIONS

Modeling and simulation analysis were performed in this study to design a grid-tied solar PV/fuel cell/inverter energy system to power a desalination plant. The results show that the hybrid renewable power system meets all the energy demand of the desalination plant without shortage. The proposed hybrid renewable energy system has an overall good performance compared to the grid: High renewable fraction (31%), low cost of energy (110 $/MWh) – 13% cost of energy reduction, and low CO_2 emissions (430 kg CO2/MWh – 32% emissions reduction.

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