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Power and Fresh Water Production by Solar Energy, Fuel Cell, and Reverse Osmosis Desalination

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ABSTRACT

This paper presents sizing, energy management strategy, and cost analysis for a configuration consisting of solar photovoltaic (PV) panels, fuel cell (FC) storage system, and reverse osmosis (RO) desalination technology for combined power and fresh water production. In this system, PV is the main power supply source; fuel cell is a storage system accompanied by Hydrogen production and storage devices; and for fresh water production, RO technology is considered as desalination unit. Energy production strategy, developed on the basis of solar irradiance, hourly electricity consumption, and daily fresh water demand to minimize the capacity of components. To this goal, a flowchart diagram is designed, and sizing method is modeled using MATLAB software based on this flowchart. Finally, economic analysis for co-production of fresh water and electricity is discussed, and results of sensitivity analysis for variations of net present value (NPV) cost in terms of different fuel cell storage system prices and different interest rates are presented. Results show that described energy management strategy causes the configuration to follow hourly electrical demand and daily fresh water requirement precisely, so that the total surplus energy production during a day is very little and negligible. Moreover, calculations show that the largest part of costs is due to the energy storage system. So, while the solar PV is the main energy source and solar irradiance in Khark Island more than Astara, the overall configuration cost is greater in Khark Island just because of greater energy storage system costs, nevertheless, using such energy storage systems is necessary due to intermittent inherent of solar energy.

1. INTRODUCTION

Today, many societies face fresh water scarcity due to global changes, growing populations, and over consumption of water resources especially in arid to semi-arid areas. Hence, without a sustainable management, many nations will encounter critical situations to supply sufficient fresh water for their people. One of possible solutions for this problem is using Thermal desalination technologies; however these technologies need significant amount of energy to work. The other efficient technology for water purification is Reverse Osmosis (RO), although this desalination technology also consumes a lot of electrical energy; moreover, growing demand for electrical energy makes decision makers think about establishing some new power plants. Therefore, coupling desalination technologies with power plants will be an efficient approach for co-generation of power and fresh water, especially in remote areas. In the meantime, limited amounts of fossil fuels and environmental considerations are two important reasons to use other solutions except conventional fuels. Renewable energy sources (RES) seem the most reliable options from a perspective of sustainability. On this basis, application of RES combined with desalination technologies to provide people with both electricity and fresh water demands seems to be very attractive in the future, especially in coastal arid to semi-arid regions such as islands. Gude et al. (2010) [1] and Yoosefi et al. (2014) [2] presented different approaches for coupling RES with desalination technologies. In their works, they described how different RES options can be combined with desalination possibilities to produce fresh water and electricity. In both works, the authors did not mention any technical or design considerations for each scenario they introduced.

Solar energy and applications of solar technologies have been studied for many years. Solar energy technologies are among high ranked options between other renewable energies due to availability of solar irradiations in most places on the earth. The most important defect of solar energy is inaccessibility to solar radiations out of

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daylight hours; moreover, fluctuations in power generation due to weather conditions made designers and engineers look for ways storing produced energy in order to provide consumers with a continuous power supply in different situations and times. There are several storage systems to be coupled with solar plants and other renewable energies among which Hydrogen storage and fuel cell technology is an attractive option. Jallouli et al. (2012) [3], Biswas et al. (2012) [4], and Li et al. (2009) [5] presented sizing and energy management strategies for solar PV systems coupled with fuel cell and battery storage devices to supply electrical energy for a specific hourly demand. Their works offered strategies for sizing hybrid systems optimally, but none of these studies covered desalination units and their load demand considerations to produce both fresh water and electricity for different populations. Also, they have investigated both battery and fuel cell storage unit as a combined storage system, and they did not develop any comparison and energy management strategy for each single storage device in order to be applied separately.
Touati et al. (2012) [6] investigated a configuration consisting of PV panels and fuel cell storage system to produce fresh water using RO desalination unit. They made some calculations to size different components, but they did not introduce an exact energy management strategy and sizing method by which the system could follow the exact load demand, so that they met a significant energy surplus during their sizing method. Moreover they focused on supplying RO desalination unit energy requirement, and did not make any plan for supplying any other specific electrical energy demand to have a combined power and fresh water production plant.
In current study, according to an hourly electrical load demand and daily fresh water requirement for certain number of people, and with regard to solar irradiance for a given location, a configuration including solar PV power production, PEM fuel cell electrical energy generator, electrolyser as Hydrogen supply unit, and reverse osmosis as the desalination unit is considered, and energy management strategy based on the designed flowchart is described and minimum size of each component is calculated to meet the exact demands. The sizing method is applicable for any population of inhabitants and any location and also for any kind of hourly and daily consumption of electricity and fresh water demand curve.
Mathematical models for sizing the configuration components are built using MATLAB. The system is assumed to be off-grid and there would be no other source of energy except solar irradiance and storage system. Scheme of the configuration considered in this study is shown in Figure 1. The PV panels are assumed to be equipped with maximum power point tracker (MPPT). The energy produced by PV panels should first be used to supply hourly electrical energy demand. If there is excess power, then it could be used in two ways: producing and storing Hydrogen or producing fresh water.

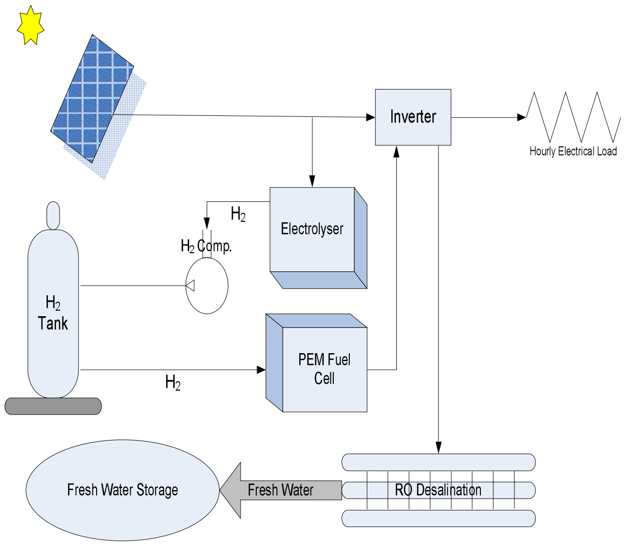

Figure 1. Schematic of PV-FC-RO configuration.

2. SIZING AND MODELING

In this section, the procedure to calculate solar irradiance during any day is described, and electrical hourly load demand and daily fresh water requirement for a typical population is introduced. Then each component is modeled to be used in mathematical calculations in MATLAB software.

2.1. Solar irradiance

Here, the calculation procedure of solar irradiance is described and the results are used to find hourly solar irradiance during any day in current study [7].
The radiation over atmosphere at any time as a function of irradiance angle (θ) is given by the following equation:

$$I\_b = \frac{G_{SC}\cos\theta}{d^2} \tag{1}$$

Where:
- G_{SC} is solar constant and its value is 1367 W/m^2 (Willson, 1978) [7].
- d is relative distance between sun and earth.
- θ is irradiance angle.
d^2 parameter is a function of the day of year, and is calculated by the equation presented by Duffie and Beckman (1991) as below:

$$d^2 = \frac{1}{1 + 0.033\cos\left(\frac{n2\pi}{365}\right)} \tag{2}$$

Where n is the number of the day during a year. For example, for first day of January, n=1; for first day of February, n=32; etc. On this basis, the relative distance between sun and the earth can be determined for different days of the year. In a similar equation, radiation flux over the atmosphere is calculated as below (Budyko, 1974) [7]:

$$I\_b = S\sin E \tag{3}$$

$$S = G_{sc}\left(\bar{d}/d\right)^2 \tag{4}$$

$$\left(\bar{d}/d\right) = 1/\left(1-0.01673\cos\left(n2\pi/365\right)\right) \tag{5}$$

$$E = \pi/2 - \theta_Z \tag{6}$$

In above equations, θ_Z is called Zenith Angle and calculated by:

$$\cos\theta_Z = \sin\varphi\sin\delta + \cos\varphi\cos\delta\cos h \tag{7}$$

Where φ is latitude and δ is Declination Angle which is calculated as below (Graham Cogley, 1979) [7]:

$$\delta = 0.4093\sin\theta\left[2\pi\left(n-79.75\right)/365\right] \tag{8}$$

The Declination Angle can be also calculated by below equation (Duffie and Beckman, 1980) [7]:

$$\delta = 23.45\sin\left(360\,\frac{248+n}{365}\right) \tag{9}$$

On this basis, solar irradiation for two regions located in south and north of Iran are depicted in Figure 2. for first day of each solar year season which are coincide with 80_{th}, 173_{th}, 266_{th}, and 357_{th} days in Gregorian date, respectively. Khark Island is located in Persian Gulf, Iran, with latitude of 29.23, and Astara is located in north of Iran with latitude of 38.42.

In this study, 229_{th} day of the year is considered as the reference day for calculations which is coincided to 25_{th} Mordad of Solar calendar. On this day the electrical consumption for considered population living in Khark Island is maximum, and combined power and fresh water production plant should be sized to supply demanded loads on this day, too. Solar irradiance for 229_{th} day of the year for two regions, Khark Island and Astara, are depicted in Figure 3.

2.2. Electricity and fresh water demands

Electrical load demand for 400 persons in Khark Island on 229_{th} day of the year is depicted in Figure 4.

In addition to electrical energy demand, a daily fresh water demand should be considered for these 400 persons and related energy requirement must be calculated. For this purpose, per capita daily water consumption is assumed to be 150 liters per day. A typical reverse osmosis water desalination unit consumes 3-4 KWh electrical energy for producing 1m3 of fresh water [8]. In this study, energy consumption of RO desalination unit is assumed 4 KWh/m^3. Accordingly, daily electrical energy consumption in RO unit (E_{RO}) for providing considered number of people (N) with fresh water can be calculated as below:

$$ERO = N * 4(KWh/m^3) * FW_d\ (m^3/day) \tag{10}$$

Where "FW_d" is daily fresh water demand for each person.

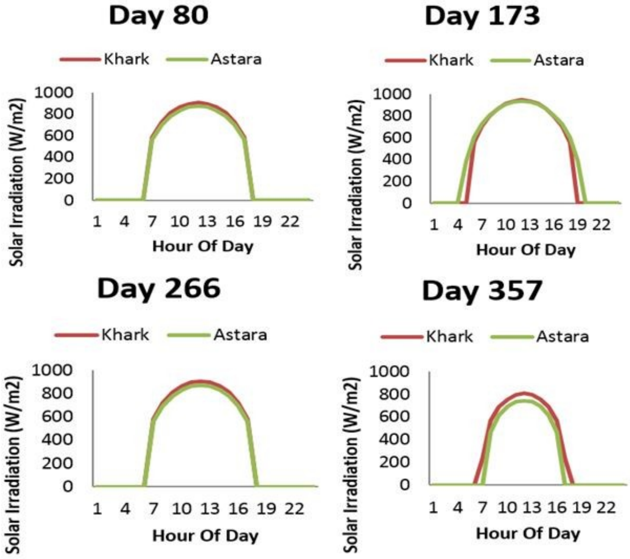

Figure 2. Hourly solar irradiance on 4 different days for two locations.

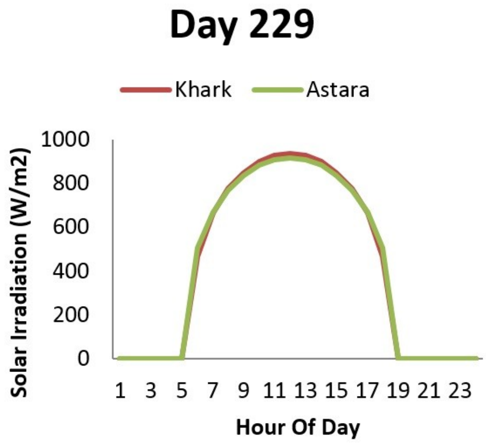

Figure 3. Solar irradiance for two regions on 229_{th} day of the year.

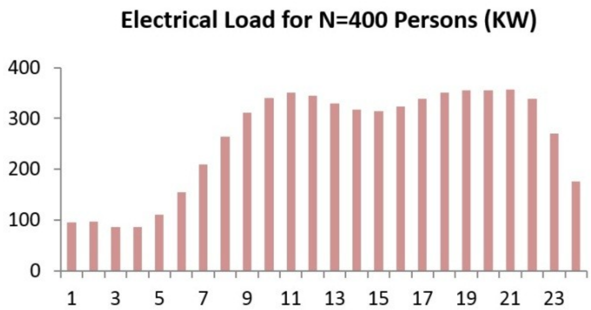

Figure 4. Hourly electrical load demand for 400 persons.

2.3. PV modeling

Total solar energy reachable from PV modules is estimated by the equation below. By this equation, one could calculate electrical energy produced by PV modules for different values of solar irradiance [4].

$E_{PV}= I(t)*\eta_{PV}*\eta_{MPPT}*A_{PV}$ (11)

In above equation, I(t) is average solar irradiance during tth hour of the day according to data available for specific time and location conditions. APV is total area of PV modules, and according to the amount of APV and knowing the area of each PV module, required total number of PV modules can be determined.

2.4. Fuel cell modeling Proton Exchange Membrane (PEM) fuel cell is considered in this study because its working conditions is suitable for combined power and water production using reverse osmosis technology. PEM fuel cell stack consists of several cells connected to each other in series. Each cell of PEM fuel cell includes anode and cathode electrodes which are separated by a solid membrane. Hydrogen fuel and air are continuously inserted to anode and cathode electrodes, respectively. Chemical reactions within each electrode are as below:

Anode-side reaction:

$H_2 \rightarrow 2H^+ + 2e^-$

Cathode-side reaction:

$2H^+ + \frac{1}{2}O_2 + 2e^- \rightarrow H_2O$

Therefore, the overall reaction in any cell of PEMFC is:

$H_2 + \frac{1}{2}O_2 \rightarrow H_2O$

The output voltage of PEMFC can be calculated as below:

$V_{FC}= V_{Nernst}- V_{Ohmic}- V_{act}- V_{con}$ (12)

Where V_{ohmic}, V_{act}, and V_{cons} are ohmic, activation, and concentration losses. Consuming Oxygen is normally supplied by air and Hydrogen consumption is calculated from the equation below [5]:

$M_{FC} = (P_{FC} * 3600) / (2*V_C*\eta_{FC}*F) = E_{FC} / (2* V_C* \eta_{FC}*F)$ (13)

$P_{FC} = I_{FC} * V_{FC} * N_{FC}$ (14)

Where V_{FC} is the output voltage of PEMFC and equals to 1.48 (v) which indicates the maximum output voltage of PEMFC. η_{FC} is the efficiency of PEMFC and usually varies between 40 to 60 percent. In this study, the efficiency of PEMFC is assumed 50%. F is Faraday's constant and its value is 96485 (C/mole). M_{FC} is the amount of consumed Hydrogen in (mole/hour). P_{FC} and E_{FC} are power and energy produced by PEMFC, respectively.

2.5. Electrolyser modeling An electrolyser consists of several cells in series. Two electrodes are separated by a liquid or solid polymer membrane. The electrical current going through the electrolyser causes water decomposing into Hydrogen and Oxygen. This process can be indicated as below:

$H_2O + \text{Electricity} \rightarrow H_2 + \frac{1}{2}O_2$

As electrolyser commences to work for producing Hydrogen, voltage difference between two electrodes should be greater than a minimum value for water decomposition, which can be calculated as below [9]:

$V_H = -\frac{\Delta H}{2F} = 285.84/(2*96485) = 1.48 \text{ (V)}$ (15)

Where ΔH is high energy value of Hydrogen in (kJ/mole). Voltage efficiency of electrolyser is also given by:

$\eta_V= \frac{1.48}{Velz} * 100\%$ (16)

In this study the efficiency of electrolyser is considered 74% [10]. Therefore, the operating voltage of electrolyser is V_{elz} = 2 (v).

According to Faraday's law, the amount of Hydrogen could be produced by an electrolyser with a power of P_{elz} during an hour can be calculated as below:

$M_{elz} = (P_{elz} * 3600) / (2 * V_{elz} * F) = E_{elz} / (2 * V_{elz} * F)$ (17)

In above equation, the unit of M_{elz} is (mole/hour). In current study, the electrical energy consumed by electrolyser to produce Hydrogen at any time equals to the difference between electrical energy supplied by PV modules and hourly electrical energy demanded at the same time.

$E_{elz} + E_{Compressor} = (E_{PV}(t) – E_L(t))$ (18)

2.6. Hydrogen compressor modeling

Theoretical speaking, the most efficient way for compressing any gas is an Adiabatic process [5]. Efficiency of mechanical compressors (μ_C) is normally between 40-75%. The relation between compressor power W_C (W) and Hydrogen mass flow rate m_C (kg/s) is given as the equation below [5]:

$W_C = C_P * \frac{T1}{\eta c} *((\frac{P2}{P1})^{\frac{r-1}{r}} - 1) * m_C$ (19)

Where C_P is Hydrogen specific heat at constant pressure and its value is 14304 (kJ/kg.K). T_1 is Hydrogen intake temperature which is assumed to be 293 (K). P_1 and P_2 are intake and outlet pressure of Hydrogen gas to compressor, respectively. r is the Isentropic constant of Hydrogen gas and its value is 1.4. Selection of the compressor is based on intake and outlet pressures. Here, the intake and outlet pressures of Hydrogen gas are 0.6 and 20 MPa, respectively. Whenever the electrolyser is active, the compressor is at its working mood too in order to pressurize the produced Hydrogen to the storage pressure in Hydrogen storage tank.

2.7. Hydrogen tank modeling By storing produced Hydrogen in the tank, there would be the possibility of using its energy when needed. Using the following equation, one can calculate the amount of energy reachable from certain amount of Hydrogen [5]:

$E_{tank} = (M_{tank} * 2 * LHV) / 1000$ (20)

$V_{tank} = (M_{tank} * T_{tank} * R) / P_{tank}$ (21)

In the equation above, E_{tank}, M_{tank}, and V_{tank} indicate the size of the Hydrogen tank which are in kWh, mole, and liter, respectively. T_{tank} is the temperature of the gas inside the tank (K), and P_{tank} is its pressure (MPa). R is gas constant (0.8211 atm/mol.K), and LHV is low heat capacity of Hydrogen (33 kWh/kg). The mole mass of hydrogen gas is equal to 2 (gr/mol).

3. ENERGY MANAGEMENT STRATEGY

For developing energy management strategy, a flowchart is designed and depicted in Figure 5. Based on this flowchart, MATLAB codes are created to calculate the exact size of each component. The purpose of the energy management strategy is to minimize net present value (NPV) cost of the configuration. For this reason, and by following the energy management strategy, minimum size of each component is determined by which, simultaneously, demands for hourly electrical energy and daily fresh water are met. Hourly electrical load is considered in accordance with the diagram depicted in Figure 4. for 400 persons, and fresh water demand is also predicted for the same number of people.

In this flowchart, x is a coefficient multiplied to the difference of PV production and hourly load demand at any time in order to allocate an appropriate amount of energy to fresh water production in RO unit. This coefficient is optimized with the purpose of minimizing overall surplus energy produced by whole configuration components. In other words, after investigating the decrease in overall daily energy surplus, it has been found out that there is an optimum amount for x by which the total energy production exactly matches the total energy consumption. The optimum value for the configuration PV-FC-RO is 0.26, as shown in Figure 5. This optimum value for x also minimizes the total initial cost for the configuration by decreasing the size of each component to the least possible amount for supplying all demands. This coefficient is optimized by applying single objective optimization based on Genetic Algorithm method. As mentioned before, the objective was minimizing the difference of produced energy and consumed energy. This is done by using MATLAB codes for relating different parameters in the configuration to each other and then changing these parameters to just one which should be minimized.

When energy produced by PV modules is less than energy required for supplying hourly energy demand, the lack of energy is supplied by storage system. It should be mentioned about developing the energy management strategy in MATLAB software that to ensure the amount of energy consumed during times without enough solar irradiancies compensated during times with sufficient irradiance, at the end of the process, the extra amount of energy required to be restored in storage system is calculated and the extra number of PV modules is estimated based on this excess energy demand. Finally, this number of extra PV modules must be added to existing PV modules to find out the total number of PV modules in order to answer whole energy demands for production and storage during a complete day. In flowchart depicted in Figure 5 this extra power of PV modules is shown with $E_{PVextra}$. It would be helpful to clarify that a main amount of energy needed to charge the storage system is supplied during the time with access to solar irradiance before, therefore, this amount should be subtracted from the total energy calculated for supplying electricity during one day, and then, the final total number of PV modules can be estimated. According to the flowchart and priorities about energy production and consumption, related codes are created in MATLAB software. These codes give an optimum size for each component to minimize NPV cost, and confirm energy production to energy consumption precisely. The energy management strategy is based on the number of inhabitants, hourly electrical load demand, daily fresh water requirement, solar irradiance at any time, technical data for each, day of the year, geographical latitude, and other such information. After calculating daily fresh water demand, this amount should be supplied during a day, and it is not important how much fresh water is produced during each hour, but, demanded amount must be available by the end of each day in fresh water storage basin. Efficiencies of components which are used within calculations in this study are indicated in Table 1.

4. ECONOMIC ANALYSIS

In current study, economic analysis is done based on net present value (NPV) cost of configuration. Indeed, NPV indicates the worth of initial investments and annual and periodic turnovers and costs of any project, and compares them with current worth. In other words, NPV converts all investments and incomes of a plan into initial cost at the beginning of the plan according to lifespan of the project and interest rate, and this way, different projects could be comparable. To convert annual costs (A) to initial cost (P), or vice versa, the following equation may be used:

$$P=A*[\frac{(1-i)^n-1}{i*(1+i)^n}] \quad (22)$$

TABLE 1. Symbols definition [4,5]

Symbol	Definition	Value
η_{PV}	PV module efficiency	0.15
η_{MPPT}	MPPT efficiency	0.9
$\eta_{con.}$	Converter effic.	0.95
η_{elz}	Electrolyser effic.	0.74
η_{FC}	Fuel cell effic.	0.5
η_{C}	Compressor effic.	0.7

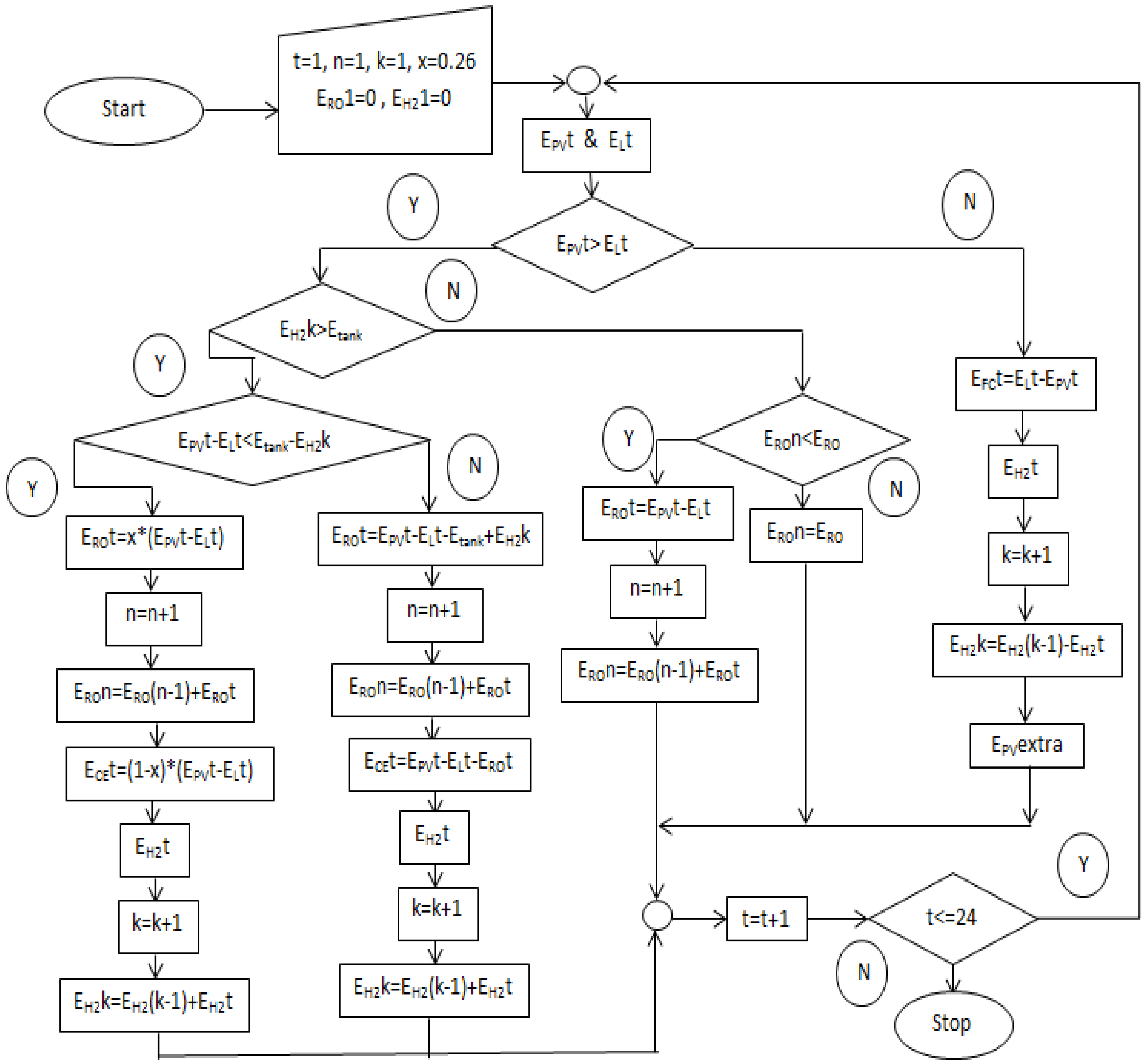

Figure 5. Energy flow chart of the configuration PV-FC-RO

Where i is interest rate, and n is lifespan of the project. By converting annual costs to initial cost, it is possible to calculate NPV cost of project adding costs of all components:

$$\sum_j P + \sum_j IC = NPV \quad (23)$$

Where j indicates each component and IC is initial cost of each component. Operation and maintenance costs are considered as annual costs. Since lifespan of the project is assumed to be 25 years, for calculating initial cost of each component its related lifespan must be considered. It is done by multiplying procurement cost of each component by the number of that component needed during the project life time. In Table 2. costs of each component are shown:

TABLE 2. Components' Costs [4, 5, 11, 12, 13, 14]

Component	**Lifespan (year)**	**Initial Cost ($)**	**Annual O&M Cost (% of Initial Cost)**
RO Desalination Unit	15	1000 per m3/day	10
PV System (Suntech, STP245)	25	183.75 per Module	0
Fuel Cell	5	3 per W	2.5
Elec. & Comp.	10	2 per W	2
Hydrogen Tank	25	50 per kWh	1
RO Desalination Unit	15	1000 per m3/day	10

5. RESULTS AND DISCUSSION

Based on calculations and energy management strategy developed in MATLAB, following results have been obtained. These results are for Khark Island (latitude 29.23) and Astara (latitude 38.42). Results are simulated for 400 inhabitants. To configure consisting solar photovoltaic panels as the main energy production source, fuel cell energy storage system, and reverse osmosis water desalination unit, the amount of energy production and consumption during a day is given in Table 3. for Khark Island and in Table 4. for Astara.

The amount of energy consumed by RO desalination unit to produce sufficient fresh water for 400 persons is 240 kWh per day.

TABLE 3. Energy production and consumption by each component during a day in Khark Island.

Day 229, Khark Island (Lat. 29.23)				
Total No. of PV Modules=NM_T=2548				
Hour of Day	**PV Production (KW)**	**FC Production (KW)**	**El. & Comp. Consumption (KW)**	**Load (KW)**
1	0	95.3531	0	95.3531
2	0	96.7132	0	96.7132
3	0	85.717	0	85.717
4	0	86.0853	0	86.0853
5	0	110.1126	0	110.1126
6	232.0818	0	62.2339	154.2894
7	330.0133	0	96.8025	209.0101
8	385.442	0	96.99	264.2045
9	422.3595	0	89.6035	310.3552
10	446.661	0	85.3363	339.9906
11	460.6158	0	88.3672	350.1568
12	465.1776	0	96.9953	343.9335
13	460.6158	0	104.8412	329.5643
14	446.661	0	103.5871	317.1771
15	422.3595	0	86.3412	314.433
16	385.442	0	49.8645	323.1114
17	330.0133	8.3164	0	338.3296
18	232.0818	119.1661	0	351.2479
19	0	355.7169	0	355.7169
20	0	355.7399	0	355.7399
21	0	356.6623	0	356.6623
22	0	337.9014	0	337.9014
23	0	270.7297	0	270.7297
24	0	175.3469	0	175.3469
Total	**5019.5244**	**2453.5608**	**960.9627**	**6271.882**

As it can be observed from Table 3. the energy management strategy developed in MATLAB software based on related flowchart described in previous sections has precisely conformed average production and consumption powers during any hour; so that not only is the average demanded power during any hour supplied, but also surplus energy during a day is minimum possible value. For example, according to Table 3. total energy surplus to requirement in a day is equal to:

Total energy surplus = 5019.5244 + 2453.5608 - 960.9627 - 6271.882 – 240 = 0.2408 kWh

This amount of surplus energy in comparison with the whole system dimensions is ignorable. On the other hand, this very few energy surplus is unavoidable, because the amount of photovoltaic modules is not a continuous value; in other words, it is not possible to have 1.257 PV modules in system but the amount of PV modules is a natural number like 2 or 3 for example. In this case, the total number of PV modules is calculated 2548 modules as shown in Table 3.

Energy production and consumption by each component are shown in Figures 5. through 7 for Khark Island. Since these general patterns are repeated for Astara, they are not depicted here in order not to extend the report.

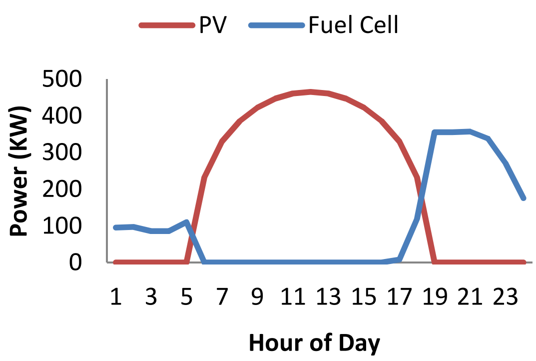

Figure 5. Hourly power production by PV and fuel cell.

Initial costs, annual operation and maintenance cost of each component, and total NPV cost for the configuration PV-FC-RO are given in Table 4. and are depicted separately in Figures 8. and 9.

It can be observed from cost tables and figures that the main part of costs is for storage system including fuel cell, electrolyser, and compressor, and this causes such configurations need high investments. On the other hand, using storage systems is unavoidable, especially in off-grid plants, due to intermittent power supply by most of RES technologies. Figure 11. depicts the variations of total net present value of the whole combined system by different per watt costs of fuel cell energy storage system.

The interest rate is considered 20% for current study, based on the normal value in Iran.

TABLE 4. Energy production and consumption by each component during a day in Astara.

Day 229, Khark Island (Lat. 38.42)				
Total No. of PV Modules=NM_T=2566				
Hour of Day	**PV Production (KW)**	**FC Production (KW)**	**El. & Comp. Consumption (KW)**	**Load (KW)**
1	0	95.3531	0	95.3531
2	0	96.7132	0	96.7132
3	0	85.717	0	85.717
4	0	86.0853	0	86.0853
5	0	110.1126	0	110.1126
6	253.3963	0	79.2855	154.2894
7	335.9041	0	101.5152	209.0101
8	386.2944	0	97.6719	264.2045
9	420.5959	0	88.1926	310.3552
10	443.3969	0	82.725	339.9906
11	456.5534	0	85.1173	350.1568
12	460.8631	0	93.5437	343.9335
13	456.5534	0	101.5913	329.5643
14	443.3969	0	100.9758	317.1771
15	420.5959	0	84.9303	314.433
16	386.2944	0	50.5464	323.1114
17	335.9041	2.4255	0	338.3296
18	253.3963	97.8516	0	351.2479
19	0	355.7169	0	355.7169
20	0	355.7399	0	355.7399
21	0	356.6623	0	356.6623
22	0	337.9014	0	337.9014
23	0	270.7297	0	270.7297
24	0	175.3469	0	175.3469
Total	**5053.1451**	**2426.3554**	**966.095**	**6271.882**

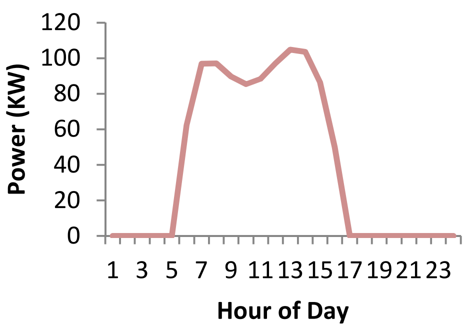

Figure 6. Hourly power consumption by electrolyser and Hydrogen compressor.

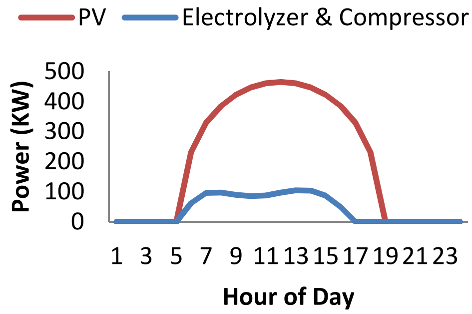

Figure 7. Comparison of PV power production and the power used by electrolyser and compressor.

But, in different situations and in different countries and regions, the amount of interest rate varies significantly. Figure 11. depicts NPV variations for different interest rates.

As it is shown in Figure 11. the more the interest rate the less NPV costs of the configuration.

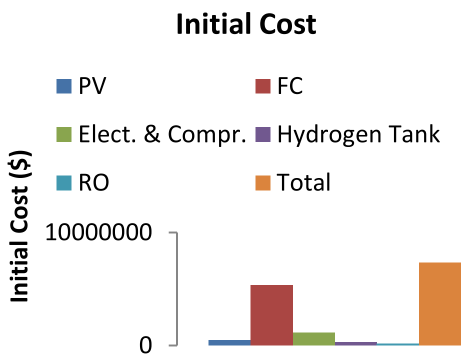

Figure 8. Initial costs of each component in configuration.

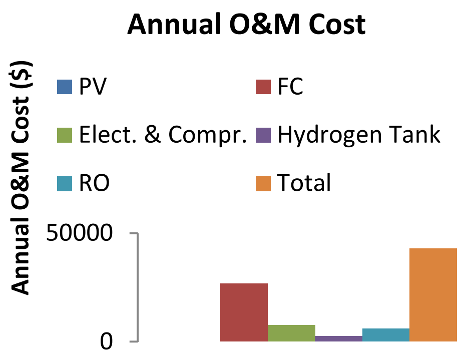

Figure 9. Annual O&M costs of each component

6. CONCLUSIONS

Results show that the main part of costs would pay for energy storage system, and high cost of fuel cell makes this combination very expensive. So, while the solar PV is the main energy source and solar irradiance in Khark Island is more than Astara, the overall configuration cost is greater in Khark Island just because of greater energy storage system cost; nevertheless, using such energy storage systems is necessary due to intermittent inherent of solar energy.

Based on calculations for two regions, Khark Island and Astara, in Tables 5. and 6. the required size of each component and related initial and O&M costs are presented for supplying 400 persons with demanded hourly electrical load and daily fresh water.

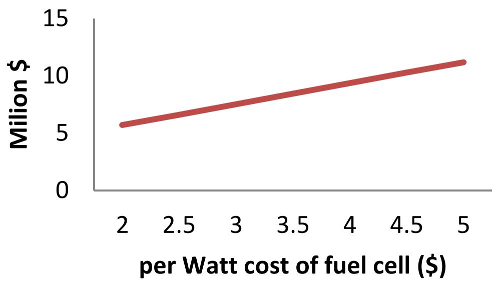

Figure 10. Total NPV cost for different fuel cell prices

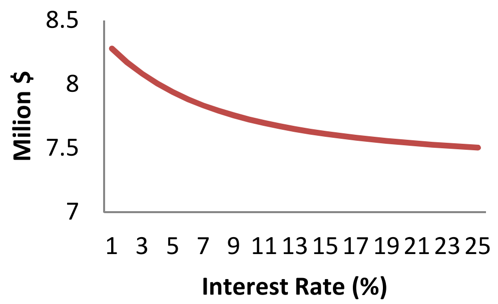

Figure 11. Total NPV cost for different interest rates

TABLE 5. Components sizes and costs for Khark Island

Component	Capacity	Initial Cost ($)	Annual O&M ($)
PV	465 KW	468195	0
FC	357 KW	5.35E+06	2.68E+04
Electr. & Compr.	105 KW	1.13E+06	7.56E+03
Hydrogen Tank	5240 KWh	262000	2620
RO	60 m3/day	60000	6000
Total	**-**	**7270195**	**42930.1**

TABLE 6. Components sizes and costs for Astara

Component	Capacity	Initial Cost ($)	Annual O&M ($)
PV	470 KW	4.72E+05	0
FC	357 KW	5.35E+06	2.68E+04
Electr. & Compr.	100 KW	1.11E+06	7.42E+03
Hydrogen Tank	5240 KWh	262000	2620
RO	60 m3/day	60000	6000
Total	**-**	**7254000**	**42794.4**

As Tables 5. and 6. show, while the total required number of PV modules is less for Khark Island in comparison to Astara, the total initial cost is more for Khark Island. The reason is that for storing enough energy, in form of hydrogen, during times without sufficient solar irradiance there would be a larger capacity for electrolyser and compressor unit in Khark Island, and as mentioned before, the storage system costs more in unit of capacity comparing to the PV modules.

Results show that sizing strategy follows hourly electricity demand and daily fresh water requirement precisely, and is able to determine the exact size of each component according to hourly and daily demands.

As calculations indicate, such a combined system is accompanied with a relatively large initial cost in comparison to low costs of using fossil fueled systems, at least in Iran. But, considering sustainable development and global warming issues these alternative systems are unavoidable in the near future. Moreover, all equipments are currently been using worldwide and there is no technical limitation in design, construct and operating such systems. Ignoring current relatively high costs for theses systems, there would be promising solutions for providing new cities with required power and fresh water especially in coastal regions.

7. ACKNOWLEDGEMENT

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