JJEE
Volume 7, Number 4, December 2021
Pages 304-322
Jordan Journal of Electrical Engineering
ISSN (Print): 2409-9600, ISSN (Online): 2409-9619

# Optimum Sizing of Stand-Alone Hybrid Photovoltaic Systems Equipped with Reverse Osmosis Desalination System for a Rural House in Iran

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*Received: March 25, 2021* *Revised: May 07, 2021* *Accepted: May 12, 2021*

***Abstract—*** Energy and water crisis affects every aspect of modern human life, and thus, addressing both in one solution is a growing trend. Merging hybrid renewable energy systems (HRES) and water desalination system in one system is a promising solution. In this paper, optimization of stand-alone hybrid photovoltaiv (PV) systems for powering a house equipped with a reverse osmosis (RO) water desalination system in Sinak village, Tehran, Iran, is discussed. RO system configuration, regular house load and RO deferrable load, solar radiation capability and HRES components have been analyzed in the first part of this paper. The second part deals with optimization, cost analysis and sensitivity analysis - using HOMER Pro software - of two HRES scenarios equipped with RO: i) a PV system with battery storage and ii) a PV system with battery storage and a gas generator. Moreover, different dispatch strategies for controlling the investigated systems - namely cycle charging (CC) and load following (LF) - are described. In the last part, a comparison between the two scenarios is performed. The obtained results show that the hybrid PV-battery-RO system is more energy-effective, has less control complexity and has a capability of meeting the load demand with with zero carbon emissions. Results of the conducted economic analysis reveal that the system has a net present cost (NPC) and a cost of electricity (COE) of 10,245 US$ and 0.31 US$/kWh, respectively, while fewer sensitivity variables affect the system's cost.

***Keywords—*** Hybrid renewable energy systems; PV-battery system; Reverse osmosis water desalination; HOMER Pro software; Techno-economic analysis; Sensitivity analysis.

## 1. INTRODUCTION

Climate change is a probable consequence of the overexploitation of fossil fuel-driven energy, and greenhouse gas (GHG) emission - as an immediate result of this fossil fuel burning - has a remarkable adverse effect on environmental pollution. The first solution for the global warming issue is reducing GHG emissions by considering clean energy sources [1]. Hybrid renewable energy systems (HRES) have become popular recently because of their promising advantages - over conventional energy sources - like cost reduction over time, fewer emissions, higher reliability, better stability, more efficiency and desirable performance. The main objective of designing a HRES is to merge two or more renewable and non-renewable energy sources in one system to meet energy requirements [2].

Energy is a crucial commodity in the modern world, and water is essential for human life. About 97% of the global water resources are saltwater including seawater, groundwater and oceans' water. As a result, only 3% of the global water is in the form of freshwater. Moreover, only 10% of this potable water is accessible for household applications. Nowadays, water scarcity is the most significant human issue due to increasing water demand [3]. A water desalination system is a terrific method to resolve this water crisis. Desalination is the process of removing salt from the sea or brackish water to make it pure for drinking. There

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Article's DOI: 10.5455/jjee.204-1616695846

are numerous water desalination methods and the central problem for these methods is the high level of energy consumption. However, the reverse osmosis (RO) method is a popular method because of its low energy consumption, low-priced technology and wide accessibility [4].

Energy management and optimization increase the efficiency of any HRES. Akorede et al. [5] proposed a critical review on optimization approaches of HRES. This study suggests that cost analysis, system reliability and environmental considerations are the main factors that affect the optimization results. They introduced three main categories for optimization methods: classical optimization algorithms, simulation and optimization software such as HOMER, HYBRID2, HOGA, RETScreen, and HYBRIDS and modern optimization algorithms. As the feasibility of a renewable system with one component is not realistic, system optimization helps researchers merge numerous renewable sources such as solar and wind into one system. For example, researchers of [2, 6] introduced an appropriate hybrid design for existing infrastructure, accurate cost analysis and control methods. Various methods have been introduced in research for optimization; Peng et al. [7] investigated an HRES combined with a water desalination system for a remote area in Iran. Their proposed system consists of a wind turbine, photovoltaic (PV) arrays, batteries and a RO desalination unit. They used numerous optimization methods like bee swarm, particle swarm, simulated annealing, harmony search, chaotic search, and Tabu search algorithm for optimization. The research approves that HRES reduces system costs and increases system reliability in general.

Maleki et al. [8] analyzed various possibilities for bringing hydrogen energy storage to the hybrid system for water desalination of stand-alone sites in Iran. They proposed three hybrid systems and used artificial bee swarm optimization (ABSO) method for optimization. They proved that PV-hydrogen-RO is the most cost-effective energy system in comparison with PV-wind-hydrogen-RO and wind-hydrogen-RO. Mostafaiepour et al. [9] investigated off-grid PV systems to power a RO desalination system in different districts of Boushehr province in Iran. They used HOMER Pro software and Excel software to analyze technical and economic aspects of the systems. Their proposed PV-RO desalination system includes a RO membrane, high-pressure pump, motor, batteries, converter and PV arrays.

Numerous studies analyze the system's techno-economic aspects as far as small-scale PV-driven RO water desalination system is concerned. Da Silva et al. [10] investigated techno-economic aspects of a small-scale PV-RO system in Brazil. They predict that the designed system with 26 to 33 $m^2$ PV panel can provide 250 people with their freshwater needs for two days at a cost from 1.44 to 1.65 $/$m^3$. Two small-scale PV-RO systems are suggested by Hajji et al. [11] to provide 20 $m^3$/day desalinated water in the south of Morocco. The first system consists of a 36 $m^3$/day RO unit, 23 kW PV panel and 50.5 kWh battery storage with a lower initial investment cost of approximately 93,400 US$. The second system generates water with a lower cost of 1.6 US$/$m^3$ in the system with a 72 $m^3$/day RO unit, 32 kW PV panel and 38.5 kWh battery bank.

Different power resources can power the desalination system. El-Ghonemy [12] analyzed four power supply systems for a small-scale RO unit: PV-battery-inverter system, PV-battery-inverter-diesel generator system, diesel generator system and local national electricity grid. The author showed that the cost of energy (COE) for the first, second and the last system is 0.46, 0.25, and 0.1 $/kWh, respectively.

Iran has a good potential for solar energy, as it is located in the earth's sunbelt. Moreover, the water crisis in Iran has worsened because the total per capita annual water has been decreased [13]. Based on these two facts, a HRES that includes a PV panel that feeds a RO water desalination unit is a promising solution. This study compares two stand-alone hybrid PV systems for a rural house in Iran equipped with a RO water desalination system. Two scenarios are introduced:

a) PV system with battery storage.
b) PV system with battery storage and gas generator.

In this paper, there are three main parts. Firstly, site characteristics such as load calculation, solar radiation system configuration and design methods are presented. Secondly, the design results and simulation of the aforesaid two scenarios are executed in HOMER Pro software and techno-economic analysis of the proposed scenarios is described. Finally, results, discussion and comparison of the possible scenarios are made.

## 2. MATERIALS AND METHODS

Appropriate design of a HRES is achievable when every aspect of the system has been analyzed. Different energy sources and demands in the system bring more complexity to the design, and every parameter should be considered. The following framework has been considered in this paper for an accurate evaluation of the system:

a) Characteristics of the selected site.
b) Water system configuration.
c) Load demand data.
d) Solar radiation.
e) System components.
f) Economic analysis.

### 2.1. Characteristics of the Selected Site

Iran, located in an arid and semi-arid region, is among the top water-stressed countries and suffers water shortages in various industrial, agricultural and domestic sections because of uneven deducted rainfall patterns [13]. Tehran, the capital of Iran, is located in the north of the country and faces severe population migration and pollution in the last few years. Sinak village, as the selected location for this study, is a village in Lavasanat District, Shemiranat County, Tehran Province, Iran (35°51'06.1"N 51°41'14.3"E).

The selected house for this study is a village house, which has two characteristics: firstly, like most of the houses in rural areas, there is no electrical grid to power the house, and as a result, the only option for such houses is the use of traditional stand-alone systems for their electrification, which is costly and produces noise and pollution. Secondly, the selected site's water source is a well water, containing high amounts of harmful ingredients and contaminants. Atefeh et al. [14] investigated the Lavasane–E Kochak district's underground drinking water quality. They proved that the average total dissolved solids (TDS) parameter in this region is around 600 ppm.

Four people live in that house, and their major sources of electricity consumption are lighting, running electrical appliances and water pumping. People use natural gas for cooking and heating in Iran because of its availability, and as a result, electricity consumption is relatively low. Because of the Iranian houses' low energy consumption rate, the PV panel is a promising component in the HRES.

### 2.2. Water System Configuration

Based on the house's current system configuration, the well brackish water is pumped by a submersible pump to an above-ground tank. A jet pump is utilized to increase the tank's water pressure and then directs water to the house. The submersible pump - in this house - is located at a depth of 25 m from the ground surface. It has three stainless steel impellers, which can pump water to the maximum height of 38 m. The above-ground tank which has 1000 L capacity, is located on the rooftop with 3 m height from the ground. The jet pump in this house has a 2-pole electric induction motor for continuous operation, and the stator is made with low-loss laminated electric sheet steel.

The RO system is designed based on the existing water configuration for the house. Based on the site survey, the daily average of 1500 L of water consumption is the best fit for this four-person house. The RO system will only provide around 100 L/day of desalinated water for drinking and cooking. The RO unit mainly consists of a semipermeable membrane that traps minerals while the high-pressure water is injected into it [15]. ISpring RCC7P-AK is the selected RO unit. It includes a pressure pump and multiple stage filtration consisting of RO technology  that removes various contaminants. The presence of granular activated carbon (GAC) and chlorine/taste/odor (CTO) filters helps the system to remove chemicals effectively. The capacity of this small RO unit is 284 L/day and is depicted in Fig. 1 [16].


Fig. 1. The RO unit [16].

The water system configuration of the selected house with the RO system is shown in Fig. 2. In this system, pumped water from the well is used for the house's general water consumption and desalination system. The iSpring T32M 12.5 L pressurized storage tank is located after the RO membrane to increase the system's performance.

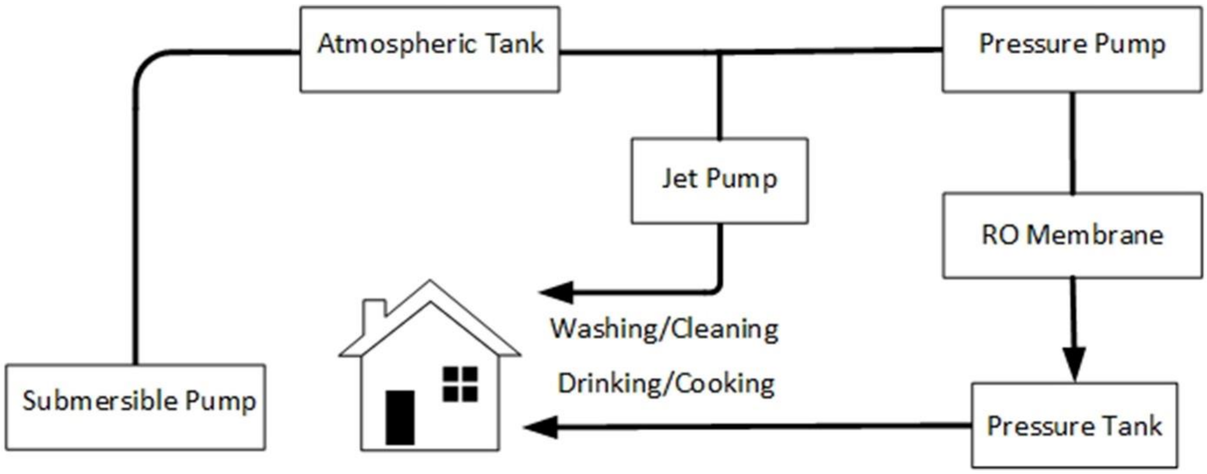


Fig. 2. Water system configuration.

### 2.3. Load Demand Data

The proposed HRES is designed to power both the house and the desalination system. House load is a regular load that exists during a day, and HRES has to provide it all day long. On the other hand, since the RO load can be met whenever excess energy exists in the HRES system it can be considered as a deferrable load [17].

Energy consumption of the rural house can be achieved from a metering system, or the total load can be calculated by listing the power consumption of household appliances. Since there is no metering system for the house in this study, the second method is applicable. Table 1 shows a list of different house appliances with their daily power and energy consumption. This table indicates that the regular daily load of the house is approximately 5.42 kWh/day.

Table 1. Daily electricity consumption by the house appliances.

| Household appliances | Rated power [W] | Time used [h] | Electricity consumption [kWh/ day] |
|---|---|---|---|
| Refrigerator | 150 | 8 | 1.2 |
| Microwave | 900 | 0.3 | 0.27 |
| Electric meat grinder | 350 | 0.1 | 0.035 |
| Blender | 400 | 0.1 | 0.04 |
| Cooker hood | 140 | 0.4 | 0.056 |
| Washing machine | 200 | 0.3 | 0.06 |
| Vacuum cleaner | 900 | 0.2 | 0.18 |
| Electric shaver | 15 | 0.2 | 0.003 |
| TV 42” LCD | 120 | 3 | 0.36 |
| Laptop | 50 | 8 | 0.4 |
| Home phone | 6 | 24 | 0.144 |
| Home internet router | 10 | 24 | 0.24 |
| Wall-mounted gas boiler | 140 | 6 | 0.84 |
| Light bulb - LED*6 | 72 | 2 | 0.144 |
| Light bulb - Common*2 | 200 | 3 | 0.6 |
| Light Bulb - LED*38 | 266 | 2 | 0.532 |
| Extractor Fan*2 | 40 | 8 | 0.32 |

The energy required for the RO and the watering systems of the house (the deferrable load) consists of all the water systems' loads, including submersible pump, jet pump, and pressure pump load. The exact amount of energy consumption of the pumps is calculated to meet the house's water usage. The submersible pump has three stainless steel impeller which can pump water to the height of 38 m, and its rated power is 1100 W. The submersible pump needs to operate 30 min to pump 1500 L of well water, which means 550 W daily power. The jet pump in this house is the Pentax PM45 peripheral turbine pump with a two-pole induction motor. The motor's power rating is 470 W, and it needs to operate one hour daily to provide water for washing and cleaning purposes.

Finally, to have 110 L (10% margin is considered) of desalinated water, the 60 W pressure pump in the RO unit needs to operate for 9.2 h/day, which means 550 W of daily energy. Table 2 presents the deferrable loads individually and the total load of the system. Based on the data in this table, the total deferrable load for the system is 1.57 kWh/day, which should be provided by the HRES.

Table 2. Deferrable load characteristics.

| Deferrable load type | Daily energy consumption [kWh/day] |
|---|---|
| Submersible pump load | 0.55 |
| Jet pump load | 0.47 |
| Pressure pump load | 0.55 |
| Total | 1.57 |

## 2.4. Solar Radiation

The selected house is located in a rural area near Tehran city on a high elevation. There is significant solar irradiance in Sinak village because of its favourable location. Based on the database, which is downloaded from NASA's prediction of worldwide energy resources, the monthly radiation and clearness index is depicted in Fig. 3. The average annual solar irradiance in this region is 4.89 kWh/m$^2$/day, while the maximum and minimum irradiance occurs in June and December, respectively.

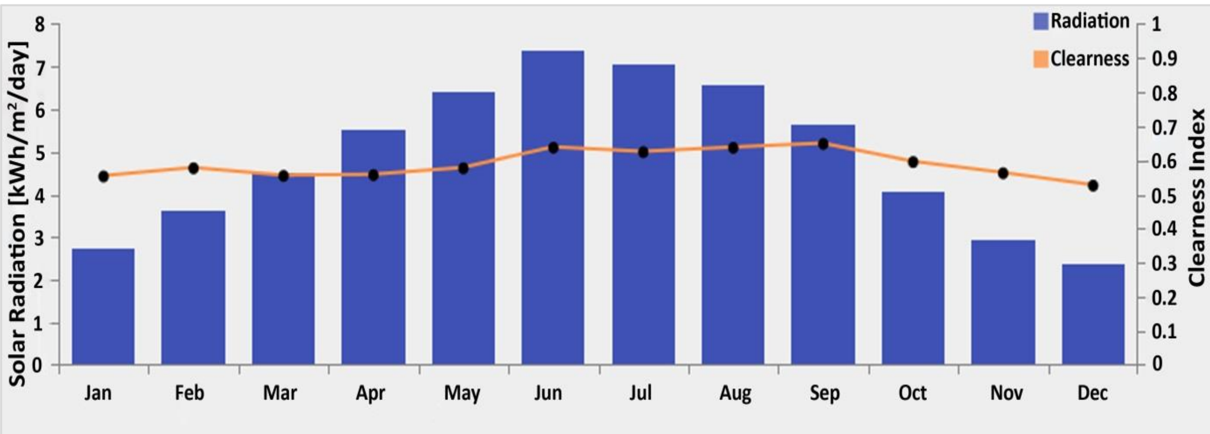


Fig. 3. Monthly solar radiation and clearness index in Sinak village.

## 2.5. System Components

### *2.5.1. The PV Module*

The PV module in this study is a fixed tracking system with an efficiency of around 17.49% with a nominal maximum DC output power of 340 W that is produced when the PV module is exposed directly to the sunlight. As a result, the output power has a direct relation with temperature as described by [18]:

$$P_{PV} = P_{PV,rated} \cdot f_{PV} \cdot \frac{G_T}{G_{T,STC}} . [1 + \alpha_P (T_C - T_{C,STC})] \quad (1)$$

Where $P_{PV,\ rated}$ is the nominal maximum output power of the PV panel, $f_{PV}$ is the derating factor of PV panel, $G_T$ is the actual solar irradiance, $G_{T,STC}$ is the solar radiation under standard test, $\alpha_P$ is the power temperature coefficient, $T_C$ is the PV cell temperature, and $T_{C,\ STC}$ is the operating cell temperature of the PV panel under standard test condition.

### *2.5.2. Battery*

Lead-acid battery is selected for this investigation with a maximum capacity is 254 Ah under the nominal voltage of 6 V. The DC bus voltage is set to 48 V in this study to reduce the DC bus current. The minimum state of charge (SOC) is 20% in the design, and the round trip efficiency is 85 %. Moreover, the total throughput of the battery is 914.30 kWh.

### *2.5.3. Gas Generator*

A gas generator is responsible for supporting the loads in the second scenario. In the worst case, the gas generator can act as the house's primary energy source if the PV panels become disconnected from the system. Natural gas in Iran is cheap, whereas Iran's natural gas price is 0.1 $\$/m^3$. The selected generator in this study has the capacity and lifetime of 1000 W and 40000 h, respectively.

### *2.5.4. Inverter*

The inverter's main responsibility is to convert the PV module's DC output power to AC to feed the load. In the sizing of the inverter, it is noticeable that the rated power should be 20% more than the total power of the peak load that is connected to the AC bus. As a result, a 4 kW solar inverter with 96% efficiency and 10 years of a lifetime is selected for this investigation.

Technical and economic data of the HRES components is listed in Table 3. All the financial information in this list is per one item in the system.

## 2.6. Economic Analysis

Optimization in HOMER Pro software is based on various considerations, and one of them is an economic analysis between possible configurations. Net present cost (NPC) is the main factor in ranking the components' optimal economic configuration. NPC is all present costs of the system during the lifetime of the project and can be found by [19]:

$$NPC = \frac{C_{annual,total}}{CRF(r, R_{project})} \quad (2)$$

where $C_{annual,total}$ is the system's annual total cost, $r$ represents the annual interest rate, $R_{Project}$ is the project lifetime (year). In Eq. (2), *CRF* is the capacity recovery factor that is achievable by the following equation, in which n is the number of years, and i is the discount rate [20].

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \quad (3)$$

Another important factor in economic optimization in HOMER Pro software is the cost of electricity (COE), which can be calculated by [20]:

$$COE = \frac{\sum_{j=1}^{n} \frac{I_j + M_j + F_j}{(1+i)^j}}{\frac{E_j}{(1+i)^j}} \quad (4)$$

In Eq. (4), $I_j$ is the invested budget, $M_j$ is the Operation and Maintenance (O&M) expense, $F_j$ is the fuel cost, and $E_j$ is the generated electricity in one year.

Table 3. Technical and economic data of the HRES components.

| Component | Specification | Description |
|---|---|---|
| PV panel | Size | 340 W |
| | Efficiency | 17.49% |
| | Temperature coefficient | 0.41 %/° C |
| | Lifetime | 25 years |
| | Tracking system | Fixed |
| | capital cost | $400 |
| | Replacement cost | $300 |
| | Operation and maintenance costs | 2.2 $/year |
| Battery | Type | Lead-acid |
| | Nominal voltage | 6 V |
| | Round trip efficiency | 80% |
| | Maximum capacity | 254 Ah |
| | Nominal capacity | 1.52 kWh |
| | Throughput | 914.3 kWh |
| | capital cost | $200 |
| | Replacement cost | $175 |
| | Operation and maintenance costs | 1.75 $/year |
| Gas generator | Size | 1 kW |
| | Lifetime | 40000 h |
| | Fuel cost | 0.1 $/m$^3$ |
| | Capital cost | $400 |
| | Replacement cost | $300 |
| | Operation and maintenance costs | 0.05 $/op.hour |
| Inverter | Size | 4 kW |
| | Efficiency | 96% |
| | Lifetime | 10 years |
| | Capital cost | $1000 |
| | Replacement cost | $750 |
| | Operation and maintenance costs | 7.5 $/year |

## 3. DESIGNING HYBRID PV SYSTEMS WITH HOMER PRO

Hybrid optimization of multiple energy resources (HOMER) software from the National Renewable Energy Laboratory (NREL) is an advanced software for simulating and optimizing microgrids by considering various energy sources, especially renewable energies such as solar and wind. Moreover, different system components can be applied to the grid-connected or stand-alone systems. In designing a HRES, various factors are considered. Type of the available renewable energy sources in the under-design system, type of the loads in the system, size of the components, environmental factors, components and overall system cost, maintenance cost and efficiency and reliability of the system are among the factors which affect system configuration [21].

An optimization approach in HOMER Pro software for a stand-alone hybrid PV system with PV as the main component is based on the following major considerations: i) designed system is cost-effective; the HOMER software introduces the most cost-effective system mainly based on the net present cost and lowest cost of electricity, ii) The system has a high renewable fraction; non-renewable sources exist in the software, such as gas generators, and the software approach is designing a system for injecting more renewable energies while providing the required uninterrupted electricity; iii) environmental factors are considered; introducing renewable energy systems to the grid produces more clean energy, and tHOMER software analyses the proposed systems to reduce emissions.

In this paper, despite other studies which design HRES as the source for a house or the RO unit, the prposed system is of double-purpose. In other words, proposed electrical system is designed to power a house and RO desalination system simultaneously. The HOMER Pro software is used for the techno-economic analysis to optimize the system and introduce a feasible solution. In rural areas, except for the factors mentioned above, availability of the components and simplicity is another factor. Based on these facts, the following two possible scenarios of stand-alone hybrid PV systems for powering the rural house are considered in this paper:

a) PV system with battery storage: There is relatively high solar radiation in the selected site. Subsequently, a PV system is a reasonable renewable option for this site. Moreover, battery storage manufacturers in Iran can produce low-priced battery systems compared to other storage technologies such as supercapacitor. As a result, the battery system is widely available. This configuration is 100% renewable without any emission. In this system, the battery bank stores renewable energy to support the system when PV power production is not enough to meet the load demand
b) PV system with battery storage and gas generator: One method to reduce renewable energy production and system cost is to inject fossil fuel-driven components into the HRES system. Although most researchers use diesel generators, a gas generator is selected in this study because the distribution system brings natural gas through pipelines to houses in Iran (even the rural ones) at an extremely low price. This hybrid system balances the system cost by decreasing PV module and battery bank sizes while producing emissions. Both battery bank and gas generator, known as supporting components, actively meet the load demand with high efficiency when the main source cannot produce energy.

### 3.1. PV System with Battery Storage

A PV system with battery storage has numerous advantages, including zero emissions, higher renewable fraction, eliminating operational noise and system controllability. A PV system with battery storage is a widespread hybrid system in which the supporting storage system can cover power shortages in a green manner. As far as cost reduction is concerned, in countries with high fuel costs, eliminating conventional fossil fuel-driven resources can reduce the system cost. In this paper, this scenario has a 100% renewable fraction with a 2.68 kW PV array size and a converter of 4 kW. Two kinds of daily loads are defined: the primary house load of 5.42 kWh with a 1.74 kW peak and a 1.57 kWh deferrable RO system load. Result of the HOMER Pro software optimization suggests a 24 6-volt, 254 Ah batteries for this scenario with 8 batteries in each string. The total capacity of system's battery is approximately 762 Ah, and the annual throughput is 1,579 kWh. DC bus voltage is 48 V, and battery system autonomy is 100 hours which means that the system can operate more than 4 days without solar energy. The actual system configuration in HOMER software is shown in Fig. 4.

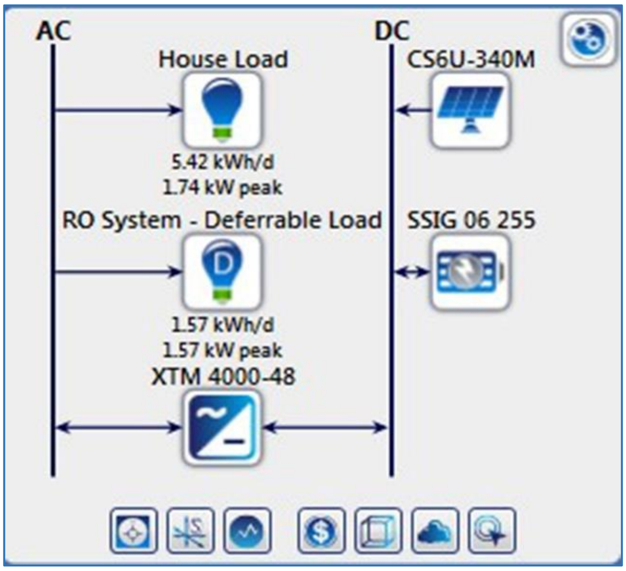


Fig. 4. Configuration of the PV-Battery system in HOMER Pro.

Decision-making about how the resources in HRES serve the loads is critical because appropriate timing for switching on or off the components will affect the system sizing. In the software, control of resources in HRES is achievable by using two main dispatch control techniques: cycle charging (CC) and load following (LF) dispatch strategies. The dispatch strategy for the system consisting of battery storage is CC. As depicted in Fig. 5, with this strategy, PV array feeds regular and deferrable higher priority loads, and excess energy will charge the battery. As the battery is the only backup system in this scenario, its size should be large enough to power the regular load in the absence of the solar system in the CC dispatch strategy. Table 4 projects the cost summary of the system. Based on this table, the NPC during the project's lifetime is around $10,245. Moreover, there is no $CO_2$ emission, and the system is environmentally friendly.

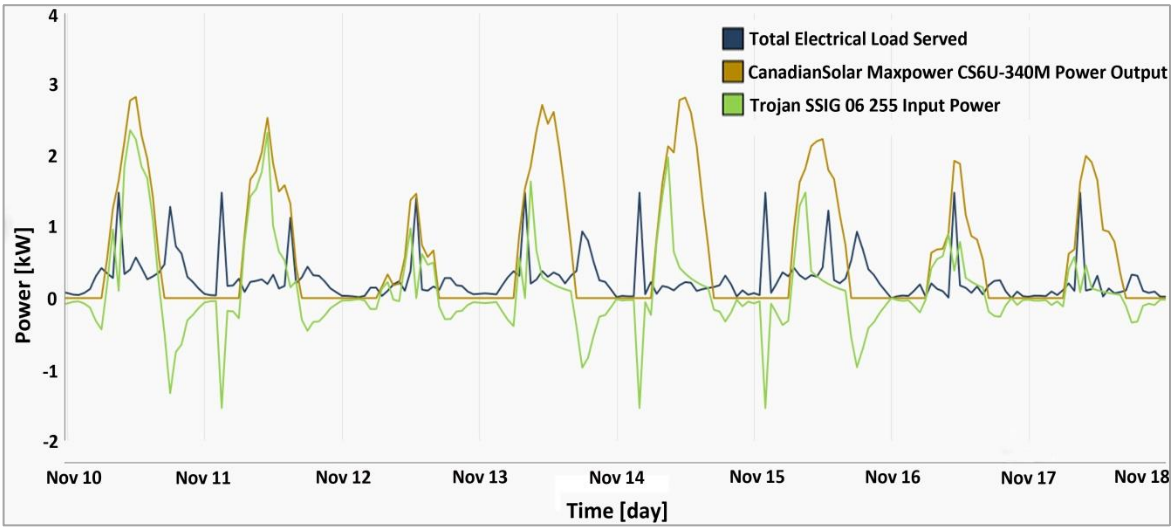

Fig. 5. Power balance of the PV-Battery system.

Table 4. Cost summary of the PV-battery system.

| System component | Cost [$] | | | |
|---|---|---|---|---|
| | Capital | Replacement | O&M | Total |
| Canadian Solar MaxPower CS6U-340M | 2,363.05 | 0.00 | 224.02 | 2,587.07 |
| Trojan SSIG 06 255 | 4,800.00 | 1,898.29 | 542.96 | 7,039.41 |
| Studer Xtender XTM 4000-48 | 370.40 | 245.42 | 35.91 | 618.46 |
| The whole system | 7,533.45 | 2,143.71 | 802.89 | 10,244.93 |

In the techno-economic analysis of the HRES, sensitivity analysis is one method to check the system's robustness. Various inputs can affect the system's output such as the system's cost, the effect of which is investigated in this study. As far as the sensitivity variables that are highly effective in the cost of the system in this scenario are concerned, variations in regular house load and solar radiation are considered to check the system's NPC. For this analysis, each sensitivity variable is changed by ± 10% and ± 5% from their average values, i.e., 4.878, 5.149, 5.42, 5.691, and 5.962 kWh/day for house load and 4.4032, 4.6478, 4.8925, 5.1371, and 5.3817 kWh/m$^2$/day for solar radiation. These variables can be defined in Homer Pro software, and the sensitivity analysis results - in the surface plot - are depicted in Fig. 6. They indicate that NPC is sensitive to the variations in house load and solar radiation equally and changes, accordingly, from $9,885 to $11,768.

### 3.2. PV System with Battery Storage and Gas Generator

Increasing the reliability of a HRES is crucial in designing, and it is achievable by adding more power source or storage components to the system to provide a power shortage of the renewable source. Although adding different components to the system will increase its complexity, more factors for controlling the microgrid are available. In this scenario, 1 kW gas generator and 8 batteries (1 string) with a total capacity of 254 Ah and 1.28 kW PV array power the same load in the previous scenario. The battery system's autonomy is 33.5 h, which indicates that the batteries can feed the loads for 1.4 days in lack of gas generator and PV array. Moreover, the annual throughput of the battery strings is 760 kWh. Fig. 7 depicts the actual configuration for this scenario in HOMER Pro software.

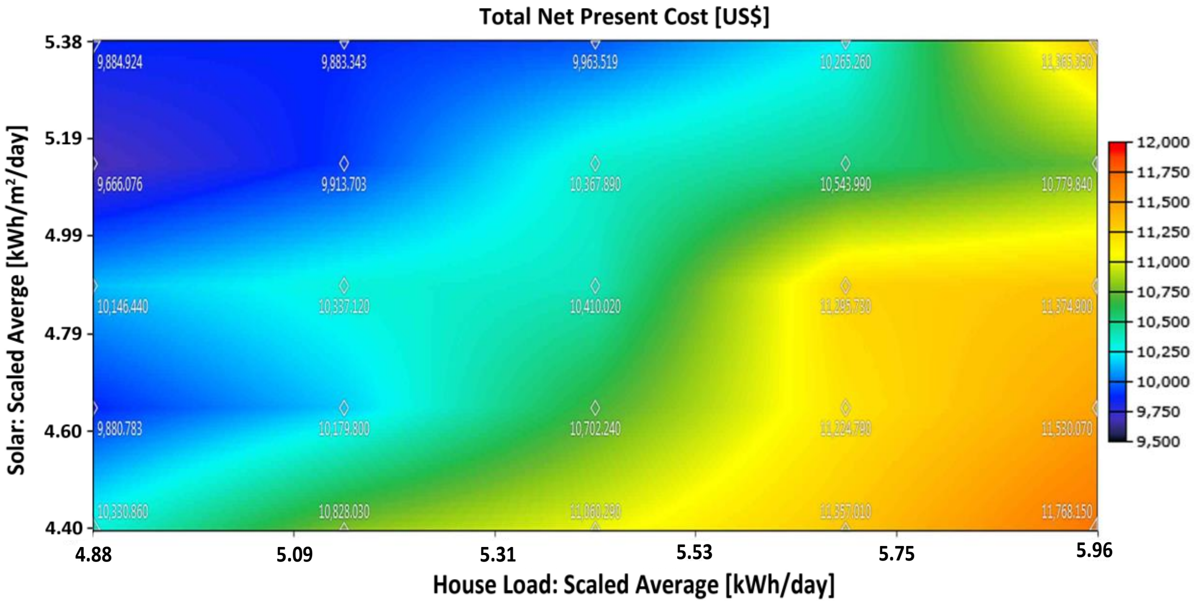


Fig. 6. Surface plot of the sensitivity analysis for the PV-battery system.

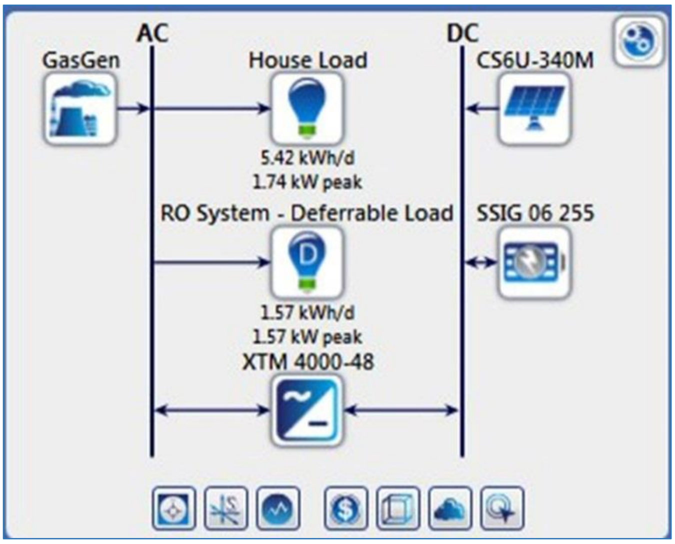


Fig. 7. Configuration of the PV-battery-generator system in HOMER Pro.

The controlling process in this scenario is more complicated than the previous one; LF dispatch strategy in this configuration has been applied to the system. In LF dispatch, the generator produces power to serve the regular load, and renewable sources feed deferrable load and battery storage. It means deferrable load and batteries have a lower priority for the gas generator. The power balance between components in the system is depicted in Fig. 8, and system operation in LF strategy follows the below steps [2, 22]:

- $P_{PV} = P_{Load}$: PV feeds the load, the battery does not discharge and the gas generator is off.
- $P_{PV} > P_{Load}$: PV feeds the load, PV charges the battery (if required) and the gas generator is off.

- $P_{PV} < P_{Load}$:
  - $SOC = SOC_{min}$: Gas generator serves the primary load, PV feeds deferrable load and charges the battery.
  - $SOC > SOC_{min}$: Cost of producing energy for generator and battery is calculated:
    - ✓ $C_{battery} > C_{generator}$: Battery will serve the load.
    - ✓ $C_{battery} < C_{generator}$: Generator will serve the load.

The cost summary of the system is depicted in Table 5. Decreasing the initial capital cost to $3,260 and NPC to $6,460 are the main advantages of having a gas generator in the system. However, producing $CO_2$ emissions by burning 399 $m^3$ natural gas and decreasing renewable fraction to 58.1% are the main drawbacks of this scenario. The gas generator in this scenario adds extra cost to the system because of fuel cost, which amounts to $515.

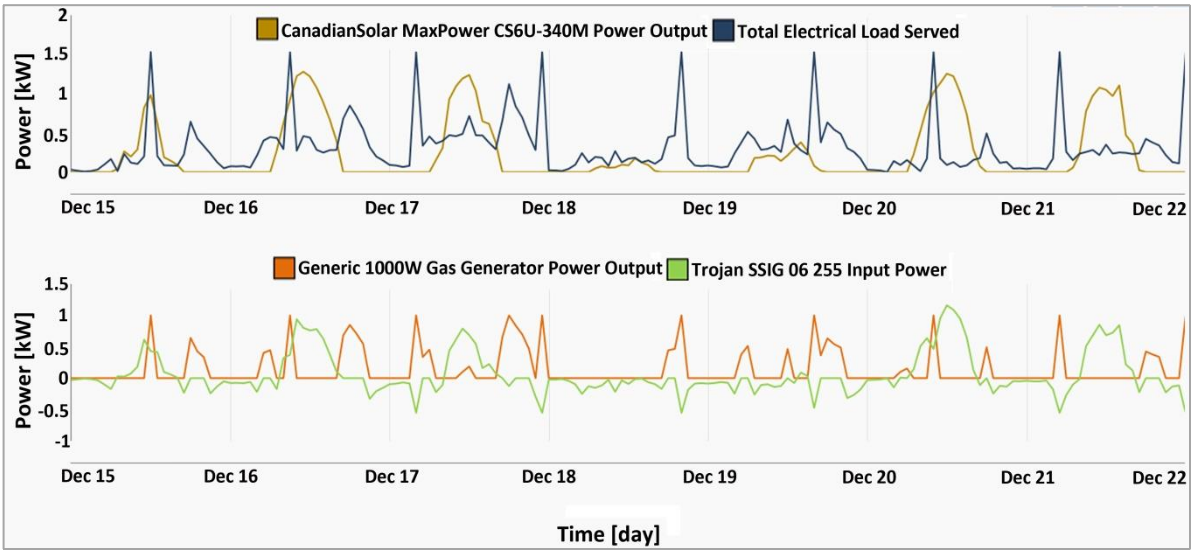

Fig. 8. Power balance of the PV-battery-generator system.

Table 5. Cost summary of the PV-battery-generator system.

| System component | Cost [$] | | | | |
|---|---|---|---|---|---|
| | Capital | Replacement | O&M | Fuel | Total |
| Canadian Solar MaxPower CS6U-340M | 1,127.16 | 0.00 | 106.86 | 0.00 | 1,234.02 |
| Generic 1000W Gas Generator | 400.00 | 82.98 | 1,149.90 | 515.38 | 2,084.44 |
| Trojan SSIG 06 255 | 1,600.00 | 1,274.13 | 180.99 | 0.00 | 2,920.67 |
| Studer Xtender XTM 4000-48 | 132.54 | 87.82 | 12.85 | 0.00 | 221.30 |
| The whole system | 3,259.70 | 1,444.92 | 1,450.60 | 515.38 | 6,460.43 |

The sensitivity analysis for the PV system with battery storage and gas generator is the same as for the previous scenario. Two main sensitivity variables are regular house load and solar radiation, which are varied by ± 10% and ± 5% from their mean values. As a result of varying the house load from 4.878 to 5.962 kWh/day and the solar radiation from 4.4032 to 5.3817 kWh/$m^2$/day in five equal steps, the NPC has changed from $5,970 to $6,947 as revealed by the surface plot depicted in Fig. 9. It also show that the variation of house load and solar radiation affects the NPC equally. Another sensitivity variable is natural gas price, and the effect of its variation is discussed in the next section.

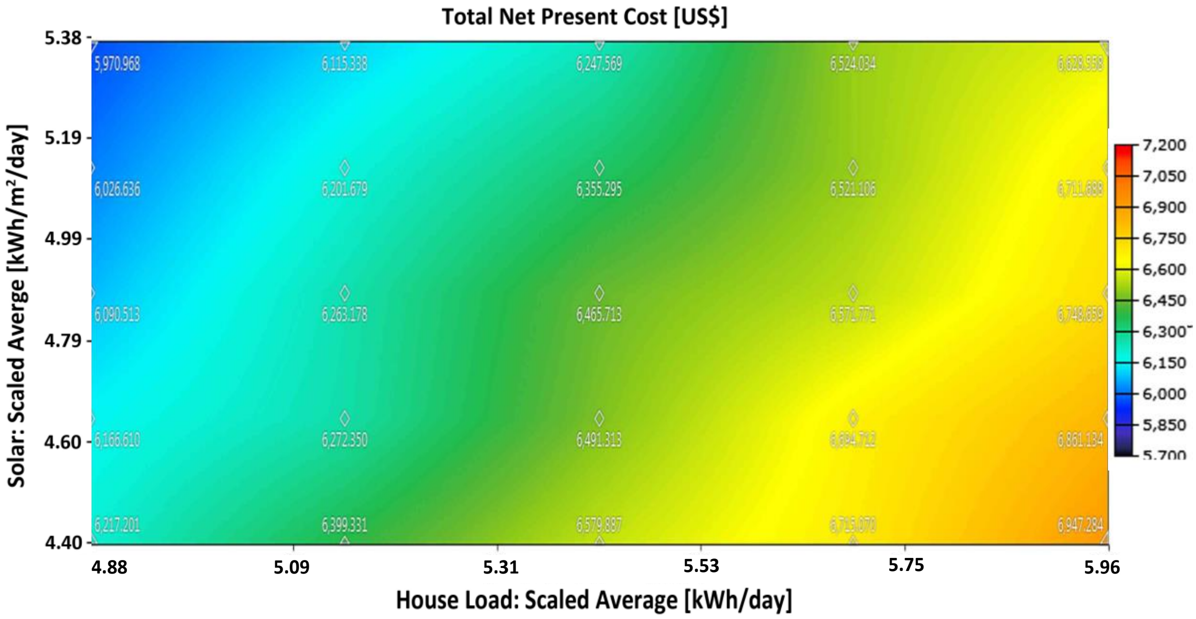

Fig. 9. Surface plot of the sensitivity analysis for the PV-battery-generator system.

## 4. RESULTS AND DISCUSSION

The HRES for a rural house equipped with RO water desalination system needs precise initial analysis to achieve appropriate configuration. This analysis is essential for two reasons: firstly, the electrical system is stand-alone in rural areas, and the renewable system has to produce uninterruptable electricity for primary house load. Secondly, the water desalination system provides essential water for drinking and cooking, and as a result, the power of the RO system should be guaranteed. Different factors should be considered for configuration selection, such as cost analysis, control methods of the system, system complexity and environmental factors.

Comparison between the two – proposed in this investigation - scenarios is based on three categories, namely energy, cost, and sensitivity analysis. Energy-related comparison details are presented in Table 6. Based on these results, the advantages of utilizing both battery and generator in the second scenario (in the PV-battery-generator system) compared to first scenario (the PV-battery system) are the need for fewer PV panels (4 instead of 8) and a 66.6% reduction in the number of batteries. On the other hand, there are some drawbacks of adding the gas generator in the second scenario. The renewable fraction of the first scenario is 100%, which means it produces clean energy. In the second scenario, annual fuel consumption is 399 $m^3$, while in the first one is zero. Battery autonomy in the first scenario is more than the second one, which means the system can operate longer without other resources. In the second scenario, there is carbon emission, and the controlling system is LF which means more complexity in the system. Moreover, as far as installation is concerned, new installation consideration for the generator is required while PV array and batteries are in the system, and extra components can be added , easily, to the system. From the energy perspective, the first scenario (PV-battery system) seems to be a reasonable solution.

Table 6. Energy-related comparison between the two proposed scenarios.

| Item | Scenario | |
|---|---|---|
| | PV-battery | PV-battery-generator |
| PV size | 2.68 kW | 1.28 kW |
| Generator | 0 | 1.068 kW |
| Battery numbers | 24 | 8 |
| Converter | 4 kW | 4 kW |
| Renewable fraction | 100% | 58.1% |
| Fuel consumption | 0 | 399 $m^3$/year |
| Autonomy | 100 h | 33.5 h |
| Excess electricity | 1,665 kWh/year | 511 kWh/year |
| Unmet Load | 1.08 kWh/year | 1.57 kWh/year |
| $CO_2$ Emission | 0 | 770 kg/year |
| Dispatch strategy | CC | LF |

The cost comparison between the PV-battery system and PV-battery-generator system is depicted in Fig. 10. NPC, initial capital cost, replacement cost, and COE for the system with the generator are lower and amount to around $6,460, $3,260, $1,445, and $0.2, respectively, because the cost of natural gas is remarkably low in Iran. However, the system with a gas generator has higher O&M and fuel costs which affects the system cost in the long term.

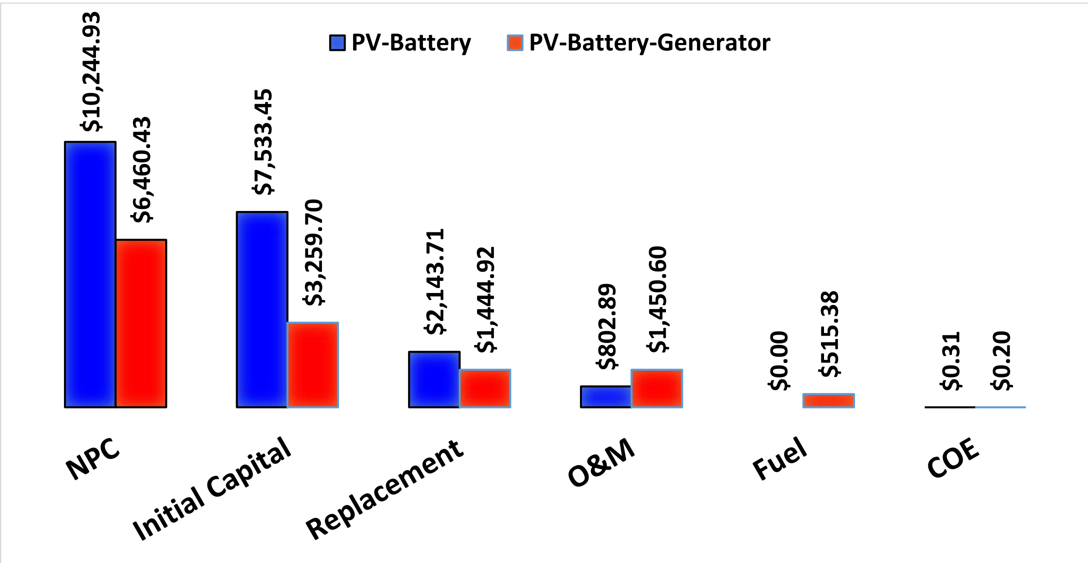


Fig. 10. Cost analysis of the investigated scenarios.

Sensitivity analysis in this study indicates that both scenarios are sensitive to the variations in both the house load and solar radiation. Figs. 11 and 12 show Their effect on the system's NPC. In these figures, NPC is depicted based on the percentages of variations in each sensitivity variable when other factors are not varied and fixed to their mean values. NPC of the PV-battery system fluctuates from -2.5% to 9.2% and from 6.2% to -4.2% by varying the house load and solar radiation from -10% to 10% from their mean values, respectively. Moreover, NPC of PV-battery-generator system fluctuates from -5.8% to 4.3%

and from 1.7% to -3.3% by the same variation (-10% to 10% of house load and solar radiation). However, in the second scenario, another sensitivity variable affects NPC, which is natural gas price. In Iran, natural gas price is fluctuating rapidly, and subsequently, the cost of the system is fluctuating. As Fig. 12 indicates, NPC varies from -3.3% to 1.6%, with similar percentages of fluctuation in gas price from -10% to 10% from its current market price. In other words, the PV system with a generator is more sensitive since it is affected by three variables.

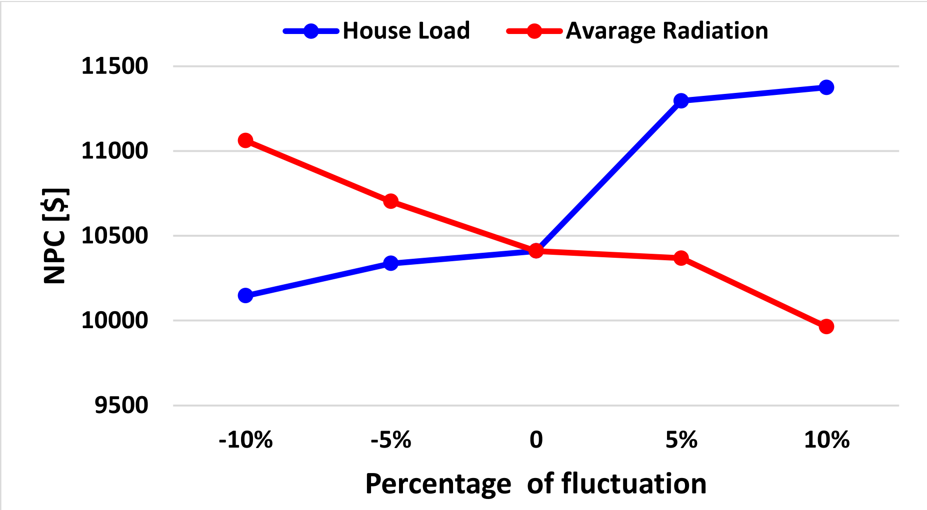


Fig. 11. Impact of house load and solar radiation on NPC of the PV-battery system.

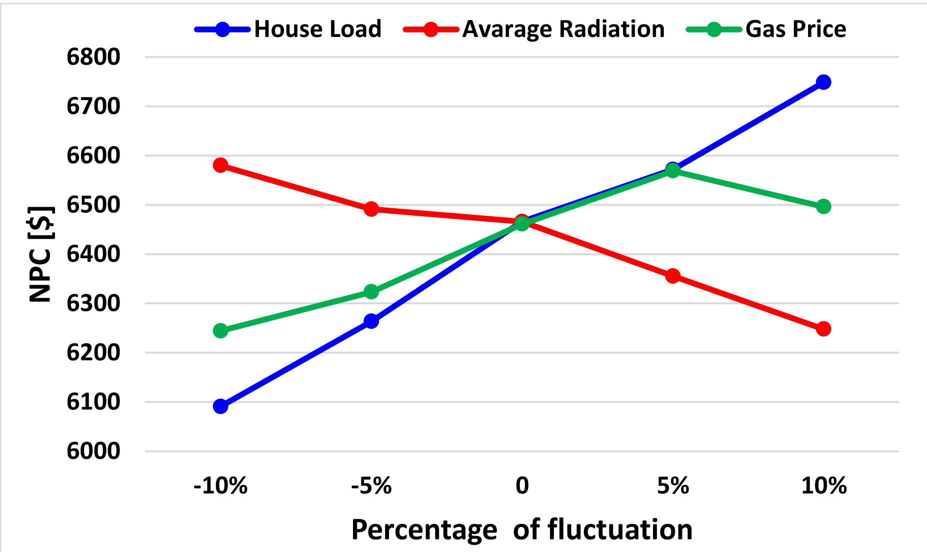


Fig. 12. Impact of house load, solar radiation and gas prices on NPC of the PV-battery-generator system.

A list of research about small-scale RO systems in Iran is presented in Table 7 to compare the present study result. Different locations such as Khorasan, Davarzan, and Kish Island are selected to design a RO system with PV panels, wind turbines, hydrogen storage, battery bank storage, diesel generator and water storage tank. The designed – in this investigation - PV-battery-RO system is a double purpose system that can power a house and water desalination system with zero GHG emissions.

Table 7. Features comparison of proposed scenario with other systems.

| Authors | System | Location | Optimization method | Features |
|---|---|---|---|---|
| Maleki et al. [7] | PV-wind-hydrogen storage-RO | Davarzan, Iran | Artificial bee swarm optimization | Large-scale system<br>GHG emission-free<br>Cost-effective and reliable system<br>Sensitivity analysis check |
| Peng et al. [6] | PV-wind-battery-RO | Khorasan, Iran | Hybrid nineteen evolutionary algorithms | Medium-scale system<br>Minimizing HRES life cycle cost<br>high reliability<br>Complex optimization method |
| Esfahani et al. [23] | PV-water storage tank-RO | Kish Island, Iran | Pinch analysis and genetic algorithm | Small-scale system<br>Large water storage tank<br>Zero required outsourced water<br>Total annual cost of 13,652 $/year. |
| Wu et al. [24] | PV-battery-diesel generator-RO | Khorasan, Iran | Tabu search | Small-scale system<br>GHG emission in the system<br>Cost-effective optimization<br>NPC: $28,130 , COE: 0.5975 $/kWh |
| This study | PV-battery-RO | Tehran, Iran | HOMER Pro software | Small-scale system<br>Double purposes electrical system<br>GHG emission-free<br>Sensitivity analysis check<br>Cost-effective optimization<br>NPC: $10,245 , COE: 0.31 $/kWh |

HOMER Pro software is used for optimization as a precise, easy to use, and flexible method for future changes. The designed system is cost-effective in which NPC and COE in the system are $10,245 and 0.31 $/kWh, respectively. Moreover, sensitivity analysis confirms that fewer sensitivity variables cause less sensitivity for the PV-battery-RO system in this study.

## 5. CONCLUSIONS

HRES are among the wide-ranging solutions nowadays for addressing the water scarcity in rural areas. A RO water desalination system powered by a small-scale hybrid PV system is the best option for this purpose. In this study, the selected rural house in Iran was precisely surveyed, and two types of daily loads were defined: 5.42 kWh/day primary house load and 1.57 kWh/day deferrable RO load. HRES components are introduced in detail based on the site information. This study suggested two major scenarios for powering the loads to optimization and comparison: i) PV system with battery storage and ii) PV system with battery storage and gas generator. Moreover, two different dispatch strategies, including CC and LF , were described.

Both scenarios are simulated and optimized in the HOMER Pro software to achieve the most cost-effective solutions. Based on the software's optimization results, although the system with both battery and gas generator has less NPC and initial capital cost around $6,460 and $3,260, this scenario use LF dispatch strategy and has 399 $m^3$/yr of natural gas consumption, which causes carbon emission. On the other hand, the PV-Battery-RO system, as a selected scenario in this paper, has fewer O&M costs and zero fuel costs. This system is environmentally friendly with zero carbon emission, has more autonomy by 100 hours working without an electricity source, and has less control complexity due to the utilized CC dispatch strategy and the fewer system's components.

The proposed small-scale stand-alone PV-battery system in this study is a double-purpose system that can simultaneously power a rural house and RO system. Cost analysis performed with HOMER Pro software indicate that NPC and COE in this system are $10,245 and 0.31 $/kWh, respectively, which are comparatively lower than designs in other reported research works. Moreover, sensitivity analysis indicates that although both presented scenarios are affected by variation in house load and solar radiation, the PV-battery system is less sensitive because it is affected by fewer sensitivity variables compared to other systems.

## 6. LIMITATIONS AND FUTURE WORKS

This study proposed different ideas about powering a rural house equipped with the RO system by HRES based on cost analysis optimization. The price of components is fluctuating in Iran, and subsequently, the cost analysis will be affected. Experimental control unit for controlling different aspects of the system, such as the deferrable load and RO unit, is challenging. As a result, a SCADA system for monitoring the critical parameters in the system can be investigated in a future work. Moreover, as a future investigation, dynamic simulation of the electrical system can be performed to analyze the behaviour of the designed system under various operating conditions.

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