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Optimal planning of renewable energy resource for a residential house considering economic and reliability criteria

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ABSTRACT

In this century, problems such as the scarcity of fossil fuel resources and related environmental contamination have led to the emergence of new energy systems based on renewable energy resources. In this paper, an optimal planning approach is proposed based on 100% renewable energy system (RES) for a residential house. In respect to renewable resources potential in the site location and electrical demand, the best combination of resources is chosen based on minimum energy supply cost and maximum reliability. Furthermore, different scenarios are suggested by considering different levels of capacity shortage (CSH) and unmet electricity load (UEL) percentage. As a case study, the real electricity consumption data for a single family household is considered in Hesarak, Tehran, Iran. The final optimal solution for this 100% RES with the objective function of cost minimization and reliability constraint include 4 kW PV, 2 kW wind turbine, 4 kW converter and 6 battery strings. This scenario with CSH of 1.1% and UEL of 0.9% has the net present cost of 20,527 $ that while having low cost, the reliability of this system is also good compared to other scenarios.

1. Introduction

To meet the growing demand for energy with a cost-effective method with respect to the environmental issues and social priorities, there is a need for a sustainable energy system [1]. Such a system provides the possibility to move toward sustainable development and reaching all people of the world to effective, accessible, clean and safe energy. Today, about 1.3 billion people (mainly in developing countries and rural areas) do not have access to electrical energy [2]. This is due to various reasons for instance lack of resources, inadequate infrastructures and long distance from the utility grid. In order to solve these problems and increasing access to the electricity in remote locations, there are two solutions. The first solution is the increasing of the electricity production by conventional methods and developing distribution and transmission networks to remote areas. And the second solution is the implementation of on-site generation systems. The first option because of many problems such as high investment costs, low efficiency of energy conversion, high losses in transmission and distribution lines and especially a lot of environmental pollutions is not a good choice for power supply of future energy systems [3]. Distributed generation (DG) sources and in particular renewable energy resources (RER) in many parts of the world have become a viable and desirable option to replace with traditional systems.

Each of RER has merits and demerits. Despite the fact that RER provides many technical, economic and environmental advantages, their intermittent nature leads to uncertainty in the prediction of power generation and resulting in decreased reliability of the system [4]. These weaknesses can be overcome with the integration of RER with each other or with conventional power sources in the form of hybrid renewable energy systems (HRES). Hybrid systems for power supply have lower costs, lower storage capacity, higher efficiency and reliability than systems which use only one source for power supply [5].

Large-scale renewable energy systems such as solar and wind farms mostly are connected to the grid and are used to supply the power of urban areas. In these systems, the main electricity grid is used as a backup system in the case of power deficit. Also in the case of excess power production, it can be sold to the main grid. In addition to the mixing of energy sources, the use of equipment such as diesel generators and energy storage systems (ESS) as a backup system is conventional and leads to higher system reliability in remote areas [6]. The use of this storage systems provides the possibility for 100% renewable power generation in remote areas [7]. At the situation that 100% demand must be met by RER, the most important issue in the implementing of HRES is optimal planning of these systems [8]. This planning process requires a detailed assessment of the potential of existing resources, related environmental, economic and technical

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Nomenclature

$L_{res,AC}$	required operating reserve on the AC bus
$L_{res,DC}$	required operating reserve on the DC bus
r_l	input operating reserve as a percent of hourly load
$L_{l.AC}$	hourly average AC primary load
$L_{l.DC}$	hourly average DC primary load
r_{pl}	input operating reserve as a percent of annual peak load
$L_{pl.AC}$	highest hourly average AC primary load experienced by the system during the year
$L_{pl.DC}$	highest hourly average DC primary load experienced by the system during the year
r_{wind}	input operating reserve as a percent of wind power output
$P_{wind,AC}$	hourly average AC wind power output
$P_{wind,DC}$	hourly average DC wind power output

constraints as well as the reliability of the system. So far, several works have been done in the literature for optimal planning and management of HRES.

A review of the literature in the field of optimal planning methods and tools, control and operational optimizing of HRES in remote areas has been done by Bernal-Agustín and Dufo-López [9]. Kaundinya et al. [10], compared and evaluated the various aspects of decentralized power supply systems in both grid-connected and off-grid modes. Different planning and evaluation methods of off-grid power supply systems can also be found in Ref. [11]. Erdinc and Uzunoglu [12], reviewed various methods such as the commercial software or various optimization methods such as heuristic methods in the field of the optimal planning of HRES. Evaluation of HRES in remote areas focusing on PV-based systems in terms of optimal sizing methods, component modeling, control and optimization of operational procedures have been studied by Bajpai and Dash [13]. Mahesh and Sandhu [14], reviewed the PV/wind/battery energy systems in terms of optimal sizing, the design of the converter, component modeling and operational optimization in both grid-connected and off-grid modes. Reviews on the HRES usage in the micro-grids in various aspects of the planning, optimization tools and methods taking into account the role of different ESS studies in terms of optimal planning and management can be found in literatures [15,16]. Also, a review of the main features of rural and remote areas energy systems in terms of energy consumption, different methods of planning, case studies, techno-economical, policy and sustainability evaluation can be found in Ref. [2]. Also examples of reginal HRES assessment can be found in [17,18].

Sinha and Chandel [5], studied simulation tools for planning, optimization, and evaluation of HRES. The results of their study show that HOMER due to the possibility of sensitivity analysis on the input data, evaluating the technical, economic, environmental and reliability criteria as well as fast and easy evaluation of a large number of system components, has the most applications among simulation software. Bahramara et al. [19], reviewed and classified the different research carried out by HOMER in the field of optimal planning and management of HRES. Their study results show that most investigation by using HOMER have been focused on off-grid systems and economic and environmental criteria. Also, it shows that there are a few numbers of studies, which focused on 100% RES and technical, economic, environmental and reliability indices simultaneously.

In studies related to the HRES planning, paying attention to the trade-off between economic and reliability indicators is the most important task [20]. The use of backup systems such as diesel generators or ESS can lead to higher reliability of the system. In addition, designing a proper reserve system, especially for 100% RES, can lead to higher system reliability while resulting in lower costs and optimal use of the resources. On the other hand, since the reserve system is mostly intended as a percent of demand or production of resources in the planning process, the impact of the reserve system should be considered in optimization results. Despite the importance of this subject, so far limited works have paid attention to the impact of reliability indices and reserve system on the planning and the optimization process.

Adding wind turbines to an energy system based on diesel power plants in a village has been studied in Ref. [21]. Authors have intended the reserve system as a percent of the hourly load and hourly wind turbine output power, however, its effect on system performance has not been discussed. They also concluded that due to a large amount of demand and high contribution of diesel generators in power generation changes the maximum annual capacity shortage (MACS) has no impact on the optimum combination of systems elements. Hrayshat [22], has performed the planning of a power supply system based on PV, diesel generators, and batteries as an off-grid system for a house in a remote area. Sensitivity analysis has been carried out in different levels of solar radiation, diesel prices, reserve system on PV energy output, MACS and the minimum share of renewable energy. But they did not report any conclusion about MACS and operational reserve in the sensitivity analysis. A similar work by adding a wind turbine to the previous combination has been implemented in Ref. [23]. Reserve system has been considered as a percent of the hourly load and power output of the wind turbine. However, the impacts of reserve system and different amounts of MACS on the optimal combination of systems and optimal performance results, have not been discussed. Türkay and Telli [24], designed and evaluated an HRES includes PV, wind turbine along with the using of the fuel cell and hydrogen storage tank. They examined the impact of various system components costs and the amounts of MACS on the off-grid system performance. Hafez and Bhattacharya [25], evaluated the various combination of RER, diesel generators and grid for providing the power of a micro-grid. They studied the effects of diesel prices, distance from the main grid and unmet load on the optimal performance of the system. But the effects of the reserve system and unmet load on the optimal planning process and performance of the proposed scheme have not been investigated. Rawat and Chandel [26], investigated an HRES based on PV and wind turbine installed on an institutional building and other optimal options were offered to replace with the existing system. Various features of the optimal system in the presence of different amounts of the MACS and their effects on the net present costs and excess electricity generation were studied. Although the effects of reserve system on the optimal performance and reliability of the system has not been investigated.

In this paper, an optimal planning approach is proposed based on 100% RES for a residential house by HOMER software. The best combination of resources is chosen with respect to RER potential in the study area and electrical load demand. The home is off-grid and RER should provide all of the power demand. The results for different modes of operating reserve and unmet electric load are discussed and various suggestions are classified based on cost and reliability requirements. Eventually, the optimum combination of an HRES is suggested based on the minimum net present cost of the system. But unlike previous studies, the effect of relevant reserve systems has been intended in this process and the optimum values for the capacity shortage and unmet load has been determined. As a case study, a real electricity consumption data for a single family household has been considered in Hesarak, Tehran, Iran.

The rest of this paper is categorized as follows: In Section 2, methods, basic definitions and mathematical relationships are explained. Section 3 contains a description of the system, its essential assumptions and study parameters. In Section 4, simulation results are described and discussed and finally in section 5 conclusion of the study is illustrated.

2. Methodology

Each power supply system usually needs to an operating reserve in order to deal with some unforeseen events such as a sudden increase in demand or loss of production units. Operating reserve (OR) is surplus operating capacity that can instantly respond to a sudden increase in the electric load or a sudden decrease in the renewable power output. OR provides reliable power supply despite variability in the RER and electric demand. Because of the random behavior of the electric load, power systems must always provide some amount of operating reserve. Without this OR, the operating capacity of the system would be sometimes less than the demand and part or all of the load would lost.

In the planning of the energy system in addition to power generation costs, the value of load lost should be considered. Ignoring reservations in the system leads to the loss of a part or lot of load and additional costs for the system. Thus, reducing the risk of unexpected going out and the unmet load is possible with an appropriate operating reserve. Operating capacity (OC) is the total amount of electrical capacity that can be generated at any time. This amount is associated with operating reserve and electric load (EL) according to Eq. (1).

Required operating reserve (ROR) is the minimum amount of operating reserve that the system must be able to provide. Systems that include the wind and solar power sources require an additional operating reserve to be protected against random decreases in the renewable power supply. Therefore required operating capacity (ROC) achieved each time step by adding the required operating reserve to the electric load (Eq. (2)). Any shortfall is known as a capacity shortage (CSH) (Eq. (3)). In short, the above discussions can be expressed mathematically below:

$$OR = OC - EL \tag{1}$$

$$ROC = ROR - EL \tag{2}$$

$$CSH = ROC - OC \tag{3}$$

On the other side, unmet electric load (UEL) fraction is the proportion of the total annual electrical load that went unserved because of insufficient generation and stems from capacity shortage (Eq. (4)). Therefore:

$$UEL = EL - OC \tag{4}$$

$$CSH = UEL + ROR \tag{5}$$

Because operating reserve resists against increasing the load or decreasing the renewable power output, the ROR is a function of both the load and the renewable power output. Therefore the amount of ROR typically changes from hour to hour. Various methods such as deterministic or probabilistic methods are proposed for determining the reserve capacity. In deterministic methods reserve capacity is generally considered to be one of the following forms [27]:

1. A certain percent of system average load and/or peak load
2. Equal to the capacity of the largest production unit
3. A specific and fixed capacity
4. A combination of the above

HOMER calculates the required operating reserve on the AC and DC buses using the following equations:

$$L_{res,AC} = r_l L_{l.AC} + r_{pl} L_{pl.AC} + r_{wind} P_{wind,AC} \tag{6}$$

$$L_{res,DC} = r_l L_{l.DC} + r_{pl} L_{pl.DC} + r_{wind} P_{wind,DC} + r_{pv} P_{pv} \tag{7}$$

As it can be seen in the above relationships the ROR is considered as a definite percent of system load, peak load, the wind and solar energy production. On the one hand, the reserve system is effective in providing demand reliability and resulting in energy resources capacity planning. On the other side, the production of energy resources is also effective in the amount of reservation system. Therefore, an optimal balance must be established between these two items. So ignoring the reserve system capacity in the planning process will result in unrealistic and unreliable results.

For meeting the purpose of the study, the methodology includes:

i. Selecting an off-grid site and determine the electricity demand of this site.
ii. Choosing the appropriate resources that conform to site situation and its monthly data (such as wind speed and solar radiation).
iii. Modeling system with HOMER software and optimal planning of HRES considering reserve system impact.
iv. Defining different level of MACS and selecting the best combination of HRES based on a trade-off between economic and reliability criteria.

3. System description

In this section, the input parameters and various system components characteristics constraints and economic parameters of the system under study is described.

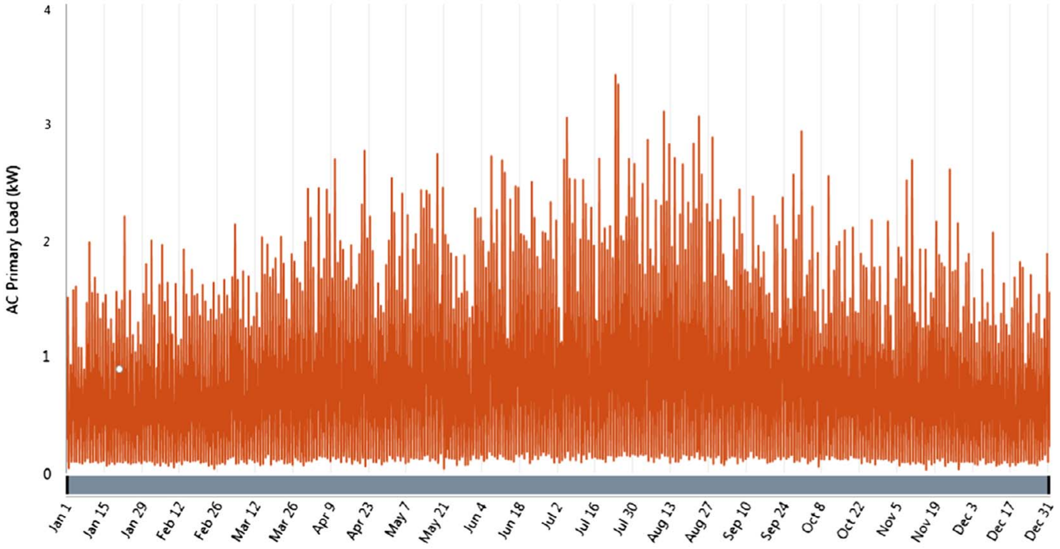

Fig. 1. Hourly AC load within a year (kW).

3.1. Site selection

In this study, an off-grid residential house in Hesarak (a village in Tarrud Rural District, in the Central District of Damavand County, Tehran Province, Iran) is considered as a case study. This house has 150 m^2 area with a 50 m^2 garden and with 4 residents. The geographical coordinates of this house are 35° 42′0″N, 52°6′0″W [28].

3.2. Electrical load demand

The load demand of this single residential house was extracted from previous year electricity bills with the combination of power data from mature energy consumer equipment such as refrigerator, lighting, cooling, and heating from Ref. [29]. Hourly and average monthly loads of this single residential house are shown in Figs. 1 and 2, respectively. This load has a 16 kW h/d average and 3.4 kW daily peak. It is assumed that up to 5% shortage in demand supply is acceptable. As a consequence, 6 scenarios have been investigated to choose the best combination of PV panels, wind turbines and battery units for meeting the 95–100 percent of load demand.

3.3. Resources assessment

In the studied site, the appropriate renewable resources are the wind and solar energies. The other renewable energy sources such as wave energy are not available in this location, and others like geothermal and biomass have not a good potential or implementation of them for a residential home entails a high cost.

3.3.1. Solar energy

Iran has an appropriate condition in the case of solar radiation, thus using PV panels is promising to use in residential houses in Iran. The solar radiation data for this case study has been taken from NASA Surface Meteorology and Solar Energy database [30]. Hourly and average monthly solar radiation data for studied area are shown in Figs. 3 and 4, respectively. Average daily solar radiation in this area is 4.89 kW h/m^2d.

3.3.2. Wind energy

The wind speed data were selected from Ref. [31]. Hourly and average monthly wind speeds are shown in Figs. 5 and 6, respectively. In this study, Weibull probability distribution function (PDF) is set by selected hourly historical data and MATLAB software, then the random data are generated for each hour.

The Weibull PDF of wind speed is given by

$$f_v(V)=\left(\frac{k}{c}\right)\left(\frac{v}{c}\right)^{(k-1)}e^{-(vc)^k} \tag{8}$$

where k, c and ν are the shape factor; the scale factor, and the random variable related to the wind speed respectively.

3.4. System components

3.4.1. PV panel

PV panel data in this study are taken from Ref. [32]. Investment cost for PV panels is1420.7 $/kW, replacement cost and operation/maintenance costs are 1420.7 $ /kW and 30.2 $/yr, respectively. The power range of PV panels is considered 0, 1, 2, 3, 4, 5, 6, 7 and 8 KW. Amount of derating factor is considered 80%. This factor reduces 20% of the production of PV in order to make an approximation of various influences such as temperature and dust. Also, the slope of the PV panels is considered to 35.5 degrees toward south direction.

3.4.2. Wind turbine

Wind turbine data have been chosen from Ref. [33], which contain the price of wind turbines and its shipping cost to Iran. The main reasons for choosing this type of wind turbine are low price and low start up wind speed (that is good for the studied site because of low average wind speed as shown in Fig. 6) and long time warranty. The power range of wind turbine is considered 0, 1, 2, 3, 4, and 5 KW. For this type of wind turbine investment cost, replacement cost and operation and maintenance costs are considered 1097 $/kW, 1097 $/kW and 10.97 $/yr respectively. Fig. 7 indicates wind turbine power curve.

3.4.3. Battery

The main problem of RESs is their intermittent nature and fluctuations of their production, which makes it difficult to control and schedule them. Adding an energy storage system increases the reliability in off-grid mode and facilitate the integration of renewable sources to the main system. In this study Trojan IND17-6V (with a maximum capacity of 1231 Ah and 7386 kW h energy) type of battery has been used with the following configuration:

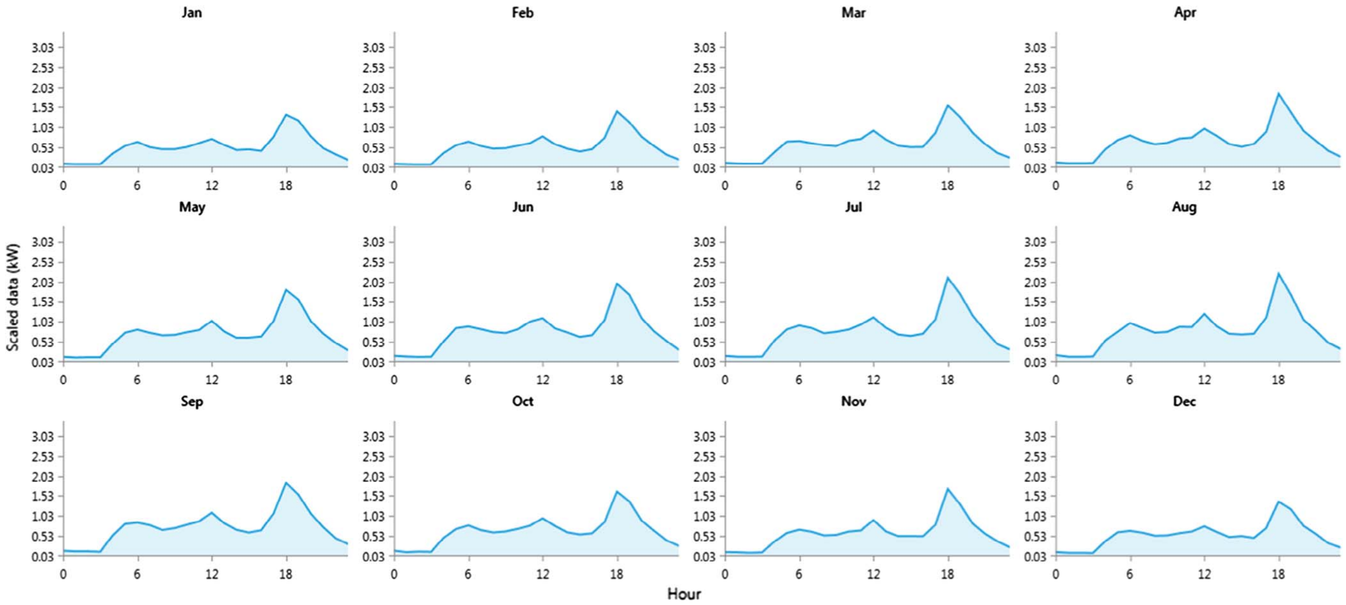

Fig. 2. Average monthly load profiles within a year.

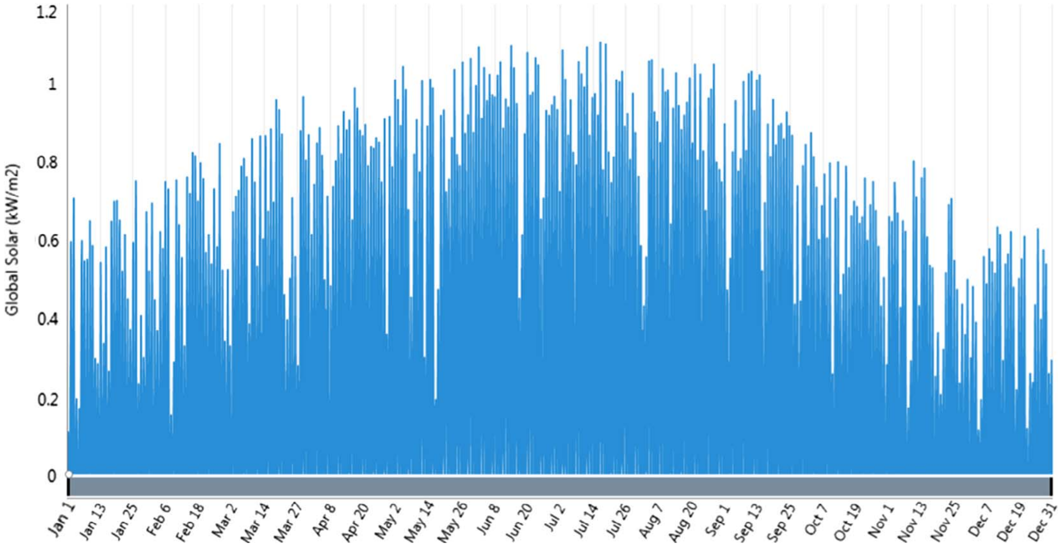

Fig. 3. Hourly solar radiation kW h/m$^{2.}$

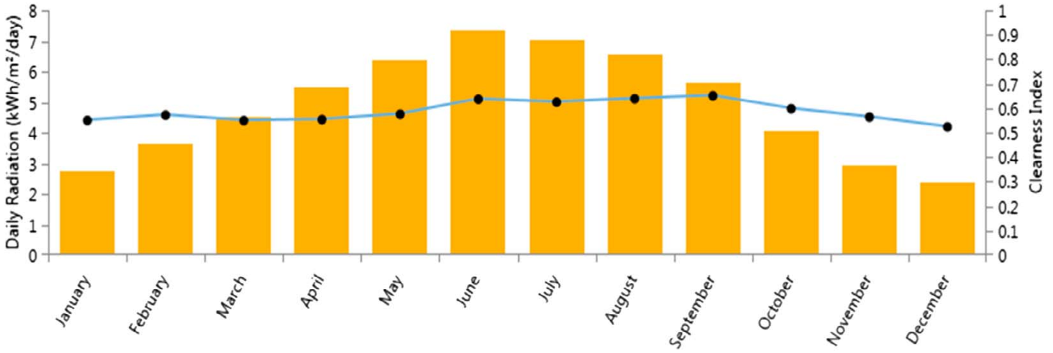

Fig. 4. Average monthly solar radiation kW h/m^2/day and clearness index.

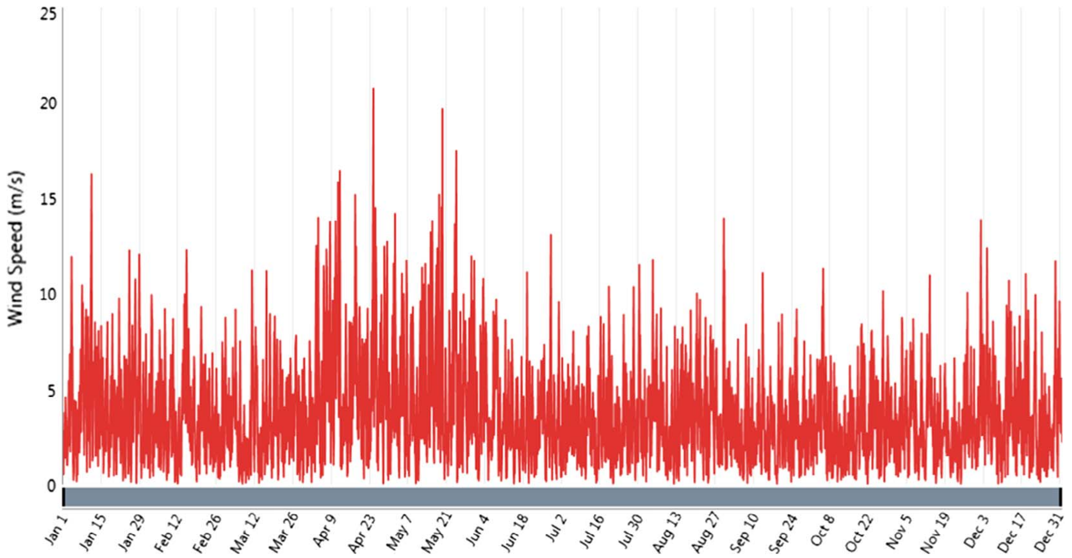

Fig. 5. Hourly wind speed (m/s).

The search space for batteries is 0, 2, 4, 6, 8 and 10 strings. The price of each battery is 800 $. The replacement cost and operation and maintenance costs are considered 800$ and 16 $/yr, respectively [34].

3.4.4. Converter

For converting the DC output of the PV panels, an inverter has been used in this study with the following configuration:

The cost of the inverter is intended 600 $ with 15-years warranty and replacement cost of 600 $ and operation and maintenance costs of 30 $/yr. The search space for the inverter is 0, 2, 4, 6, 8 and 10 kW. The efficiency of inverter and rectifier are considered 90% and 85%, respectively [34].

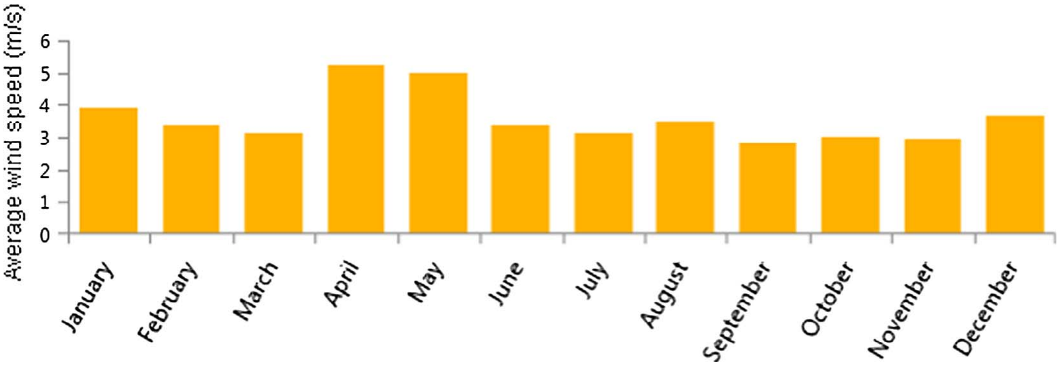

Fig. 6. Average monthly wind speed (m/s).

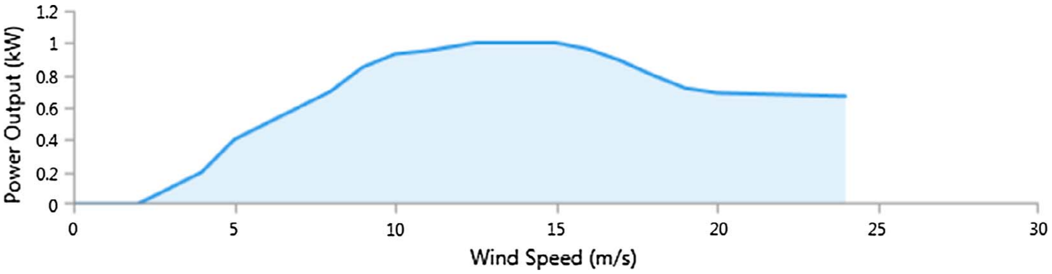

Fig. 7. Wind turbine power curve.

Table 1
Cost assumptions and life time for system components.

Component	Investment cost ($/kW)	Yearly operation & maintenance costs ($/kW)	Replacement cost ($/kW)	Lifetime (years)
PV	1420.7	30.2	1420.7	20
Wind turbine	1097	10.97	1097	20
Converter	600	30	600	15
Battery	800	16	800	20

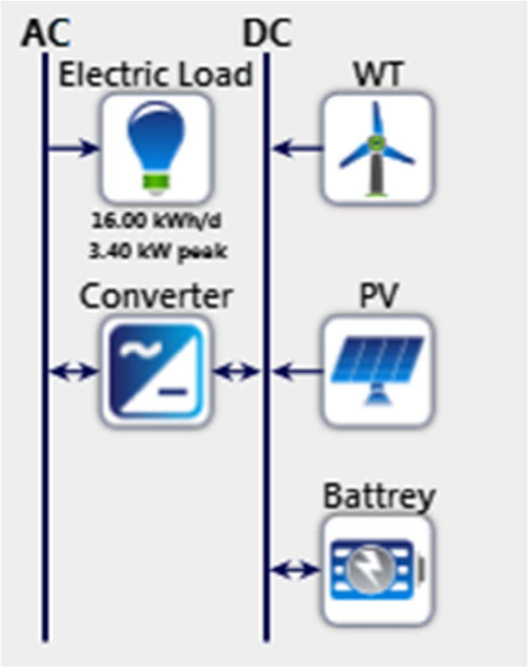

Fig. 8. Schematic representation of the system under study.

3.5. Economic parameters

In this paper, the lifetime of the project is 20 years and the interest rate is considered 15%. Real interest rate is nominal deference of interest rate and inflation rate [35]. The main purpose of this study is to minimize the total cost of energy supply with different OR and unmet demand level (UEL). For obtaining the best solution, HOMER uses Net Present Cost (NPC) with respect to the capital costs, replacement costs and operation and maintenance costs of the components and their power ranges. NPC obtain from the following equation:

$$NPC = I - \sum_{t=1}^{T} \frac{CF_t}{(1+k)^t} \tag{9}$$

where I, k and CF are initial investment cost, interest rate, and cash flow during the time steps, respectively. Lifetime and economic parameters of the hybrid energy system components for electrical energy supply is given in Table 1.

3.6. Control strategy

Two different control strategy can be used by HOMER software; load following and cycle charging. In load-following strategy generators just work in an emergency to meet the load demand and other options with low priority like battery charging is assigned to renewable energies. In the cycle charging strategy generators are used for demand supply and battery charging simultaneously. The load following strategy is used in this study.

Table 2
Optimum system costs for base case.

Component	Capital cost ($)	Replacement cost ($)	O & M ($)	Salvage ($)	Total cost ($)
PV array	5681.90	0.00	1656.90	529.10	6809.70
Wind turbine	3291.00	0.00	451.40	0.00	3742.40
Battery	6400.00	0.00	1755.70	0.00	8155.70
Converter	2400.00	1352.80	1645.90	744.96	4653.70
Total	17,773.00	1352.80	5509.90	1274.10	23,362.00

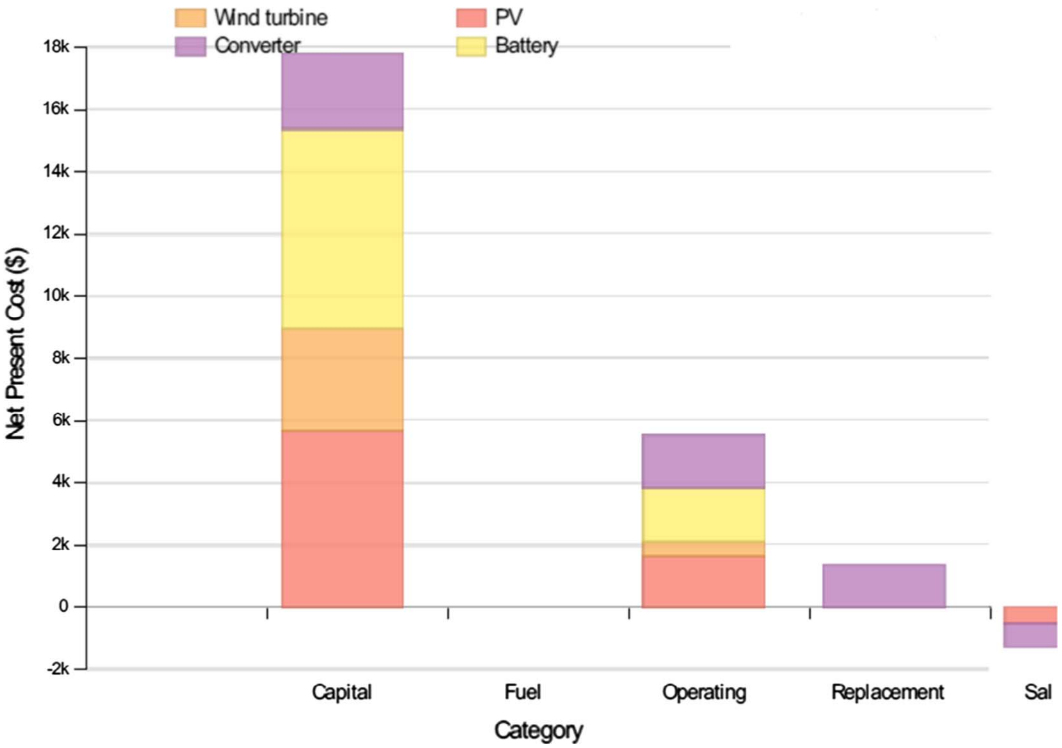

Fig. 9. Distributed costs of the proposed system.

Table 3
Simulation results for the base case.

Term	Quantity	Units
LCE	0.2919	$/kW h
NPC	23,362	$
PV rated capacity	4.00	kW
PV mean output	17.51	kW h/d
PV capacity factor	18.23	%
PV total production	6389.3	kW h/yr
PV hours of operation	4376	hr/yr
Wind total rated capacity	3.00	kW
Wind mean output	0.37	kW
Wind capacity factor	12.20	%
Wind total production	3205.6	kW h/yr
Wind hours of operation	5322	hr/yr
Battery energy in	3236.9	kW h/yr
Battery energy out	2633.1	kW h/yr
Battery losses	605.99	kW h/yr
Converter energy in	6483.8	kW h/yr
Converter energy out	5835.4	kW h/yr
Converter losses	648.35	kW h/yr
Converter capacity factor	16.5	%
Converter hours of operation	8750	h/yr
Renewable fraction	100	%
CO_2 Emission	0	kg/yr

4. Result and discussion

In this section, the actual data of a residential house in Hesarak, Tehran is used as a case study. Determining an optimal combination of renewable resources based on the minimum cost of energy supply is the first objective of this section. The effects of operating parameters especially specific values of operating reserves on the performance and cost of the system are discussed in this section. A sensitivity analysis on different levels of CSH and UEL is done and the results are classified in order to allow the user to select the best combination of feasible solutions. In order to select the optimal combination of the system components and studying the effect of reserve four different scenarios have been investigated.

(1) Base case
(2) System with load reserve
(3) System with peak load reserve
(4) System with load and peak load reserve

Since all the load demand must be provided by the proposed system without creating an unmet electric load, so the amount of maximum annual capacity shortage is assumed to be zero. In the first scenario (base case) which is without operating reserve, all load demand must be provided by the proposed system that means the amount of CSH is zero. In the second scenario, operating reserve is considered based on a specified percent of the system load. In the third scenario operating

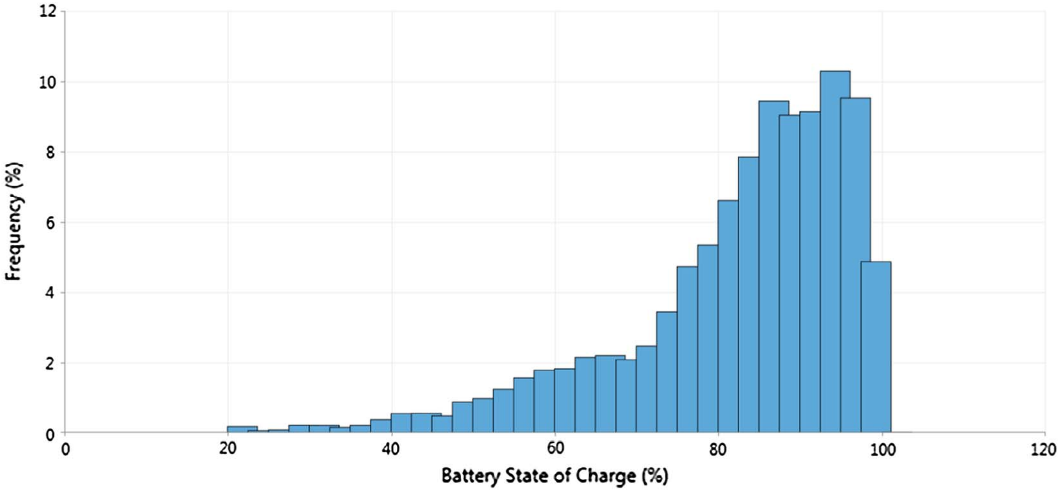

Fig. 10. Histogram of battery state of charge level frequency.

Table 4
Total power production and consumption.

Term	Quantity)kW h/yr(
PV production	6389
Wind turbines production	3206
Total production	9595
AC primary load	5835
Excess electricity	2507.4
Unmet electric load	4.6
Capacity shortage	4.6

reserve is computed based on a percent of the peak load. And finally, in fourth scenario operating reserve is considered as a percent of load and peak load.

Schematic representation of the system under in this study is given in Fig. 8. The system includes an array of PV panels, wind turbines, battery storage system and converter.

4.1. Base case

In this case, the value of r_l & r_{pl} are assumed to be zero and according to the simulation results, the optimal system consists of a 4 kW PV array, 3 kW wind turbines, a 4 kW converter and 8 batteries. The NPV of the system is equal to 23362.00 $. Table 2 summarizes different costs of the optimum system during long-term periods.

According to Table 2, the total investment cost for the system is equal to 17,773.00$. Battery units and PV panels have the highest initial investment costs respectively. In this system similar to the other RES maintenance cost is much less than the investment cost. The total cost of the system is 23,362.00$ at the present time. Furthermore, for developing a RES in Iran the government pays 50 percent of the initial investment cost of renewable systems in the residential sector. Also, excess electricity of these systems is purchased with a reasonable price that encourages consumers to use RES for their energy supply and makes this projects economically reasonable [36].

Distributed costs of the proposed system are given in Fig. 9, based on components types. As shown in Fig. 9, the operating and replacement costs are very lower than the initial investment cost. This shows that RES operation is so stress-free and low-priced. Salvage (Sal in Fig. 9) is the economic value of the system that will obtain at the end of the project lifetime.

Simulation results for the base case are given in Table 3 that offers a comprehensive overview of the system performance during the project lifetime.

Leveled cost of energy (LCE) in Table 3 is the cost of power production per kW h that is an important factor for comparing different types of the energy systems. With the installation of the proposed RES, the cost of power output per kW h will be equivalent to 0.2919 $. The mean value for the output power of PV panels is 0.73 kW that is equal to 18.23% of its nominal power. In Table 3 it can be seen that operating hours and power production of the PV array are more than wind turbines. Because, unlike the solar radiation, the wind speed is relatively low in studied location. The efficiency of battery and converter are 81% and 90%, respectively. All demand of household is provided by renewable energy resources, so greenhouse gasses (GHG) emission of this system is zero, which indicates its environmental compliance.

Fig. 10, shows the histogram of battery state of charge level frequency. As it can be seen from this figure the battery charge status is high in most of the times. Because reserve system is not predicted and all of the demand must be met, so the battery charge state should be appropriate to compensate the shortage of renewable resources production.

Table 4, summarizes the total power production and consumption of the proposed system.

The total PV power generation is 6389 kW h/yr which is 66.6% of total power generation. As explained above PV power generation is more than wind turbine generation because of suitable solar radiation in the studied area. Fig. 11, illustrates that appropriate wind speed causes more wind turbine power generation in April and May. It is also obvious from Table 4 that UEL and CSH values are 4.6 kW h/yr which is

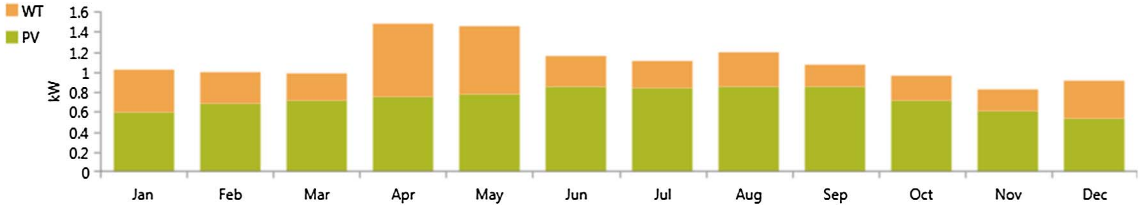

Fig. 11. Average power production for each month.

Table 5
Simulation results for system with load reserve.

Term	Quantity	Units
LCE	0.2919	\$/kW h
NPC	23,362.00	\$
PV production	6389	kW h/yr
Wind turbines production	3206	kW h/yr
Total production	9595	kW h/yr
AC primary load	5835	kW h/yr
Excess electricity	2497.1	kW h/yr
Unmet electric load	4.6	kW h/yr
Capacity shortage	4.8	kW h/yr

Table 6
Simulation results for system with load reserve.

Term	Quantity	Units
LCE	0.2975	\$/kW h
NPC	23,816.00	\$
PV production	7987	kW h/yr
Wind turbines production	2137	kW h/yr
Total production	10,124	kW h/yr
AC primary load	5835	kW h/yr
Excess electricity	2998.5	kW h/yr
Unmet electric load	2.5	kW h/yr
Capacity shortage	5.5	kW h/yr

Table 7
Simulation results for system with load and peak load reserve.

Term	Quantity	Units
LCE	0.3016	\$/kW h
NPC	24,153.00	\$
PV production	6389	kW h/yr
Wind turbines production	2137	kW h/yr
Total production	8526	kW h/yr
AC primary load	5835	kW h/yr
Excess electricity	1394.6	kW h/yr
Unmet electric load	1.6	kW h/yr
Capacity shortage	3.3	kW h/yr

less than 0.1% of total load. It means that the proposed system provides the whole load with less than 1% unmet load.

4.2. System with load reserve

In this scenario, the amount of reserve is defined as a percentage of the load in each time step and $r_l = 0.1$. So operating load reserve is 10% of load in each time step. The main results are summarized in Table 5.

According to simulation results, the optimal system consists of a PV array with a capacity of 4 kW, three micro-wind turbines with a total capacity of 3 kW, a 4 kW converter, and 8 batteries. The system has a net present cost of \$ 23,362.00. The results are similar to the first scenario and the only difference is an increased amount of CSH and less amount of excess electricity. In addition to an operational reserve, the amount of CSH is slightly higher than the base case and an amount of excess electricity produced in the base case has been consumed to provide the requested reserve.

4.3. System with peak load reserve

In this scenario, load reserve is defined as a percentage of the annual peak load and so $r_{pl} = 0.1$. Therefore operating load reserve is 10% of annual peak load. The results are summarized in Table 6. According to the optimization results, the optimal system includes 5 kW PV panels, 2 kW wind turbines, a 4 kW converter and 8 batteries. The cost of this system is 23,816.00 \$.

Table 6 shows that optimized system combination is changed in this scenario. Wind turbine capacity has been dropped to 2 kW and PV panels capacity is increased to 5 kW. The amount of LCE and NPC are increased, PV power generation is enhanced and total generation and excess electricity are increased. It is also seen that with creating reserve load, the reliability of the system has been improved and UEL is dropped to 46% while CSH is more than the base value. In fact, this system is more expensive but more reliable.

4.4. System with load and peak load reserve

In this scenario, load reserve defines as the percent of load and annual peak value so that $r_l = r_{pl} = 0.1$ which means considering load reserve as 10% of annual peak load and 10% of load in each time steps. According to optimization results, the optimal system includes 4 kW PV panels, 2 kW micro wind turbines, 4 kW converter and 10 batteries. The total cost of this system is 24,153.00\$. Results of this scenario are summarized in Table 7.

In this scenario, the system uses more batteries instead of increasing PV power generation that is more expensive but more reliable. The reason of using more batteries in this system is the added amount of requested reserve which can provide electrical demand with a proper number of batteries. Table 7 shows that excess electricity is 66.6% less than base value but NPC and LCE both are increased 3.3% compared to the base value. In scenario 4, the system uses more batteries that are more expensive but more reliable. Also, wind turbine capacity in scenario 4 is decreased from 3 kW to 2 kW that leads to a reduction in excess electricity production. By using more batteries in scenario 4, more amount of excess electricity can be stored and this stored energy can provide more electrical demand. This leads to decrease in excess electricity compared to the base case. Reliability is improved by creating a more operating reserve and UEL value reaches to 1.6 kW h/yr that is the minimum value between all scenarios. Also with decreasing of UEL, CSH reaches to its minimum value. Table 8 summarizes the results of 4 mentioned scenarios.

One interesting point in Table 8 is that despite the lower amount of UEL in scenario 3 (compared to scenarios 1 and 2), the capacity shortage is high? As indicated in Eq. (5), the amount of capacity shortage is equal to the sum of required operating reserve (ROR) and UEL. In scenario 3 the ROR is considered as a definite percent of peak load (Highest hourly average AC primary load) that has a higher amount compared to scenarios 1 and 2 and causes the capacity shortage in Scenario 2 to be higher. In comparing scenarios 3 and 4, it can be said that the amount of ROR in scenario 4 is greater, but the presence of battery will lead to a large part of this amount of ROR to be supplied (more amount of excess electricity can be stored and this stored energy

Table 8
Summarized results for all scenarios.

Scenarios	PV (kW)	Wind (kW)	Battery (strings)	Converter (kW)	NPC (\$)	LCE (\$/kW h)	Excess electricity (kW h/yr)	UEL (kW h/yr)	CSH (kW h/yr)
1	4	3	8	4	23,362	0.2919	2507.4	4.6	4.6
2	4	3	8	4	23,362	0.2919	2497.1	4.6	4.8
3	5	2	8	4	23,816	0.2975	2998.5	2.5	5.5
4	4	2	10	4	24,153	0.3016	1394.6	1.6	3.3

Table 9
Sensitivity analysis data based on MACS.

MACS	CSH (%)	UEL (%)	PV (kW)	Wind (kW)	Battery (strings)	Converter (kW)	NPC($)	LCE ($/kW h)	Excess electricity (kWh/yr)
0	0.1	0.1	4	3	8	4	23,362	0.2919	2507.4
1	1.1	0.9	4	2	6	4	20,527	0.2587	1466.1
2	2.0	1.3	5	1	6	2	19,000	0.2402	1961.4
3	2.2	1.5	4	2	6	2	18,147	0.2300	1510.4
4	4.03.13.3	3.1	5	1	4	2	17,856	0.2300	2106.7
5	4.3	3.4	4	2	4	2	17,063	0.2204	1654.7

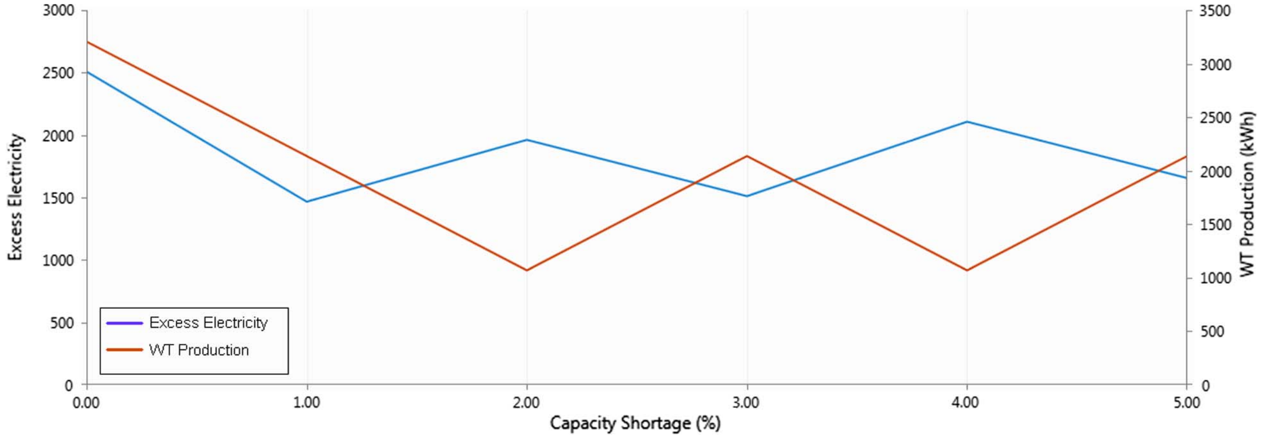

Fig. 14. Ratio of excess electricity production and wind turbine production to MACS.

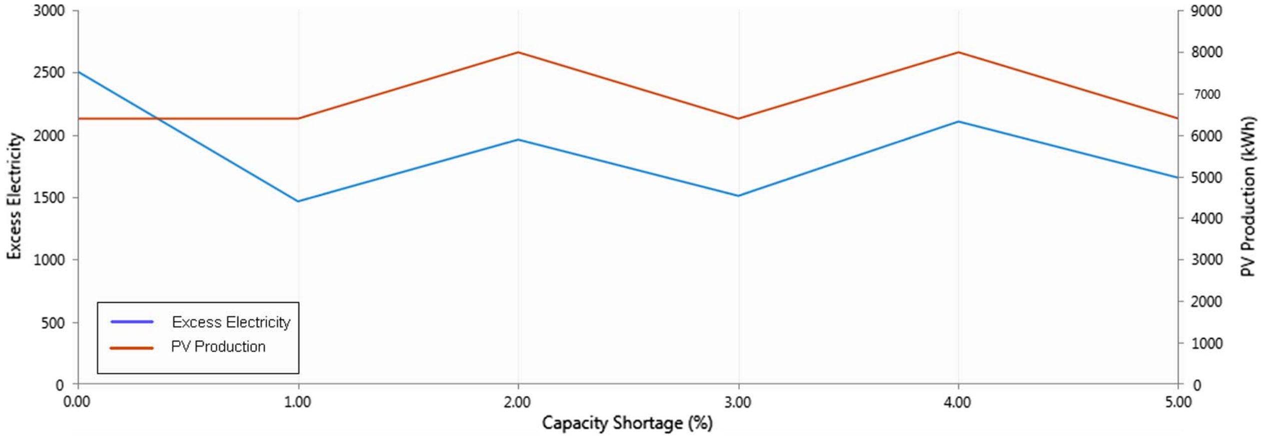

Fig. 13. PV production and excess electricity changes related to MACS.

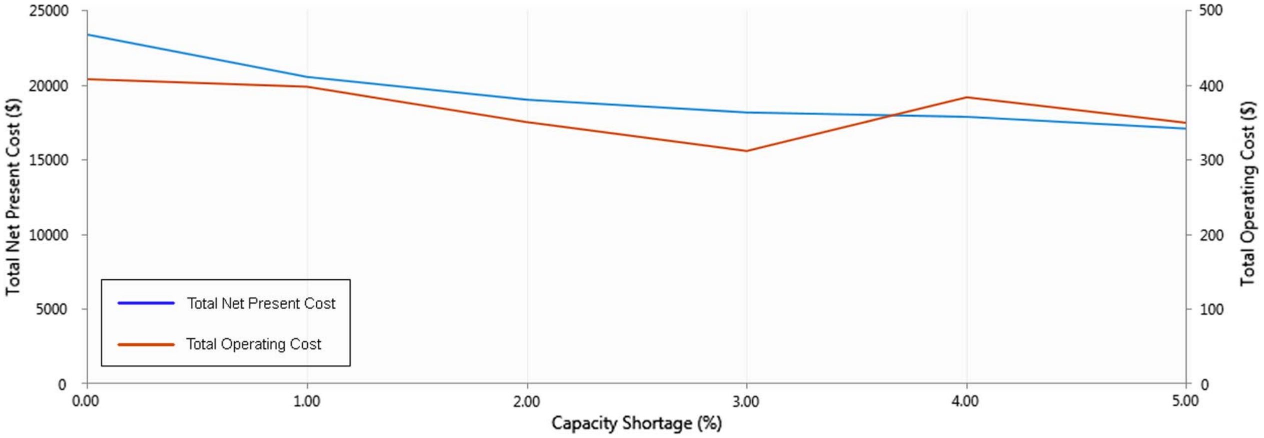

Fig. 12. NPC and total operating cost changes related to MACS values.

Table 10
Marginal NPC changes.

MACS	CSH (%)	UEL (%)	Marginal NPC changes (%)
0	0.1	0.1	–
1	1.1	0.9	12.18
2	2.0	1.3	7.4
3	2.2	1.5	4.4
4	4.0	3.1	1.6
	3.13.3		
5	4.3	3.4	4.4

can provide more electrical demand), and the amount of capacity shortage in scenario 4 is lower than scenario 3.

As a final result from Table 8, it can be found that the effect of the annual load peak reserve is more than the load reserve in each time steps. The increase in the load reserve is more beneficial rather than increase in system resources and storage units. As a result, system costs increase with improving reliability. According to the reliability criteria, system combination in scenario 4 is the best choice. On the other hand, the system in the scenario 1 is the most economical system. However, the most optimal system in terms of reliability and costs consideration is the system in the scenario 2.

4.5. Sensitivity analysis

In this section, taking into account the proposed system in Section 4.4, a sensitivity analysis is done on different amounts of CSH. These amounts can be considered as the MACS in the input of HOMER. The main purpose of this section is to evaluate the effects of user-defined constraints for the MACS on the performance of the system. Here the values 0, 1, 2, 3, 4 and 5 are selected for MACS and the simulation results are shown in Table 9.

Table 9 summarizes the simulation results of hybrid power supply system for different values of MACS. When MACS rises from 0 to 1 (We show it with MACS1) the battery strings are reduced from 8 to 6 and wind turbine from 3 kW to 2 kW. This leads to a reduction in NPC and capacity excess electricity (according to Fig. 14, by reduction of wind turbine capacity excess electricity, is decreased). In MACS2 the PV capacity rises 1 kW and at the same time installed converter capacity and wind turbine decrease 2 kW and 1 kW respectively. Therefore, the excess electricity increases by increasing the PV capacity (which is shown in Fig. 13). Also because of reduction in converter and wind turbine capacity (Even with increased capacity of PV), NPC is reduced. In MACS3 the PV capacity is reduced 1 kW and wind turbine capacity rises 1 kW. The investment cost (and in general NPC) of 1 kW PV is more than 1 kW wind turbine. Therefore NPC is reduced compared to MACS2. Also reduction in PV capacity leads to a reduction in excess electricity. In MACS4 the battery strings are reduced from 6 to 4 and wind turbine from 2 kW to 1 kW. This leads to a reduction in NPC. Also with increased capacity of PV and at the same time reduction in battery strings the amount of excess electricity rises sharply. In MACS5 the wind turbine capacity rises 1 kW and at the same time installed PV capacity decrease 1 kW. The NPC of 1 kW PV is more than 1 kW wind turbine. Therefore NPC is reduced compared to MACS4. Also, a reduction in PV capacity leads to a reduction in excess electricity.

One of the main characteristics of residential loads is the presence of needle peaks in their consumption curves. As seen in Fig. 1, the ratio of power consumption above 2 kW to total load is very low. On the other hand, as shown in Table 8 and in the first two rows of Table 9, the proposed system uses a 4 kW converter. And the capacity of the converter is reduced to 2 kW, when the MACS value increases and a part of the demand is not provided. This unmet load is mostly the demands above 2 kW and the designed system does not meet these demands and an affordable converter with less capacity can be used.

In all of these cases, CSH value does not exceed its specified value (MACS) by the user. Whatever the amount of MACS is increased, the system is allowed to have a more unmet load, and so the components with less capacity and price can be used. In any power supply system, there are some peak loads with very short time periods. When the system is forced to provide all these peak loads, the components with higher capacity is needed. Therefore, with an allowed amount of UEL, there is a need for a tradeoff between system reliability and the cost of using additional components. Table 9 illustrates that by reducing the amount of MACS (higher reliability), the capacity of the storage system, which is an expensive component, is increased. Also with a reduction in PV panel capacity, the cheaper supply system (wind turbines) is used.

Fig. 12, shows the changes in the NPC and total operating cost (TOC) to MACS changes. As it can be seen from this figure, NPC decreases with increasing MACS, but this is not true about TOC. Because system operating costs can be increased by adding a component with higher operational cost. For example, by increasing the amount of MACS from 3% to 4% total operating cost is increased due to increasing of PV installed capacity, which has higher operating cost than other system components. Note that when MACS increase from 1% to 2% the PV capacity rises 1 kW, but at the same time installed converter capacity is reduced 2 kW and the total operating cost is decreased because operating cost of 2 kW converter is less than 1 kW PV panel.

Fig. 13, demonstrates the variation of PV production and excess electricity with respect to MACS changes. This figure depicts an important result that amount of excess electricity follows the PV production pattern. This means that usually, the electricity consumption pattern does not match the PV production pattern. In other words, maximum PV production occurs when there is no essential need for this energy and also the lack of sufficient energy storage system is caused excess electricity production. While the wind power is vice versa and its generation is opposite of excess electricity production (Fig. 14). This means that more amount of wind production is consumed by load instantaneously, and so wind power has a low share in excess electricity production.

HOMER in its optimization process searches for the system configuration with the lowest total net present cost. For the optimal system, among the scenarios examined, the detailed results are presented in Table 6. As seen, the total power production by 4 kW PV is 6389 kW/year. This amount for 3 kW wind turbines is 3206 kW/year. Obviously, the production of each kilowatt of PV equals 1597 kW and the production of each kilowatt of wind turbines is 1069 kW. Therefore, the ratio of power production of 1 kW PV to power production of 1 kW wind turbine is 1.49. On the other hand, the ratio of the investment cost of 1 kW PV to investment cost of 1 kW wind turbine is 1.29. Therefore, the ratio of power generation to the investment cost of PV is better. In this case, it may be concluded that it is better to always use photovoltaics instead of wind turbines. But from another point of view, as indicated in the paper, photovoltaic power generation does not match with consumption pattern and it requires expensive systems like battery banks. Therefore, a trade-off between these items should be created which the result of this trade-off and the optimal combination for each

Table 11
Final optimal combination.

MACS	CSH (%)	UEL (%)	PV (kW)	Wind (kW)	Battery (strings)	Converter (kW)	NPC ($)	LCE ($/kW h)	Excess electricity (kW h/yr)
1	1.1	0.9	4	2	6	4	20,527	0.2587	1466.1

scenario are presented in Table 8.

Some of household loads can be programmed and controlled without a major impact on the level of consumers comfort. In other words, in residential consumption curve, there are some peak loads with very short time periods. When the system is forced to provide all these peak loads, the components with higher capacity is needed. Therefore, with an allowed amount of UEL (defined by customers), a tradeoff between system reliability and the cost of using additional components can be done and the components with less capacity and price can be used. To summarize, we can say that large amounts for CSH are not desirable, but the cost of the system can be reduced by adopting low amounts for CSH. In the proposed model, the customers, taking into account their level of comfort and preferences, can adopt a defined amount for the capacity shortage, and, while having proper reliability, reduce their costs.

Eventually, with consideration above discussions, a single household can be supplied with a combination of renewable energy resources and storage systems. For this decision, Table 10 can be used. Table 10 shows that for 1% increase in MACS from one case to another case, how much decreasing in NPC can be achieved. Table 10 shows that the maximum reduction in NPC occurs by increasing 1% of MACS from 0 to 1. While, in this case, the system still have appropriate reliability and only 1% and 0.8% increasing occur in CSH and UEL, respectively. As a result, the system with MACS 1%, is a reasonable suggestion in terms of cost and reliability considerations. However, consumers can choose from a variety of other combinations according to the desired indicators. The proposed approach of this study can be used for selecting the optimal power supply for off-grid systems with consideration of economic, technical and reliability constraints and customer priorities.

Characteristic of final optimal solution for this case study, based on a 100% RES and with the objective function of cost minimization and reliability constraint, have been summarized in Table 11.

5. Conclusion

This paper evaluates the residential house demand supply based on a 100% RES. Different indicators such as NPC, LCE, the reliability of supply system, the excess electricity and CSH have been considered to select the optimum combination of HRES. A real household data in Hesarak, Tehran, Iran has been used as a case study and the electrical demand has been extracted using consumer bills over the last year. The wind speed historical data have been imported into the MATLAB software and a Weibull probability distribution function has been assigned for each month. Then with this PDF, we generate a sort of random data have been generated for each month and this random amount have been imported to the HOMER software as an input for wind speed.

By definition of various scenarios based on the operating reserve, the best combination of the power supply system has been determined by taking the effect of reserve system into account. Results show that if the MACS is set to zero, the system should be planned to meet even very high peak load. This means that the system has to include large and expensive equipment that are not used most of the time. If customer allows a bit of capacity shortage (e.g. 1%, 2%), the planner can install smaller and affordable equipment that would be able to supply demand without some of the instantaneous peak loads. Finally, by using a sensitivity analysis on different levels of MACS, the final composition of the system has been proposed based on the cost and reliability criteria. The final optimal solution for this case study, based on 100% RES and with the objective function of cost minimization and reliability constraint includes 4 kW PV, 2 kW wind turbine, 4 kW converter and 6 battery strings. With CSH of 1.1% and UEL of 0.9% the NPC of this system is 20,527 $ that while having low cost, the system reliability is also good. Furthermore, other optimal combinations are proposed based on cost and reliability that customers can choose the appropriate system according to their desired indicators. The proposed method in this paper can be used to design a system to meet the demand in the various sectors taking the economic and reliability criteria into account.

Future work will be done to design optimal systems in other consumption sectors such as commercial, institutional and using other renewable sources and energy storage systems.

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