Research Article

Effects of Reliability Index on Optimal Configuration of Hybrid Solar/Battery Energy System by Optimization Approach: A Case Study

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Stand-alone hybrid energy systems based on solar and energy storage are an effective option for rural areas to meet the load demand. The objective of the current work is to obtain the optimal configuration of a stand-alone hybrid photovoltaic/battery energy storage system with the help of an efficient metaheuristic algorithm, improved harmony search, to supply electrical of a residential load in Iran. The objective function is a minimization of total life cycle cost (TLCC) subject to the reliability index (loss of load probability). The optimal configurations of hybrid systems are compared in respect of different losses of load probability (0 to 20%). Sensitivity analysis and effects of economic parameters based on photovoltaic and battery prices are carried out to study the possibility of the suggested scheme. The results show that, by increasing the reliability index from 0 to 20%, the optimal number of panels and batteries decreases by 52 and 1202. Also, it is found that the TLCC of the system and cost of system components are increased by decreasing of the reliability index value.

1. Introduction

The provision of electricity is one of the key elements for the economic growth of a country. Around 17% of people in the countries, specifically those living in isolated regions, still have no contact with electricity [1, 2]. Due to the high cost of network transmission to remote areas, mainly, diesel generators are used to supply load demands to remote locations. Due to the high cost of fuel, environmental pollutants, and the shortage of fossil fuels, diesel power generation is not always a beneficial and cost-effective solution. To solve this problem, the use of renewable energy has been considered by many researchers in recent years. Renewable energy systems, especially solar PV systems, are an effective solution for stand-alone locations [3].

However, uncertainty in solar radiation and the dependence of solar systems on the climate is a problem for providing continuous load in remote areas. So it is a viable solution for stand-alone locations to consider a PV system with an energy storage unit initially. Among storage systems, the battery is one of the most popular [4–7]. In this regard, it is necessary to define the optimal configuration of power scheme components to remote areas to supply the load demand with the minimum cost and maximum reliability. Therefore, efficient modeling and a powerful optimization method to solve these problems are essential.

Several studies in the literature have focused on investigating mathematical modeling, optimal sizing, and techno-economic analysis of hybrid energy schemes based on solar energy. Javed et al. [2] used a genetic algorithm to optimize a hybrid solar/wind system with storage for an isolated island. The results were compared with that of the HOMER (hybrid optimization of multiple energy resources) software. Das et al. [8] obtained a techno-economic optimal design of

Various theories and methods have been studied on power systems [19–25]; in this regard, several optimization methods have been presented on the investigation of optimal sizing of hybrid solar energy systems, including HOMER software [26–30], genetic algorithm [31], tabu search [32], simulated annealing [33], particle swarm optimization [34], grey wolf optimizer [35], harmony search [36–38], and global dynamic harmony search [39]. Yu et al. [40] proposed an efficient framework based on harmony search to find the suitable capacity and location for off-grid PV/battery systems. It is found that the optimization algorithm based on harmony search offers better results than the simulated annealing algorithm.

Previously mentioned researches have mainly focused on optimization hybrid energy systems based on solar energy with the lowest total cost. Some studies have also examined the impact of the reliability index (RI) on the hybrid energy system. Previously, studies usually used the HOMER software tool to perform techno-economic analyses based on the input information of hybrid systems. The HOMER software tools allow a quick hybrid energy system assessment, but changes in the modeling of hybrid system components are limited. The ability to modify mathematical models and input information for different renewable energy technologies is restricted in the HOMER tool. Also, in previous studies, a comprehensive analysis of the effects of critical economic parameters and reliability index on the optimization of hybrid systems by an efficient metaheuristic algorithm is rarely seen.

In this paper, an optimization model of a stand-alone PV/battery energy storage scheme to the optimal configuration of the hybrid system to supply electrical load demands is presented. The methodology followed in this study considered a remote area in Iran residential communities, namely, Rafsanjan. For optimal sizing of hybrid system components, an improved metaheuristic algorithm based on harmony search is presented. The objective function is a minimization of total life cycle cost (TLCC) and loss of load probability as a reliability index. To study the possibility of the suggested hybrid system, effects of economic parameters based on photovoltaic and battery prices are presented. Also, the optimal configurations of the hybrid system are compared in respect of different reliability indexes.

2. System Modeling

The stand-alone hybrid energy systems include a solar photovoltaic panel, storage unit based on battery, an inverter/converter system, and other devices and cables. In this system, first, the power generated by solar panels satisfies the required load. After satisfying the load demand, the power generated from PV panels is used to charge the battery bank to supply the load when sunlight is unavailable.

Then, the extra battery charge level is dumped. To optimize the scheme, all of the system components must first be exclusively modeled and then their optimal sizing calculated to meet the load demand. The full model of the stand-alone hybrid solar/battery scheme is shown in Figure 1.

2.1. The Model of Photovoltaic (PV). The proposed model for generating power of PV panel ($P_{PV}$) based on the solar radiation ($R$) and ambient temperature ($T_{amb}$) has been written as follows [41]:

$$P_{PV}(t) = P_{R,PV} \times \left( \frac{R}{R_{ref}} \right) \times \left[ 1 + N_T(T_c - T_{ref}) \right],$$

(1)

where $P_{R,PV}$ refers to the rated power of the utilized panel. $N_T$, $T_{ref}$, and $R_{ref}$ refer to the temperature coefficient (here $-3.7 \times 10^{-3}$ $(1/\degree C)$), reference temperature (here 25°C), and reference solar radiation (here 1000 W/m²), respectively [42]. The temperature of the cell can be formulated as follows [41]:

$$T_c = T_{amb} + \left( \frac{(NOCT - 20)}{800} \right) \times R_t.$$

(2)

Here, NOCT refers to the normal operating cell temperature (°C). The total produced power by PV panels is $P_{PV}(t) = N_{PV} \times P_{PV}(t)$, based on number of panels ($N_{PV}$).

2.2. The Model of Battery Storage. To increase the reliability of the hybrid system and save the surplus output power of PV, an energy storage unit (battery bank) has been used. When the output power of the PV system is higher than
the required load, the energy storage unit will start charging. Energy storage is used, when the output power of the PV panels is insufficient to supply the load demand. At this time, the energy storage unit will start discharging. The state of charge of the battery storage unit during the time from \( t-1 \) to \( t \) is given in Equations (3) and (4) [43, 44].

Charging state:

\[
S_{\text{BAT}}(t) = S_{\text{BAT}}(t - 1) \cdot (1 - \omega) + \left[ \frac{E_L(t)}{\eta_{\text{INV}}} \right] \cdot \eta_{\text{BC}}.
\]  

(3)

Discharging state:

\[
S_{\text{BAT}}(t) = S_{\text{BAT}}(t - 1) \cdot (1 - \omega) - \left[ \frac{E_L(t)}{\eta_{\text{INV}}} + (E_{\text{PV}}(t)) \right] \cdot \eta_{\text{BDC}}.
\]  

(4)

Here, \( \omega \), \( S_{\text{BAT}}(t), \eta_{\text{INV}}, \eta_{\text{BC}}, \eta_{\text{BDC}} \), and \( E_L \) refer to the rate of hourly self-discharge, state of charge of the battery at time \( t \), the efficiency of the inverter, charging, and discharging of the battery (here 1), demand of load, respectively, and \( t \) is the hourly time (1 h) [43–46].

2.3. The Model of Inverter. According to the output current of solar panels, a converter must be used to convert the direct current to alternating current. The output power of an inverter (\( P_{\text{INV}} \)) is obtained by the following Equation (12):

\[
P_{\text{INV}} = \frac{P_D}{\eta_{\text{INV}}},
\]  

(5)

where \( P_D \) is the hourly demand.

3. The Objective Function and Constraints

3.1. Objective Function. The objective function is a minimization of total life cycle cost (TLCC) subject to the loss of load probability (LLP). TLCC includes the annual operation and maintenance (O&M) cost, which occur during the
project lifetime, and annual capital and replacement (C&R) cost, which is as follows:

\[
\text{Minimize: } TLCC = C&R + O&M
\]

According to the capital cost and replacement cost, which occur in the beginning and during the project lifetime, the capital recover factor (CRF) based on the interest rate \(r\) and system life span \(n\) is mathematically modeled as follows [47]:

\[
\text{CRF} = \frac{r(1 + r)^n}{(1 + r)^n - 1}.
\]

Due to the lifetime of the batteries and inverters (here 5 and 10 years, respectively), their replacement should be considered in the optimization during the project lifetime. The present worth of battery (C&R\(_{\text{BAT}}\)) and inverter/converter (C&R\(_{\text{INV}}\)) achieved as follows:

\[
\text{C&R}_{\text{BAT}} = P_{\text{BAT}} \cdot \left(1 + \frac{1}{(1 + r)^5} + \frac{1}{(1 + r)^{10}} + \frac{1}{(1 + r)^{15}}\right),
\]

\[
\text{C&R}_{\text{INV}} = P_{\text{INV}} \times \left(1 + \frac{1}{(1 + r)^{10}}\right),
\]

Table 2: The optimal configuration of hybrid solar/battery energy system for different reliability indexes.

<table>
<thead>
<tr>
<th>RI (%)</th>
<th>LLP (%)</th>
<th>(N_{\text{PV}})</th>
<th>(N_{\text{BAT}})</th>
<th>LCC(_{\text{PV}}) ($)</th>
<th>LCC(_{\text{BAT}}) ($)</th>
<th>C&amp;R ($)</th>
<th>O&amp;M ($)</th>
<th>O&amp;M(_{\text{PV}}) ($)</th>
<th>O&amp;M(_{\text{BAT}}) ($)</th>
<th>TLCC ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0%</td>
<td>0</td>
<td>184</td>
<td>1511</td>
<td>6530</td>
<td>13,8674</td>
<td>128,661</td>
<td>17,363</td>
<td>2,208</td>
<td>15,110</td>
<td>146,070</td>
</tr>
<tr>
<td>0.3%</td>
<td>0.2968</td>
<td>181</td>
<td>1511</td>
<td>6424</td>
<td>13,8675</td>
<td>128,590</td>
<td>17,327</td>
<td>2,172</td>
<td>15,110</td>
<td>145,920</td>
</tr>
<tr>
<td>1%</td>
<td>0.8227</td>
<td>179</td>
<td>1340</td>
<td>6353</td>
<td>12,2981</td>
<td>114,559</td>
<td>15,593</td>
<td>2,148</td>
<td>13,400</td>
<td>130,180</td>
</tr>
<tr>
<td>2%</td>
<td>1.8516</td>
<td>172</td>
<td>1137</td>
<td>6105</td>
<td>10,4351</td>
<td>97,794</td>
<td>13,479</td>
<td>2,064</td>
<td>11,370</td>
<td>111,280</td>
</tr>
<tr>
<td>5%</td>
<td>4.5051</td>
<td>160</td>
<td>858</td>
<td>5679</td>
<td>78,745</td>
<td>74,696</td>
<td>10,545</td>
<td>1,920</td>
<td>8,580</td>
<td>85,250</td>
</tr>
<tr>
<td>10%</td>
<td>7.6983</td>
<td>153</td>
<td>698</td>
<td>5430</td>
<td>64,061</td>
<td>61,448</td>
<td>8,861</td>
<td>1,836</td>
<td>6,980</td>
<td>70,310</td>
</tr>
<tr>
<td>12%</td>
<td>10.5065</td>
<td>147</td>
<td>590</td>
<td>5217</td>
<td>54,149</td>
<td>52,475</td>
<td>7,709</td>
<td>1,764</td>
<td>5,900</td>
<td>60,190</td>
</tr>
<tr>
<td>15%</td>
<td>14.6732</td>
<td>140</td>
<td>430</td>
<td>4969</td>
<td>39,464</td>
<td>39,226</td>
<td>6,025</td>
<td>1,680</td>
<td>4,300</td>
<td>45,260</td>
</tr>
<tr>
<td>18%</td>
<td>17.8040</td>
<td>135</td>
<td>341</td>
<td>4791</td>
<td>31,296</td>
<td>31,830</td>
<td>5,075</td>
<td>1,620</td>
<td>3,410</td>
<td>39,910</td>
</tr>
<tr>
<td>20%</td>
<td>19.6356</td>
<td>132</td>
<td>309</td>
<td>4685</td>
<td>28,359</td>
<td>29,143</td>
<td>4,719</td>
<td>1,584</td>
<td>3,090</td>
<td>33,860</td>
</tr>
</tbody>
</table>
where $P_{\text{INV}}$ and $P_{\text{BAT}}$ are the price of inverter/converter and battery, respectively.

According to the capital and replacement cost of the components (PV, battery, and inverter), the total annual capital and replacement cost is mathematically achieved as follows:

$$C&R = CRF \times [N_{\text{PV}} \times C&R_{\text{PV}} + N_{\text{BAT}} \times C&R_{\text{BAT}} + N_{\text{INV}} \times C&R_{\text{INV}}].$$

(10)

Here, $N_{\text{INV}}$ and $N_{\text{BAT}}$ represent the numbers of inverter and battery, respectively.

The annual O&M cost of the components (PV, battery, and inverter) is mathematically achieved as follows:

$$O&M = N_{\text{PV}} \cdot O&M_{\text{PV}} + N_{\text{BAT}} \cdot O&M_{\text{BAT}} + N_{\text{INV}} \cdot O&M_{\text{INV}}.$$  

(11)

3.2. **Constraints.** To have a highly reliable system, the concept of the loss of load probability (LLP) must be considered in the optimization, which is mathematically modeled as follows:

$$\text{LLP} = \frac{\sum_{t=1}^{T} LLS(t)}{\sum_{t=1}^{T} E_{\text{Load}}(t)}.$$  

(12)

Here, $LLS$ denotes to loss of load supply which is achieved based on generated energy ($E_{\text{Gen}}$) as follows:

$$LLS(t) = E_{\text{L}}(t) - E_{\text{Gen}}(t),$$  

(13)

and $\text{LLP} \leq \text{Rl}$ where Rl stands the highest allowable value of LLP.

The numbers of PV panel and battery constraints and storage units are as follows:

$$0 \leq N_{\text{PV}} \leq N_{\text{PV-Max}},$$  

(14)

$$0 \leq N_{\text{BAT}} \leq N_{\text{BAT-Max}},$$  

(15)

$$S_{\text{BAT-Min}} \leq S_{\text{BAT}} \leq S_{\text{BAT-Max}}.$$  

(16)
Here, $N_{PV_{-Max}}$ and $N_{BAT_{-Max}}$ are the maximum numbers of PV panel and battery, respectively, $S_{BAT_{-Max}}$ is the highest quantity of the state of charge, while its minimum amount ($S_{BAT_{-Min}}$) is achieved based on the depth of discharge (DOD) and its nominal capacity ($NC_{BAT}$) as follows [44–46, 48–50]:

$$S_{BAT_{-Min}} = (1 - DOD) \cdot NC_{BAT}. \quad (17)$$

4. Results and Discussion

The presented optimization model is considered to achieve a case study in Rafsanjan. Rafsanjan is a city in the north-west of Kerman province, Iran, with an altitude of 1,460 m which is placed at 30° 24’ 24” N 55° 59’ 38” E. The winters in Rafsanjan are cold and freezing as well as hot and dried in the summers. The ambient temperature usually differs from −17°C to 43°C. The case study involves around five homes located in a remote area of Rafsanjan, Iran. Actual data of solar insolation, ambient temperature, and typical load demand of the case study based on hourly distribution during a year are used in this study (8760 h). The residential load profile of the case study for five households is shown in Figure 2, in which the minimum and maximum load demands of the system are 1.6 and 7.5 kW. The ambient temperature and solar insolation profiles of the studied area are presented in Figure 3.

The specifications of hybrid system components are given in Table 1.

In this study, the MATLAB software is used to implement the modified harmony search (HS) algorithm. The harmony search algorithm was first introduced in 2001 [54]. HS is a type of emerging metaheuristic optimization algorithm based on three operators, namely, pitch adjusting rule, harmony memory considering rule, and random search. The HS is trying to mimic the process of the musicians’ improvisation. Because of exploitation and ease of application, the HS has drawn worldwide attention mainly. The employed HS in the present study is denoted in the previous studies [55]. In a modified harmony search algorithm, the parameters of pitch adjusting rate and bandwidth of generation are improved for adjusting the convergence rate of the method to the optimal solution, while them constant in the original algorithm. The modified harmony search algorithm used in this paper is the same as that proposed in [41]. The parameters of the modified proposed optimization method used in this paper as harmony memory considering rate and the maximum number of iterations are considered 0.9 and 3000, respectively. Also, the maximum and minimum of pitch adjusting rate are 1 and 0.1, respectively. The maximum and minimum of generation bandwidth are 1 and 0.01, respectively, which are determined by the trial-and-error method. To provide valid results of the suggested algorithm, 30 independent runs are executed, and the optimal results are determined. In this optimal configuration of the hybrid solar/battery energy system, the control variables are numbers of PV panels (260-watt monocrystalline solar panel) and battery storage units (VMAX SLR155 12 V 155Ah AGM deep cycle solar battery) that the minimum bound of these variables are set to 0 and also the maximum bound of them are set to 200 and 20000, respectively. Figure 4 shows the flowchart of the suggested process. The optimal result of the suggested algorithm, in RI = 2%, shows that the optimal number of PV panels and battery storage is 172 and 1137, respectively. The best choice of TLCC and LLP is $111,280$ and 1.8516%, respectively. Since changes in the reliability index affect the cost and the optimal number of components, it is necessary to examine the effects of the reliability index on the optimization of the system.
The optimal values of O&M of the batteries and panels are $8,580 and $1,920, respectively. For RI equal to 10% and 12%, the optimal value of TLCC is decreased to $70,310 and $60,190, respectively, and the optimal numbers of PV and batteries are 153 and 147 and 698 and 590, respectively.

In RI = 15%, the minimal TLCC is $45,260, and the optimal values of $N_{PV}$, $N_{BAT}$, and LLP are 140, 430, and 14.6732%, respectively. For RI equal to 18% and 20%, the optimal values of TLCC are decrease to $36,910 and $33,860, respectively, and the optimal C&R and O&M of system are 31,830 and 29,143$ and 5,075 and 4,719$, respectively. It can be seen that by increasing the reliability index, the optimal components of the hybrid system and TLCC are decreased, as shown in Figures 5 and 6. Variation in operation and maintenance cost and capital and replacement cost of the hybrid schemes in optimized situations versus reliability index is presented in Figure 7. In Figure 8, variation in cost criteria of the optimal system component (LCC of the batteries and panels and O&M of the batteries and panels) versus RI is presented. It is found that the cost criteria reduce by increment in the value of the RI. The convergence characteristic of different reliability indexes on optimal hybrid solar/battery scheme is presented in Figure 9, which shows that by reducing reliability index from 20 to 0%, the objective function value is increase from $33,860 to $146,070, respectively.

4.2. Sensitivity Analysis of the Economic Parameters. The results of the variations of the PV panel unit cost on the optimal variables and cost criteria (in $) of the hybrid solar/battery scheme for RI = 2% are given in Table 3. It is observed that the value of LLP and TLCC of the hybrid system, for PV cost equal to 250 $/m², is 1.9608% and $115,640, respectively. In this case, the optimal values of $N_{PV}$, $N_{BAT}$, and LLP are 171 and 1136; also, the LCC of the panels and batteries are $10,287 and $104,259, respectively, and the optimal C&R and O&M of the system are $101,907 and $13,457, respectively.

In PV cost = $50/m², the optimal number of PV panels, battery storage, and TLCC is 184, 1511, and $146,070, respectively. The optimal values of O&M of the batteries and panels are $8,580 and $1,920, respectively. For RI equal to 10% and 12%, the optimal value of TLCC is decreased to $70,310 and $60,190, respectively, and the optimal numbers of PV and batteries are 153 and 147 and 698 and 590, respectively.

In RI = 15%, the minimal TLCC is $45,260, and the optimal values of $N_{PV}$, $N_{BAT}$, and LLP are 140, 430, and 14.6732%, respectively. For RI equal to 18% and 20%, the optimal values of TLCC are decrease to $36,910 and $33,860, respectively, and the optimal C&R and O&M of system are 31,830 and 29,143$ and 5,075 and 4,719$, respectively. It can be seen that by increasing the reliability index, the optimal components of the hybrid system and TLCC are decreased, as shown in Figures 5 and 6. Variation in operation and maintenance cost and capital and replacement cost of the hybrid schemes in optimized situations versus reliability index is presented in Figure 7. In Figure 8, variation in cost criteria of the optimal system component (LCC of the batteries and panels and O&M of the batteries and panels) versus RI is presented. It is found that the cost criteria reduce by increment in the value of the RI. The convergence characteristic of different reliability indexes on optimal hybrid solar/battery scheme is presented in Figure 9, which shows that by reducing reliability index from 20 to 0%, the objective function value is increase from $33,860 to $146,070, respectively.

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Table 3: The results of the variations of the PV panel unit cost on the optimal variables and cost criteria (in $) of the system.

<table>
<thead>
<tr>
<th>PV cost ($/m²)</th>
<th>RI (%)</th>
<th>LLP (%)</th>
<th>$N_{PV}$</th>
<th>$N_{BAT}$</th>
<th>LCC$_{PV}$</th>
<th>LCC$_{BAT}$</th>
<th>C&amp;R</th>
<th>O&amp;M</th>
<th>O&amp;M$_{PV}$</th>
<th>O&amp;M$_{BAT}$</th>
<th>TLCC</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>2</td>
<td>1.9927</td>
<td>171</td>
<td>1114</td>
<td>3,699</td>
<td>102,240</td>
<td>93,520</td>
<td>13,237</td>
<td>2052</td>
<td>11,140</td>
<td>106,760</td>
</tr>
<tr>
<td>100</td>
<td>2</td>
<td>1.7620</td>
<td>173</td>
<td>1125</td>
<td>5,409</td>
<td>103,250</td>
<td>96,105</td>
<td>13,371</td>
<td>2076</td>
<td>11,250</td>
<td>109,480</td>
</tr>
<tr>
<td>125</td>
<td>2</td>
<td>1.8339</td>
<td>172</td>
<td>1151</td>
<td>6,206</td>
<td>105,636</td>
<td>99,040</td>
<td>13,619</td>
<td>2064</td>
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<td>1148</td>
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<td>115,640</td>
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<td>1134</td>
<td>13,358</td>
<td>104,075</td>
<td>105,037</td>
<td>13,437</td>
<td>2052</td>
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<td>2064</td>
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4.1. Effects of the Reliability Index. The optimal configuration of hybrid solar/battery energy system for different reliability indexes (0 to 20%) are shown in Table 2. In RI = 0%, the optimal number of PV panels, battery storage, and TLCC is 184, 1511, and $146,070, respectively. It is found that by reducing the reliability index from 2 to 0%, the values of numbers of PV panels, battery storage, and TLCC increase to 12, 374, and $34,790, respectively. It can be seen that the LCC of the batteries and panels are $138,675 and $6530 for in this case, and also, the annual operation and maintenance cost and annual capital and replacement cost of the optimal hybrid system are $17,363 and $128,661, respectively. The O&M costs of the batteries and panels are $15,110 and $2,208, respectively.

In RI = 5%, the optimal values of $N_{PV}$, $N_{BAT}$, TLCC, and LLP are 160, 858, $85,250, and 4.5051%, respectively. It is found that by increasing RI from 2 to 5%, the values of $N_{PV}$, $N_{BAT}$, and TLCC decrease to 7%, 25%, and 23%, respectively, and also show that the values of LCC$_{PV}$, LCC$_{BAT}$, C&R, and O&M of optimal system decrease to $425, $25,606, $23,098, and $2,934, respectively. In this case, the

Figure 10: TLCC, LCC$_{PV}$, and C&R of the hybrid system vs. PV panel unit cost in the optimal condition.
battery storage, and TLCC is 173, 1193, and $34640, respectively.

and the optimal C&R and O&M of the system are $92,951
and $13,237, respectively. In this case, the optimal values of numbers of

panels and batteries are 171 and 1114; also, the LCC of the

system is $92,951 and $106190, respectively. It can be seen that by increasing battery cost from 300 to

$50, the values of TLCC, C&R, and LCCBAT decrease to

$71,550, $72,378, and $71,635, respectively. It can be seen

that the TLCC, C&R, and LCCBAT are $34640, $20,573,

and $27,666, for in this case, and also, the annual O&M costs

of the optimal hybrid system and batteries are $14,051 and

$11,930, respectively. In battery cost = $550, the optimal values of TLCC and LLP are $184,620 and 1.9481%, respec-

tively. It is found that by increasing battery cost from 300 to

$550, the values of TLCC and C&R increase to 74% and

84%, respectively. In Figure 11, variation in TLCC, LCCBAT,

and C&R of the optimal hybrid system versus battery cost

is presented. It can be seen that by increasing the battery unit
cost, the TLCC and C&R of the hybrid system and the LCC

of batteries are increased.

5. Conclusion

In this paper, an optimal configuration of a stand-alone hybrid photovoltaic (PV)/battery energy storage system is investigated to provide the load demand in Iran. The objective function is a minimization of total life cycle cost (TLCC) subject to the reliability index (loss of load probability) by a modified harmony search algorithm. Also, sensitivity analysis and effects of reliability index (0 to 20%) and economic parameters based on photovoltaic and battery prices are presented, and the results are analyzed. The results show that, by reducing reliability index from 2 to 0%, the values of number of PV panels, battery storage, and TLCC increase to 7%, 33%, and 31%, respectively, and by increasing the reliability index from 2 to 5%, the values of numbers of PV panels, batteries, and TLCC decrease to 7%, 25%, and 23%, respectively, and also show that by increasing PV cost from 200 to 500 $/m², the values of TLCC and C&R increase to 9.5% and 10.7%, respectively, and by reducing PV cost from 250 to 50 $/m², the values of TLCC and C&R decrease to 7.7% and 8.2%, respectively. It is found that by increasing battery cost from 300 to $550, the values of TLCC and C&R increase to 74% and 84%, respectively, and by reducing battery cost from 300 to $50, the values of TLCC and C&R decrease to 67% and 78%, respectively. Future work will be investigated different stand-alone hybrid energy systems

and $3,699, for in this case, and also, the annual O&M costs

of the optimal hybrid system and PV panels are $13,237 and

$2052, respectively. In PV cost = 500 $/m², the optimal

values of TLCC and LLP are $126,570 and 1.7103%. It is

found that by increasing PV cost from 200 to 500 $/m², the

values of TLCC and C&R increase to 9.5% and 10.7%,

respectively. It can be seen that by increasing the PV panel

number of PV panels, battery storage, and TLCC increase

to 7%, 33%, and 31%, respectively, and by increasing the

reliability index from 2 to 5%, the values of numbers of PV

panels, batteries, and TLCC decrease to 7%, 25%, and 23%,

respectively, and also show that by increasing PV cost from

200 to 500 $/m², the values of TLCC and C&R increase to

9.5% and 10.7%, respectively, and by reducing PV cost from

250 to 50 $/m², the values of TLCC and C&R decrease to

7.7% and 8.2%, respectively. It is found that by increasing

battery cost from 300 to $550, the values of TLCC and C&R

increase to 74% and 84%, respectively, and by reducing battery cost from 300 to $50, the values of TLCC and C&R
decrease to 67% and 78%, respectively. Future work will be investigated different stand-alone hybrid energy systems

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<th>LLP (%)</th>
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<th>N_BAT</th>
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<th>C&amp;R</th>
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Figure 11: TLCC, LCC_BAT, and C&R of the hybrid system vs. battery cost in the optimal condition.
based on backup system, which process hybrid energy system types and the sensitivity analysis.

**Nomenclature**

- CRF: Capital recover factor
- C&R: Capital and replacement
- C&R_BAT: Present worth of battery
- C&R_PV: Capital and replacement cost of PV panel
- C&R_INV: Present worth of inverter/ converter
- DOD: Depth of discharge
- E_Gen: Generated energy
- E_L: Energy demand
- HS: Harmony search
- LLP: Loss of load probability
- LCC PV: Life cycle cost of PV panels
- LCC_BAT: Life cycle cost of batteries
- N_T: Temperature coefficient (°C)
- N_PV: Number of PV panels
- N_INV: Number of inverter
- N_BAT: Number of battery
- N_PV_Max: Maximum number of PV panel
- N_BAT_Max: Maximum number of battery
- NC_BAT: Nominal capacity of battery
- NOCT: Normal operating cell temperature (°C)
- N: System life span
- O&M: Operation and maintenance
- O&M_PV: O&M cost of the PV panel
- O&M_BAT: O&M cost of the battery
- O&M_INV: O&M cost of the inverter
- PV: Photovoltaic
- P_BAT: Price of battery
- P_INV: Price of inverter/converter
- P_RPV: Rated power of the PV panel
- P_PV: Total produced power by PV panels (kW)
- P_D: Hourly demand
- P_INV: Output power of an inverter
- r: Interest rate
- R: Solar radiation (W/m²)
- RI: Reliability index/or highest allowable value of LLP
- R_Ref: Reference solar radiation (W/m²)
- S_BAT(t): State of charge of battery at time t
- S_BAT_Max: Highest quantity of the state of charge
- S_BAT_Min: Minimum amount of the state of charge
- TLCC: Total life cycle cost
- T_air: Ambient temperature (°C)
- T_ref: Reference temperature (°C)
- T_c: Temperature of the cell
- ω: Rate of hourly self-discharge
- η_INV: Efficiency of the inverter (%)
- η_BAT: Battery charging efficiency (%)
- η_BDC: Battery discharging efficiency (%).

**Data Availability**

No data were used to support this study.

**Conflicts of Interest**

The authors declare that they have no conflicts of interest.

**References**


