
Elaheh Sadeghi Bakhtiar 1, Afshin Naeimi 2, Ali Behbahaninia 2 and Gloria Pignatta 3,*

1 Department of Natural Resources and Environment, Science and Research Branch, Islamic Azad University, Tehran 1477893855, Iran; e.sadeghi.bakhtiar@gmail.com
2 Department of Energy System Engineering, Faculty of Mechanical Engineering, K. N. Toosi University of Technology, Tehran 1969764499, Iran; anaemii@alumni.kntu.ac.ir (A.N.); alibehbahaninia@kntu.ac.ir (A.B.)
3 School of Built Environment, Faculty of Arts, Design, and Architecture, University of New South Wales (UNSW), Sydney, NSW 2052, Australia
* Correspondence: g.pignatta@unsw.edu.au
† Presented at the 3rd Built Environment Research Forum, Sydney, Australia, 1 December 2021.

1. Introduction

A considerable part of the total energy in the world is consumed in the residential sector. Households represented 26% of final energy consumption in Europe in 2019, most of which was supplied from fossil fuels [1]. Utilizing renewable energy such as wind, solar energy, and their hybridization instead of fossil fuels is a good option to supply electricity to buildings in urban and remote areas, which can operate in both grid-connected and standalone modes [2]. In this study, by finding the optimum size of a hybrid system consisting of a wind turbine (WT) and photovoltaic (PV) panels using a genetic algorithm (GA), the demand of a grid-connected building is provided.

Barakat et al. [3] introduced multi-objective optimization of a hybrid system by defining reliability, cost, and environmental aspects as objective functions. Eken et al. [4] presented the optimum sizing of a wind-solar system using HOMER software, and Zhang et al. [5] proposed an integrated system that comprises hydropower, photovoltaic, and wind. Liu et al. [6] conducted a study on the optimal control technique of a hybrid system using power prediction. Das et al. [7] economically and environmentally investigated a PV/wind/diesel/battery-based hybrid system. Maleki et al. [8] optimized a hybrid solar-wind-hydrogen CHP system for residential applications. In addition, Dali et al. [9] performed an experimental study on a wind-solar system with battery storage that operates in grid-connected and standalone modes. Mikati et al. [10] illustrated the effect of the configuration of a small-scale hybrid wind-solar system on electricity network dependency. The innovation of this study is the use of actual wind speed, solar irradiance, and demand data of a net-zero energy building, which were measured in 15 min time steps throughout a year to make the study more realistic.
2. Materials and Methods

The WT is of the horizontal axis type and is proper for home installations, and its capacity and tower height are decision variables of the GA. The power of the WT can be calculated using Equation (1) [11]:

\[
P_w = \begin{cases} 
P_r \left( \frac{v^3}{v_{cut,in}^3} - 1 \right), & v_{cut,in} \leq v \leq v_r \\
0, & v_r \leq v \leq v_{cut,out}
\end{cases}
\]

where \( P_r \) is rated power of the WT, \( v_r \) is rated wind speed, \( v_{cut,in} \) is the cut-in wind speed, and \( v_{cut,out} \) is the cut-out wind speed. The PV panels are of the monocrystalline type and the area and the output power of a single PV panel are 1.65 m² and 0.3 kW, respectively. Additionally, the output power of the PV system can be defined using Equation (2) [12]:

\[
P_{PV} = n A_c \eta I_\beta
\]

where \( n \) is the number of PV panels, \( A_c \) is the area of a single PV panel, and \( \eta \) is its efficiency. \( I_\beta \) is the irradiance on a surface with an inclination \( \beta \) the computation method of which is given in [13]. The output power of the hybrid system is the sum of \( P_{pv} \) and \( P_w \). The self-consumption (SC) is the self-consumed hybrid system electricity (\( E_{lgc} \)) divided by total electricity generation from the hybrid system. Moreover, the renewable fraction (RF) is the \( (E_{lgc}/D) \) divided by the total demand [14]. The total cost of the system that is minimized using the optimization problem is defined as Equation (3) [11].

\[
TSC = IC + MC + RC - \sum_{x=1}^{L} C_x \frac{(1 + i)^{x-1}}{(1 + d)^x}
\]

where IC is the capital cost which comprises the total cost of purchasing WT, PVs, inverter, and controllers. MC, RC, L, \( C_x \), i, and d are maintenance cost, replacement cost, system lifetime, revenue, inflation rate, and discount rate, respectively.

3. The Case Study

The case study in this research is a one-story residential building located in Granarolo dell’Emilia, Emilia-Romagna, Italy. It is a three-bedroom building with a total floor area of 118 m² that was occupied by an elderly couple [15]. Figure 1 illustrates the hourly profile of average wind speed, solar irradiance, and electricity demand of the building over one year.
The lifetime of the hybrid system is assumed to be 20 years, and the lifetimes of the inverter and controllers are 10 and 5 years, respectively. Additionally, the total cost of maintenance is 2% of the initial cost \[16,17\]. The price of purchasing electricity from the grid and exporting it to the grid is 0.18 EUR/kWh and 0.06 EUR/kWh, respectively \[18\]. Other technical and economic parameters of the component used in this research are given in Table 1.

### Table 1. The technical and economic parameters of the hybrid system.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
<th>Refs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV capital cost</td>
<td>EUR/m²</td>
<td>118.76</td>
<td>[16,17]</td>
</tr>
<tr>
<td>PV panel efficiency</td>
<td>%</td>
<td>20</td>
<td>[16,17]</td>
</tr>
<tr>
<td>Ground albedo</td>
<td>%</td>
<td>28</td>
<td>[19,20]</td>
</tr>
<tr>
<td>Tilt angle</td>
<td>°</td>
<td>44.55</td>
<td>[21]</td>
</tr>
<tr>
<td>WT capital cost</td>
<td>EUR</td>
<td>[10,340 \times e^{(0.1291 \times P_r)}]</td>
<td>[22]</td>
</tr>
<tr>
<td>Inverter capital cost</td>
<td>EUR</td>
<td>1182</td>
<td>[16,17]</td>
</tr>
<tr>
<td>Inverter efficiency</td>
<td>%</td>
<td>98</td>
<td>[23]</td>
</tr>
<tr>
<td>PV controller capital cost</td>
<td>EUR</td>
<td>631.36</td>
<td>[16,17]</td>
</tr>
<tr>
<td>PV controller efficiency</td>
<td>%</td>
<td>98</td>
<td>[16,17]</td>
</tr>
<tr>
<td>WT controller capital cost</td>
<td>EUR</td>
<td>565.8</td>
<td>[16,17]</td>
</tr>
<tr>
<td>WT controller efficiency</td>
<td>%</td>
<td>98</td>
<td>[16,17]</td>
</tr>
</tbody>
</table>

### 4. Results

By implementing the genetic algorithm (GA) in MATLAB and minimizing Equation (3), the optimized area of PV panels, rated power of WT, and its tower height are obtained 148.5 m², 1.5 kW, and 20 m, respectively.

The capital cost is EUR 45,100, and the costs of maintenance and replacement over 20 years are EUR 13,548 and EUR 4077, respectively. Considering the total revenue of EUR 20,507 from exporting electricity to the grid, the total cost of the system (TSC) is EUR 42,218. The total monthly energy generated, consumed, imported, and exported and the demand are shown in Figure 2. About 94.4% of the total energy is generated by PVs and 5.6% of that is by WT. In addition, it is found that PV panels, WT, inverter, and controllers account for 52.16%, 36.26%, 4.13%, and 7.45% of the cost of the system, respectively.

![Figure 2. Total energy generated, demand, self-consumed hybrid system electricity, imported, and exported energy per month.](image)

### 5. Conclusions

In this study, the optimal size of a solar-wind hybrid system in a grid-connected net-zero energy building was obtained by GA. By installing PV panels with an area of 148.5 m² and a wind turbine with a rated power of 1.5 kW at a height of 20 m, the total...
cost of the system, considering EUR 20,507 revenue from exporting electricity to the grid, is around EUR 42,000. It is observed that the low average wind speed in the case study is a reason to select the wind turbine with a low rated power by the GA. In addition, the self-consumption is about 15%, and a considerable proportion of on-site generation is exported to the grid. The renewable fraction is approximately 58%, which indicates the desirable performance of the hybrid system.

**Author Contributions:** Conceptualization: E.S.B., A.N., and G.P.; methodology: E.S.B., A.N., and A.B.; data curation: G.P.; writing—original draft preparation: E.S.B.; writing—review and editing: A.N. and G.P.; supervision: A.B. and G.P. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Informed Consent Statement:** Informed consent was obtained from all subjects involved in the study.

**Acknowledgments:** The authors would like to thank the building owners of the case study building for accepting to participate in this research and allowing the continuous monitoring campaign. Furthermore, sincere thanks to editors and anonymous reviewers for putting forward guiding measures to improve the quality of this paper.

**Conflicts of Interest:** The authors declare no conflict of interest.

**References**


