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SELECTION OF THE BEST HYBRID ARCHITECTURE FOR AN OFF-GRID POWER SUPPLY SYSTEM USING TOPSIS METHOD

BY

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Abstract. In this paper the selection of the best hybrid architecture for an off-grid power supply system for a residential consumer is presented. Based on the wind, solar and temperature site resources and assuming the electric load, three hybrid power supply system architectures (wind-diesel, solar-diesel and wind-solar-diesel) will be comparatively analysed with respect to a conventional power supply system based only on a diesel engine generator. The site wind-solar potential has been obtained from NASA Surface Meteorology and Solar Energy database. The off-grid power supply systems have been modelled and simulated using HOMER Pro software. Ten attributes have been considered: six technical criteria, three financial criteria and one environmental criterion. Assuming a certain weighting strategy and using TOPSIS method it has been found that the best architecture is the wind-solar-diesel, followed by the wind-diesel system, solar-diesel system, and finally, the least preferred system being the diesel engine generator system.

Keywords: wind-solar-diesel; wind-diesel; solar-diesel; HOMER; TOPSIS.

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1. Introduction

The hybrid power systems combine different renewable energy sources, for example wind and solar, to increase the efficiency of energy resources exploitation and to limit the negative effects due to intermittent character of these renewable energy resources. Considering also a back-up system based on conventional energy sources, for example a diesel generator, and an electricity storage system, the hybrid off-grid power supply system will be able to provide electric power continuously and with a desired level of autonomy.

The principal aspects related with hybrid power supply systems, including wind and solar, with or without battery energy storage, for grid connected or off-grid configuration, are presented in (Bajpai and Dash, 2012; Dali *et al*., 2010; Khare and Nema, 2016; Krishna and Kumar, 2015; Paska *et al*., 2009).

The optimal capacity evaluation of the energy generation components for a hybrid wind-solar power supply system in terms of cost of energy, renewable fraction and fuel price is presented in (Rashid *et al*., 2017). A comparatively analysis of different architectures of the hybrid energy systems based on solar, diesel generator and storage battery is presented in (Madziga *et al*., 2018). Different wind-solar hybrid architectures have been comparatively analysed in terms of net present cost, cost of energy, operating cost and excess electricity production in (Sonali and Sayed, 2014). The simulations of all these hybrid power supply systems have been performed using the HOMER software (HOMER Energy, 2018). The physical and economic models used for simulation, the optimization and the sensitivity analysis, as well as the advantages and weaknesses of this software are presented in (Georgilakis, 2006). Deciding upon the best alternative in terms of different attributes defines a multi-dimensional criteria decision-making problem for which the principal attributes and methods used in renewable energy systems are presented in (Wang *et al*., 2009).

In this paper three hybrid power supply system architectures (wind-diesel, solar-diesel and wind-solar-diesel) will be comparatively analysed with respect to a conventional power supply system based only on a diesel engine generator. The numerical simulation of these power supply systems will be performed using the HOMER software. The decision will be made using TOPSIS method (Technique for Order of Preference by Similarity to Ideal Solution) based on ten attributes: six technical criteria (renewable annual energy production; diesel generator annual energy production; renewable fraction; excess electricity; diesel generator operational life; battery expected life), three financial criteria (net present cost; cost of energy; initial investment) and one environmental criterion (carbon dioxide emissions). Assuming a criteria weighting strategy, it has been found that the best architecture is the wind-solar-diesel, followed by the wind-diesel system, solar-diesel system, and finally, the least preferred system being the diesel engine generator system.

2. Site Resources

The proposed wind turbine site for this analysis is located in Romania, in Tulcea County, at the coordinates 44°59.0’ N 29°12.6’ E, close to village of Dunavățu de Jos. The wind, solar and temperature data have been obtained from NASA Surface Meteorology and Solar Energy database (NASA Langley Research Centre Atmospheric Science Data Centre Surface meteorological and Solar Energy -SSE -web portal supported by the NASA LaRC POWER Project), (NASA Atmospheric Science Data Centre, 2018) as follows:

- The monthly average temperature for the selected site is presented in Fig. 1. The maximum temperature is 23.55°C in August, the minimum temperature is 3.71°C in January, and the annual average temperature is 12.99°C.
- The monthly average wind speed at 50 m for the selected site is presented in Fig. 2. The maximum wind speed is 7.59 m/s in December, the minimum wind speed is 4.77 m/s in July, and the annual average wind speed is 6.24°C.
- The monthly average solar global horizontal irradiance (GHI) for the selected site is presented in Fig. 3. The maximum GHI is 6.76 kWh/m^2/day in July, the minimum GHI is 1.14 kWh/m^2/day in December, and the annual average GHI is 3.89 kWh/m^2/day.

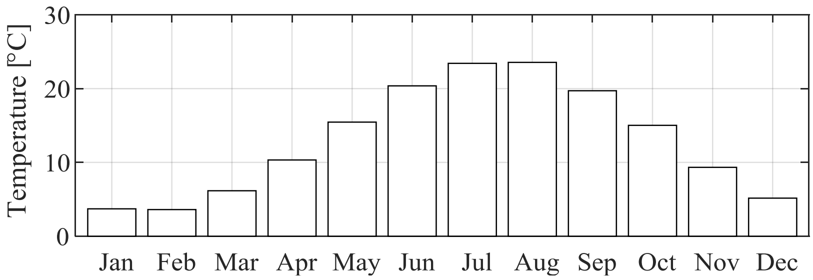


Fig. 1 – The monthly average temperature.

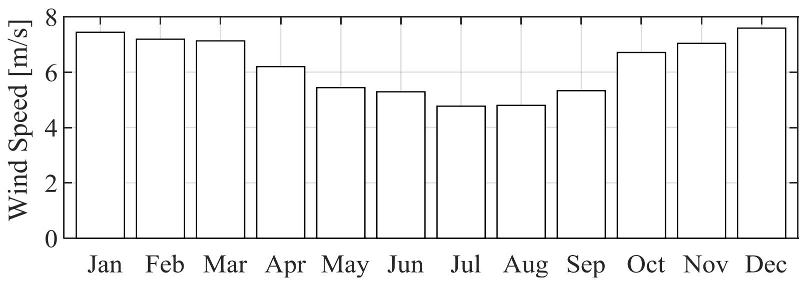


Fig. 2 – The monthly average wind speed at 50 m.

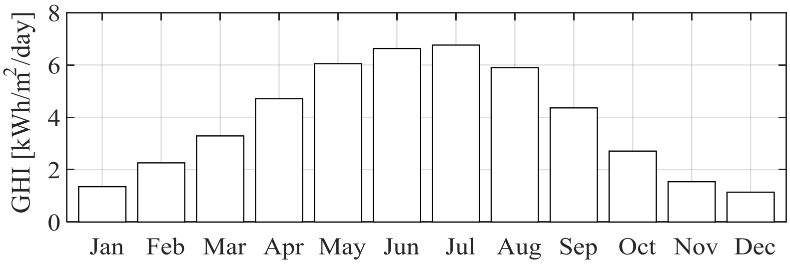


Fig. 3 – The monthly average global horizontal irradiance.

3. Electric Load

Let us suppose that there is a single AC consumer, a residential consumer, for which the annual primary load is 3650 kWh/year. HOMER is able to manage this type of consumer by a default template. The load random variability is defined by day-to-day (10.883%) and time step (20.099%) parameters. The operating reserve is considered in HOMER simulations by 10% of load in current time step, by 50% of wind power output, and 80% of solar power output. In this way, the power supply system will have enough spare operating capacity to serve a sudden 10% increase in the load, as well as a sudden 50% decrease in wind turbine output and a sudden 80% decrease in solar power output.

The electric load computed with HOMER is presented in a box and whisker plot format in Fig. 4. The top and bottom lines correspond to the overall maximum and minimum for each month. The top and the bottom of the blue box correspond to the average daily maximum and minimum of all of the days in each month. The middle red lines correspond to the overall average for the whole month. For example, in January these parameters are: overall maximum 2.06 kW, average day maximum 1.32 kW, overall average 0.5 kW, average day minimum 0.09 kW, and overall minimum 0.04 kW. The January overall maximum (2.06 kW) is the maximum for whole year and represents the peak. The year average is 0.42 kW and is obtained by computing the average of overall averages for all months. The load factor, defined by the year average divided by the peak, is 0.2.

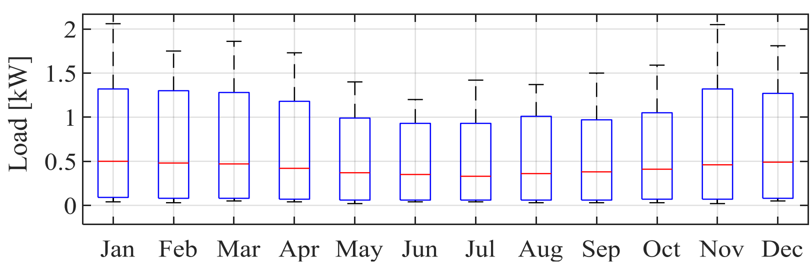


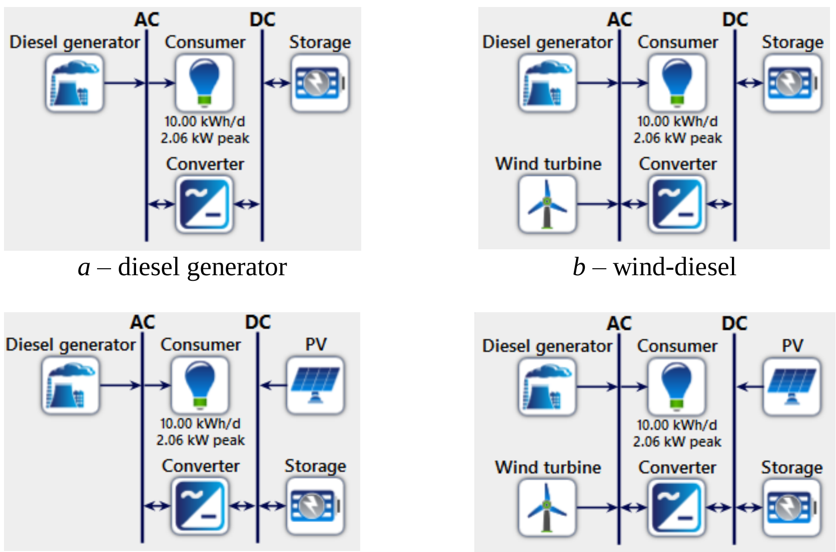
Fig. 4 – Seasonal load profile.

4. Power Supply System

The reference power supply system, based on non-renewable sources, is composed by the AC consumer, the AC diesel generator and the DC storage system, Fig. 5*a*). The AC diesel generator is connected to the AC bus line from which the AC consumer is supplied. A bidirectional converter represents a bridge between the AC and DC bus lines, and controls both the energy supply from the battery to the AC consumer (inverter), as well as the energy supply from the diesel generator to charge the battery (rectifier).

All the renewable sources-based power supply systems that will be analyzed will have the same AC consumer, the same DC storage system and the same AC diesel generator, but different renewable energy sources, defining the following power supply systems:

- Wind-diesel (Fig. 5*b*). Both the electricity generating components are connected to the AC bus line from which the AC consumer is supplied. The bidirectional converter is used for battery charging and consumer suppling.
- Solar-diesel (Fig. 5*c*). The electricity generating components (the AC diesel generator and the DC photovoltaic) are connected to a bidirectional converter with the same double role, battery charging and consumer supplying.
- Wind-solar-diesel (Fig. 5*d*). The wind turbine and the diesel generator are connected to the AC bus line, while the photovoltaic is connected to the DC bus line. The bidirectional converter is always required for charging the battery and suppling the consumer.



a – diesel generator

b – wind-diesel

c – solar-diesel

d – wind-solar-diesel

Fig. 5 – Power supply system architecture.

All these power supply systems have been simulated with HOMER software for a certain set of global parameters: project life time 20 years, nominal discount rate 2%, expected inflation rate 4%, no carbon dioxide emission penalties. The following specific parameters have been also considered in HOMER simulations:

- Wind turbine Bergey BWC XL.1 (Bergey WindPower, 2018), with rated capacity 1 kW, hub height 10 m, overall loss factor 2.97%.
- Photovoltaic Peimar SG300MBF (Peimar, 2018), with rated capacity 1 kW, efficiency 19.1%, temperature effects on power -0.4%/°C, without tracking system.
- Diesel generator with rated capacity 2.3 kW (obtained with HOMER auto-sizing feature), lifetime 15000 hours, minimum load ratio 25%.
- Storage on 24 V bus voltage, with 12 batteries on 12 V, 6 strings in parallel with 2 batteries on every string, minimum 24 hours autonomy, charging range between 100% initial state of charge and 25% minimum state of charge.

5. Methodology

Selecting the most suitable power supply system for the proposed site is a multi-dimensional criteria decision-making problem which will be solved in this paper using TOPSIS method. The main steps of the TOPSIS algorithm are (Tzeng and Huang, 2011):

- Select the alternatives A_j, j=1÷n. There are n=4 alternatives for the power supply system: (1) diesel generator, (2) wind-diesel, (3) solar-diesel and (4) wind-solar-diesel, which are presented in the decision matrix from Table 1.
- Select the criteria C_i, i=1÷m. There are m=10 criteria, that are grouped into three categories (presented in the decision matrix from Table 1):
    - Technical criteria: renewable annual energy production [kWh/year]; diesel generator annual energy production [kWh/year]; renewable fraction [%]; excess electricity [kWh/year]; diesel generator operational life [years]; battery expected life [years],
    - Financial criteria: net present cost-NPC [€]; cost of energy-COE [€]; initial investment [€],
    - Environmental criteria: carbon dioxide emissions [kg/year]).
- Compute the performance ratings x_{ij} of i-th criterion with respect to the j-th alternative and construct the decision matrix. The raw scores within the decision matrix are presented in Table 1, and have been obtained after HOMER simulations. The HOMER project file has been developed such a way that can comparatively simulate all power supply systems analysed in this paper: the diesel generator and the storage system are presented in all power supply systems, while the wind turbine and the photovoltaic have two values for the search space parameter, 0 (without) and 1 (with).

- Normalize the performance ratings with:

$$r_{ij}=\frac{x_{ij}}{\sqrt{\sum_{j=1}^{n}x_{ij}^{2}}} \tag{1}$$

- Weight the criteria to reflect their relative importance to the decision. Weights (W_i), are positive integers and have been obtained by method of direct assignation on a preference linear scale within the range 1÷*m*, where 1 correspond with the least preferred option, and m correspond with the most preferred option. In this paper the weighting strategy assumes that the technical criteria are the most preferred, while the environmental criterion is the least preferred, as follows: 10-renewable annual energy production; 9-diesel generator annual energy production; 8-renewable fraction; 7-excess electricity; 6-diesel generator operational life; 5-battery expected life; 4-net present cost; 3-cost of energy; 2-initial investment; 1-carbon dioxide emissions (Table 1).
- Compute the normalized weights with:

$$w_i=\frac{W_i}{\sum_{i=1}^{m}W_i} \tag{2}$$

- Compute the weighted normalized performance ratings with:

$$v_{ij}=w_i\cdot r_{ij} \tag{3}$$

- Identify the ideal solution (A^+) and the negative ideal solution (A^-) with:

$$A^+=\{v_1^+,v_2^+,...,v_i^+,...,v_n^+\} \tag{4}$$

$$A^-=\{v_1^-,v_2^-,...,v_i^-,...,v_n^-\} \tag{5}$$

where v_i^+ and v_i^- are the best value, respectively the worst value for the i-th criterion among all alternatives.

- Calculate the n-dimensional Euclidean distance between each alternative and the ideal solution with:

$$D_j^+=\sqrt{\sum_{i=1}^{m}\left(v_{ij}-v_i^+\right)^2},\ j=1\div n \tag{6}$$

- Calculate the n-dimensional Euclidean distance between each alternative and the negative ideal solution with:

$$D_j^-=\sqrt{\sum_{i=1}^{m}\left(v_{ij}-v_i^-\right)^2},\ j=1\div n \tag{7}$$

- Compute the ranking score (the relative closeness to the ideal solution) with:

$$R_j = \frac{D_j^-}{D_j^+ + D_j^-}, \quad j=1 \div n \tag{8}$$

- Sort the ranking scores in descending order, the best alternative have the maximum ranking score, while the worst alternative have the minimum ranking score.

6. Results and Discussion

The numerical results obtained after the HOMER simulation, which represents the performance ratings, have been used for filling the decision matrix using a spreadsheet computing format, Table 1. Considering also the weights, and using the TOPSIS methodology, the ranking scores can be finally obtained: R_1=0.15; R_2=0.62; R_3=0.4; R_4=0.7. Sorting these ranking scores in descending order, the following preference order will be obtained: $R_4 > R_2 > R_3 > R_1$, which defines the wind-solar-diesel power supply system as the most preferred system, and the diesel generator system as the least preferred system.

Table 1
Decision Matrix

Criteria	Unit	Weight	Alternatives			
			1	2	3	4
			Diesel generator	Wind-diesel	Solar-diesel	Wind-solar-diesel
Renewable AEP	[kWh/year]	10	0	1952	1275	3227
Generator AEP	[kWh/year]	9	4087	1989	2818	981
Renewable fraction	[%]	8	0	45.5	22.8	73.1
Excess electricity	[kWh/year]	7	175	25.3	128	281
Generator operational life	[years]	6	2.9	4.85	4.87	11
Battery expected life	[years]	5	4.67	4.54	4.38	4.4
Net present cost	[€]	4	73603	56883	54927	41559
Cost of energy	[€]	3	0.817	0.632	0.61	0.461
Initial investment	[€]	2	3755	9567	4505	10317
CO_2emissions	[kg]	1	4626	2468	3010	1158
Ranking scores			0.15	0.62	0.4	0.7
Preference order			4	2	3	1

7. Conclusions

To analyse the performance of different architecture of hybrid off-grid power supply systems and to decide which architecture is the most preferred for a certain site with a given energy resources the TOPSIS method can be successfully used. Defining the alternatives, selecting the attributes, defining the wind-solar resources for a specific site, computing the raw scores, and defining the attributes weights are the principal steps of this analysis. The default computing algorithm of HOMER software considers only the net present cost as optimization criterion; therefore, HOMER software will be used only for computing the raw scores.

Using wind and solar will increase the renewable fraction from 22.8% (solar only) to 45.5% (wind only), and finally, to 73.1% (wind and solar), decreasing thus the hours of operation per year (3092-wind only, 3081-solar only, 1367-wind and solar) and the number of starts per year (1410-wind only, 875-solar only, 628-wind and solar) of the diesel generator, and finally, increasing the generator operational life (4.85 years-wind only, 4.87 years-solar only, 11 years-wind and solar) with positive effects on the net present cost of the power supply system. Another advantage of the wind-solar-diesel architecture is the decreasing of the fuel consumption that will reduce the carbon dioxide emissions.

The final conclusion of this paper is that the wind-solar-diesel power supply system is the most preferred. This result is strongly dependent on the site wind and solar resources, and the wind turbine, photovoltaic and diesel generator technical and financial parameters, having thus, the significance of a case study.

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SELECTAREA CELEI MAI BUNE ARHITECTURI HIBRIDE PENTRU UN SISTEM DE ALIMENTARE DE TIP OFF-GRID FOLOSIND METODA TOPSIS

(Rezumat)

În lucrare se prezintă un studiu privind selectarea celei mai bune arhitecturi pentru un sistem off-grid de alimentare cu energie electrică pentru un consumator rezidențial. Pornind de la parametrii energetici ai locației propuse (potențialul eolian, potențialul solar și distribuția de temperatură) și impunând un anumit consum de energie electrică, trei arhitecturi diferite (eolian-diesel, solar-diesel și eolian-solar-diesel) vor fi comparativ analizate în raport cu un sistem de alimentare cu energie electrică din surse fosile bazat doar pe un generator diesel. Parametrii energetici ai amplasamentului au fost obținuți din baza de date NASA Surface Meteorology and Solar Energy. Sistemele

de alimentare cu energie electrică au fost modelate și simulate folosind programul HOMER Pro. Au fost considerate 10 criterii, dintre care 6 criterii tehnice, 3 criterii financiare și 1 criteriu din categoria factorilor de mediu. Presupunând o anumită strategie de ponderare a criteriilor și utilizând metoda TOPSIS s-a obținută următoarea ierarhizare a alternativelor: cea mai bună arhitectură este sistemul eolian-solar-diesel, urmată apoi de sistemele eolian-diesel, solar-diesel și în sfârșit, arhitectura cea mai puțin recomandată fiind sistemul bazat pe generatorul diesel.