FEASIBILITY ANALYSIS AND OPTIMIZATION OF STAND-ALONE FUEL CELL/WIND TURBINE/PV HYBRID ENERGY SYSTEM

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Abstract: In this paper, a stand-alone hybrid energy system consisting of fuel cell, wind turbine, photovoltaic system, batteries and inverter is presented. The study is focused on determining the optimal configuration of the system, which will meet the electrical and thermal load, respecting the total net present cost. HOMER software is used to achieve this purpose. The emissions of pollutants are also analyzed.

Key words: fuel cell, wind turbine, photovoltaics, optimal configuration, net present cost.

1. INTRODUCTION

The analysis and design of hybrid energy systems can be challenging, due to the large number of alternative technologies, the differences in technology costs and the uncertainty in key parameters. Renewable energy sources add further complexity because their power output may be intermittent, seasonal, and nondispatchable, and the renewable resources availability may be uncertain.

When designing hybrid energy system, stand-alone or grid-connected, it is necessary to decide about the configuration of the projected system. This includes deciding on the following questions: what type of technologies will be used for energy generation? Which components will be part of the system? How many, what size and with what characteristics will be the used components? The large number of alternative technologies, the differences in technology costs as well as the energy resources availability make the decision itself difficult.

In this paper, a stand-alone hybrid energy system to supply the electrical and thermal load demand is considered. The system consists of fuel cell, wind turbine, photovoltaic system, batteries and inverter, and is modelled in the software tool HOMER. The objective of this study is to determine the optimal configuration of the system that will meet the needs of consumers, respecting the total net present costs.

Sensitivity analysis is also performed in HOMER in order to examine how the average annual wind speed and average annual solar radiation will affect the configuration of the system. Also, the emissions of pollutants are analyzed for different system configurations. HOMER software is used to perform simulation, calculation and optimization [1].

2. RELATED WORK

Much research has been done regarding the hybrid energy systems. In [2], techno-economic performance of stand-alone electricity generation systems for off-grid communities located in different climatic areas of Peru was investigated. Seven scenarios, including different combinations of diesel generators, wind turbine units, and solar panels, were assessed. Optimal sizing of each configuration, which minimizes the corresponding net present cost (NPC), was determined and the achieved optimal systems were also evaluated considering other economic indices and their environmental performance.

The study, in [3], was developed to design a grid-connected hybrid energy systems including PV and fuel cells, and discuss the influence of the major types of PV tracking technique on technical and economic performance of the system. In the case study, the results show that the vertical single axis tracker was ranked 1st in terms of highest PV generation, penetration of renewable energy to the grid, lowest CO_2 emission, highest energy sold to the grid and lowest purchased, and lowest NPC and levelized cost of energy. The authors in [4] investigated a wind turbine/PV/fuel cell hybrid power system using HOMER software and an m-file MATLAB code for the clonal selection algorithm optimization method. The optimal results of the two methods using the same load data and weather conditions have been illustrated and compared to each other.

The authors in [5] presented the optimal design of a stand-alone hybrid photovoltaic and fuel cell power system without battery storage to supply the electrical load demand of the city of Brest, Western Brittany in France. The proposed optimal design study was focused on economical performance and was mainly based on the loss of the power supply probability concept. In [6], the authors proposed an optimization method to manage the optimal energy management of the PV–wind–diesel–battery hybrid system with respect to both economic benefits and its reliability. The Dynamic Programming approach was used to establish the optimal schedule of power sources. This method can minimize the operation cost of the hybrid system and CO_2 emission while satisfying the technical conditions such as reliability, safety, etc. in scenarios with the different initial states of charge.

A research carried by [7] present a techno-economic feasibility study of hybrid energy systems (PV/wind turbine/diesel system with storage batteries) for electricity generation. The incorporation of storage units also reduced the net present cost, excess energy fraction and CO_2 emission. They found out that the use of hybrid energy systems in such locations improved the standard of living and economic activities of the rural populace.

The authors in [8] investigated several hybrid renewable energy system combinations of solar, wind and energy storage free of diesel generators to supply energy for remote communities. The study showed that the wind turbine operations range must be considered. Increasing the wind turbine fraction could also lead to significantly lower costs as well as the PV solar cell number and number of batteries. In [9], the authors proposed a two-step methodology to optimize and analyze a PV/wind/battery/diesel hybrid energy system to meet the power demand of Fanisau, a remote and off-grid village in northern Nigeria. In the first step, the MATLAB was used to run simulations and optimize the system via the genetic algorithm with a time interval of 1h over a year for the load demand and energy output. Then, techno-economic and emissions analysis was carried out in the second step to compare the obtained optimized system to the traditional modes of rural electrification in sub-Saharan Africa.

3. PROPOSED RESEARCH

Wind turbines and photovoltaic systems can be integrated in the hybrid energy system in areas where there are favorable conditions for the use of wind and solar energy resources. Fuel cells is another technology option which have the potential for clean and very efficient power generation, and can be one of the components in a hybrid energy systems.

In this paper, a stand-alone hybrid energy system consisting of fuel cell (FC), wind turbine (WT), photovoltaic system (PV), batteries and inverter is analyzed. Fuel cell produce both electricity and heat, while wind turbine and photovoltaic system generate electricity. The batteries store the excess electricity produced, while in adverse weather conditions part of the consumption is satisfied by the previously accumulated electricity in the batteries. Figure 1 presents the FC/WT/PV hybrid energy system that is modelled in HOMER software. The boiler is an idealized component that can serve un unlimited thermal load at only the cost of fuel. Waste heat recovered from a generator reduces the fuel consumption of the boiler. So, the boiler is treated as a backup source of heat that can serve any amount of thermal load whenever necessary.

The objective of this study is to obtain the optimal configuration of the system, which should satisfy the given electrical and thermal load, respecting the total net present costs. In the paper the emissions of pollutants are also analyzed. Sensitivity analysis is also performed in HOMER in order to examine how the average annual wind speed and average annual solar radiation will affect the configuration of the system. For this purpose the software tool HOMER is used. HOMER's optimization and sensitivity analysis algorithms make it easier to evaluate the many possible system configurations [10].

Lifetime of the project is 25 years, while the interest rate is 6%. As dispatch strategy load following is selected. The possibility for inclusion of multiple generators in the system and multiple generators to operate simultaneously is allowed. It is also allowed excess electricity to serve thermal load.

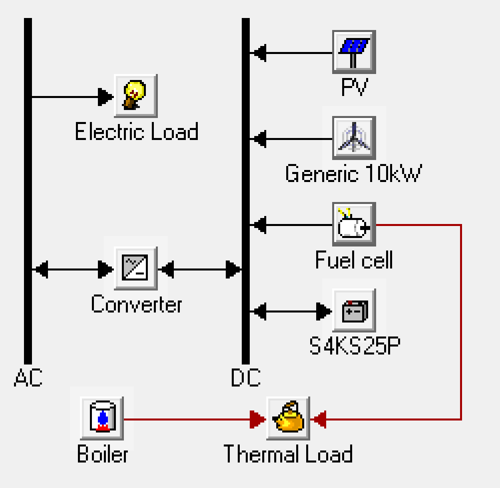


Fig. 1. Schematic representation of the FC/WT/PV hybrid energy system under consideration

3.1. Methodology

Before performing the simulations, several steps need to be realized. First it is need to define the type of the system (combination of technologies) and its configuration (which components, how many and with which characteristics would figure in the model) and enter their respective input data. Also, it is necessary to enter the data for the system load, the energy resources availability over the analyzed time period, economic parameters, to define a dispatch strategy and constraints which are conditions the system must satisfy [11].

Based on the input data, different system configurations, or a combination of components, are simulated and a list of feasible system configurations sorted by net present cost is created. For each feasible solution the costs for installation, replacement and operation of the system over the lifetime of the project are estimated. The system cost calculations account for costs such as: capital, replacement, operation and maintenance (O&M), fuel, and interest.

The total net present cost is calculated by the following relation [1]:

$$C_{NPC} = \frac{C_{ann,tot}}{CRF(i, R_{proj})} \quad [\$] \tag{1}$$

where $C_{ann,tot}$ is total annualized cost [\$/yr], i is interest rate [%], R_{proj} is project lifetime [yr] and CRF() is capital recovery factor given by:

$$CRF(i,N)=\frac{i(1+i)^{N}}{(1+i)^{N}-1} \tag{2}$$

Salvage value is the value remaining in a component of the power system at the end of the project lifetime. HOMER assumes linear depreciation of components, meaning that the salvage value of a component is directly proportional to its remaining life. It also assumes that the salvage value is based on the replacement cost rather than the initial capital cost. This is expressed mathematically as [1]:

$$S=C_{rep}\frac{R_{rem}}{R_{com}}\ [\$] \tag{3}$$

where C_{rep} is replacement cost [\$], R_{comp} is component lifetime [yr] and R_{rem} is the remaining life of the component at the end of the project lifetime, expressed by:

$$R_{rem}=R_{com}-(R_{proj}-R_{rep})\ [\mathrm{yr}] \tag{4}$$

R_{rep} is the replacement cost duration [yr].

HOMER defines the levelized cost of energy (*COE*) as the average cost per kWh of useful electrical energy produced by the system. To calculate the *COE*, HOMER divides the annualized cost of producing electricity (the total annualized cost minus the cost of serving the thermal load) by the total useful electric energy production. The equation for the *COE* is as follows [1]:

$$COE=\frac{C_{ann,tot}-c_{boiler}E_{thermal}}{E_{prim,AC}+E_{prim,DC}+E_{def}+E_{sales}}\ [\$/\mathrm{kWh}] \tag{5}$$

where c_{boiler} is boiler marginal cost [\$/kWh], $E_{thermal}$ is total thermal load served [kWh/yr], $E_{prim,AC}$ is AC primary load served [kWh/yr], $E_{prim,DC}$ is DC primary load served [kWh/yr], E_{def} is deferrable load served [kWh/yr], $E_{grid,sales}$ is total grid sales [kWh/yr].

3.2. Input data

Load data

Figure 2 presents the average daily electrical load profile, while Figure 3 presents the average daily thermal load profile in each month for the analyzed period.

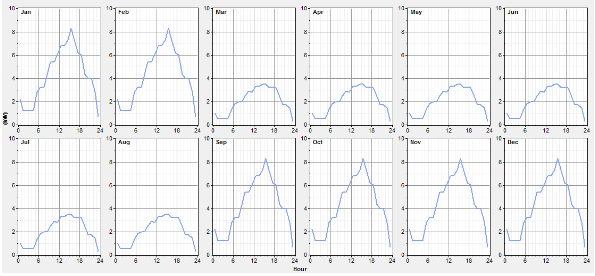


Fig. 2. Average daily electrical load profile

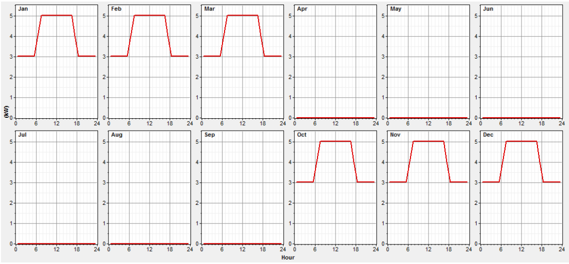


Fig. 3. Average daily thermal load profile

Characteristics of the components

Fuel cell. The data of fuel cell costs: capital costs (C_c), replacement costs (C_R), operation and maintenance costs ($C_{O\&M}$) are presented in Table 1. Lifetime of the fuel cell is 40000 h. The fuel cell uses natural gas as a fuel. The fuel price is $0.15\ \$/\text{m}^3$.

Wind turbines. Generic 10 kW has been selected as the type of wind turbine. The power curve for these type of wind turbine is presented in Figure 4. Lifetime is set to be 20 years. The hub height is 15 m. The data of wind turbine costs are given in Table 1, [12].

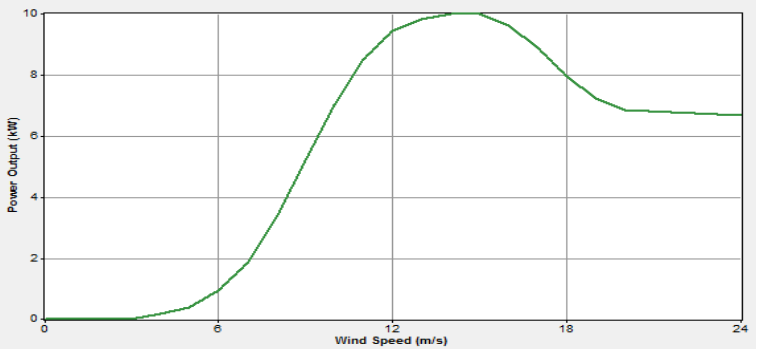


Fig. 4. Power curve of Generic 10 kW wind turbine

PV system. The derating factor of the photovoltaics is chosen to be 90%. Photovoltaics are modeled with a fixed slope of placement. Lifetime of the photovoltaics is 25 years. The data of photovoltaic system are given in Table 1, [13].

Batteries. There are 5 types of storage models in HOMER, [10]. For the considered system Surrette 4KS25P, a kinetic model of batteries, is chosen as the battery type. 10 units of these batteries are considered. Table 1 presents the costs for this type of batteries.

Inverter. The DC-AC converter is used which converts DC power from WT, PV and FC converted into AC to be served as AC electrical load. The inverter efficiency is 90%. The costs for the converters used are given in Table 1. 10 kW size of inverter is considered. Lifetime is 15 years.

Table 1. Component costs

	Quantity/ Size	C_c (\$)	C_R (\$)	$C_{O\&M}$
FC	5 kW	15000	12500	0.030 (\$/h)
PV	1 kW	2710	2300	54 (\$/yr)
WT 10 kW	1	30000	25500	450 (\$/yr)
Battery	1	950	950	19 (\$/yr)
Inverter	5 kW	1250	1125	10 (\$/yr)

Energy resources availability data

Solar energy as a resource is used for our location. Data for solar radiation are taken from the NASA website, [14]. The average annual solar radiation for the selected location is $4.73\ \text{kWh/m}^2/\text{d}$. Figure 5 shows the profile of the average daily solar radiation in the individual months during a year. The graph also shows the data on the clearness index.

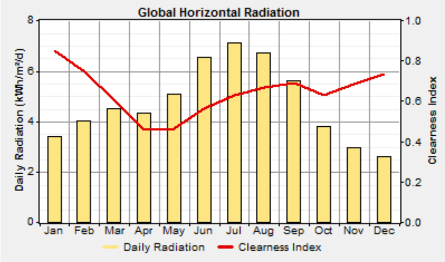


Fig. 5. Profile of the average daily solar radiation in the individual months

Figure 6 shows the average monthly wind speed over a year for this location. According to the entered data, at anemometer height of 10 m, the average annual wind speed in the considered case is $5.899\ \text{m/s}$. Figure 7 presents the Weibull distribution for the given input data of wind speeds.

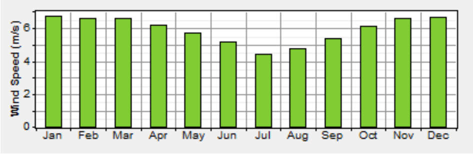


Fig.6. Average monthly wind speed

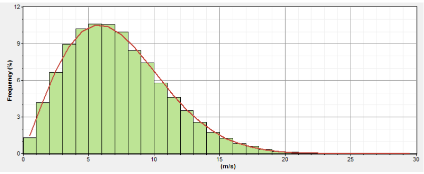


Fig. 7. Weibull distribution

4. RESULTS AND DISCUSSION

At first the basic electricity generation scenario, for a stand-alone hybrid energy system consisting of 9 kW fuel cell, 1 wind turbine Generic 10 kW (G10), 5 kW photovoltaic system, 10 units of batteries and 10 kW inverter is considered. The net present cost by component is presented in Figure 8. The net present cost for the whole hybrid system is $125{,}018\ \$$. Also the salvage value (11,09 \$) is presented on the figure. Monthly average electricity production of FC/WT/PV system is given in Figure 9. The expected electricity production from the wind turbines is 21,881 kWh/yr, from the PV system is 6,707 kWh/yr and from fuel cell is 9,280 kWh/yr. Monthly average thermal production is given in Figure 10. The renewable fraction is 0.519. Levelized Cost of Energy is $COE = 0.345\,[\$/\mathrm{kWh}]$. \

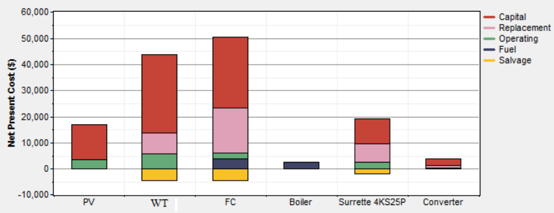


Fig. 8: Net present cost by component

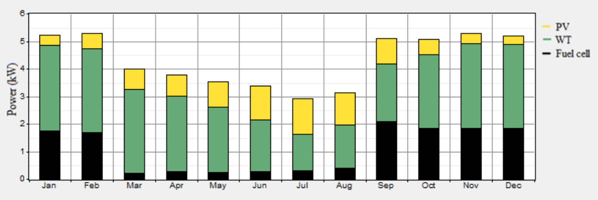


Fig. 9. Monthly average electricity production of FC/WT/PV system

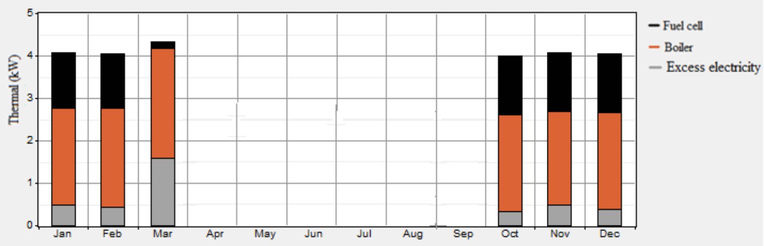
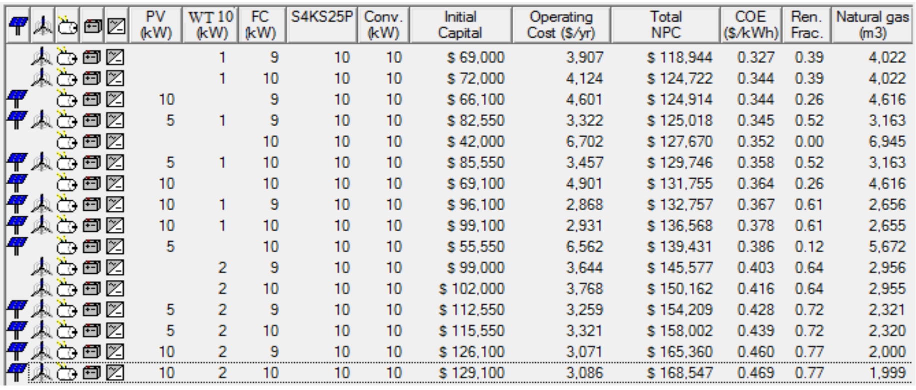


Fig. 10. Monthly average thermal production

Another case that is further analyzed is with the following inputs for the components: size of fuell cell: 9 kW, 10 kW, wind turbines 10 kW (1, 2), size of photovoltaic system: 5 kW, 10 kW, and system with the presence and absence of fuel cell, photovoltaics and wind turbines.

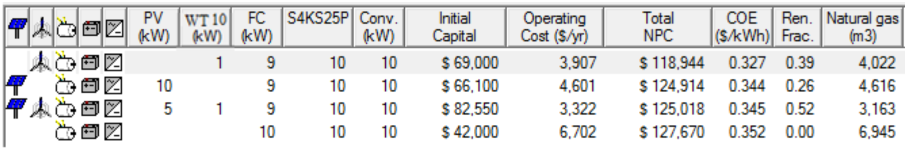
The generated list of feasible solutions, with some of the output results, for this analyzed case, which are sorted by total net present cost are given in Figure 11. The simulation results show that the optimal system is the system with 1 wind turbine 10 kW and 9 kW fuell cell. For the first three system configurations the emissions are larger than in the basic system previously described (which here is on the 4th place).



PV (kW)	WT 10 (kW)	FC (kW)	S4KS25P	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Natural gas (m3)
	1	9	10	10	$ 69,000	3,907	$ 118,944	0.327	0.39	4,022
	1	10	10	10	$ 72,000	4,124	$ 124,722	0.344	0.39	4,022
10		9	10	10	$ 66,100	4,601	$ 124,914	0.344	0.26	4,616
5	1	9	10	10	$ 82,550	3,322	$ 125,018	0.345	0.52	3,163
		10	10	10	$ 42,000	6,702	$ 127,670	0.352	0.00	6,945
5	1	10	10	10	$ 85,550	3,457	$ 129,746	0.358	0.52	3,163
10		10	10	10	$ 69,100	4,901	$ 131,755	0.364	0.26	4,616
10	1	9	10	10	$ 96,100	2,868	$ 132,757	0.367	0.61	2,656
10	1	10	10	10	$ 99,100	2,931	$ 136,568	0.378	0.61	2,655
5		10	10	10	$ 55,550	6,562	$ 139,431	0.386	0.12	5,672
	2	9	10	10	$ 99,000	3,644	$ 145,577	0.403	0.64	2,956
	2	10	10	10	$ 102,000	3,768	$ 150,162	0.416	0.64	2,955
5	2	9	10	10	$ 112,550	3,259	$ 154,209	0.428	0.72	2,321
5	2	10	10	10	$ 115,550	3,321	$ 158,002	0.439	0.72	2,320
10	2	9	10	10	$ 126,100	3,071	$ 165,360	0.460	0.77	2,000
10	2	10	10	10	$ 129,100	3,086	$ 168,547	0.469	0.77	1,999

Fig. 11. Feasible solutions sorted by total net present cost for the second analyzed case

The pollutant emissions by operating of the FC/WT/PV, FC/WT, FC/PV and only FC energy systems, given in the categorized list of feasible solutions (Fig. 12), are presented in Table 2. If we compare the results it is clear that from the FC/WT/PV system all pollutant emissions are the smallest.



PV (kW)	WT 10 (kW)	FC (kW)	S4KS25P	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Natural gas (m3)
	1	9	10	10	$ 69,000	3,907	$ 118,944	0.327	0.39	4,022
10		9	10	10	$ 66,100	4,601	$ 124,914	0.344	0.26	4,616
5	1	9	10	10	$ 82,550	3,322	$ 125,018	0.345	0.52	3,163
		10	10	10	$ 42,000	6,702	$ 127,670	0.352	0.00	6,945

Fig. 12. Categorized feasible solutions sorted by total net present cost for the second analysed case

Table 2. Pollutant emissions by operating of different types of energy systems

Pollutant	**Emissions (kg/yr)**			
	FC/WT/PV	**FC/WT**	**FC/PV**	**FC**
Carbon dioxide	6,116	7,772	8,914	13,402
Carbon monoxide	12.7	18.4	24.6	41.6
Unburned hydrocarbons	1.4	2.04	2.72	4.61
Particulate matter	0.955	1.39	1.85	3.14
Sulfur dioxide	16.3	20.6	23.6	35.4
Nitrogen oxides	113	165	219	371

Sensitivity analysis is also performed in HOMER in order to examine how the average annual wind speed and average annual solar radiation will affect the configuration of the system. Let the average annual wind speed (*Va*) change from $4.8\,\text{m/s}$; $5.9\,\text{m/s}$ and $6.3\,\text{m/s}$ and the average annual solar radiation (*Sa*) change from $4\ \text{kWh/m}^2\text{/d}$; $4.73\ \text{kWh/m}^2\text{/d}$ and $5.3\,\text{kWh/m}^2\text{/d}$. The Figure 13 presents the optimal system type graph. The conclusions for the obtained results and optimal system type graph are presented in the next Table 3, where the cost effective combination of the system for various conditions is given.

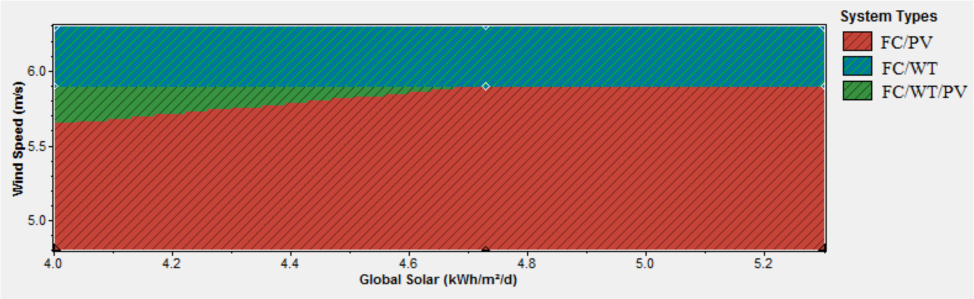


Fig. 13. Optimal system type graph

Table 3. Conclusions for the obtained results of the realized sensitivity analysis

If *Va*	**If *Sa***	**Cost effective combination of the system**
$4.8\text{ m/s} \le Va \le 5.65\text{ m/s}$	$4\text{ kWh/m}^2\text{/d} \le Sa \le 5.3\text{ kWh/m}^2\text{/d}$	**FC/PV**
$5.9\text{ m/s} \le Va \le 6.3\text{ m/s}$	$4\text{ kWh/m}^2\text{/d} \ge Sa > 5.3\text{ kWh/m}^2\text{/d}$	**FC/WT**
$4.8\text{ m/s} \le Va < 5.9\text{ m/s}$	$4.63\text{ kWh/m}^2\text{/d} < Sa \le 5.3\text{ kWh/m}^2\text{/d}$	**FC/PV**
$Va = 5.89\text{ m/s}$	$4\text{kWh/m}^2\text{/d} \le Sa \le 4.63\text{ kWh/m}^2\text{/d}$	**FC/WT/PV**

5. CONCLUSION

In this paper, a stand-alone hybrid energy system consisting of fuel cell, photovoltaic system, wind turbine, batteries and inverter has been investigated. The system has been modelled in HOMER software and this tool was used to perform simulation, calculation and optimization. Emissions of the various types of the system are presented too. Sensitivity analysis is also performed in HOMER in order to examine how the average annual wind speed and average annual solar radiation will affect the configuration of the system.

In the program, the simulations are realized based on the technical and economic data of the system's components that have been modeled, as well as data for the electrical load, thermal load, data of the energy resources availability (in this case for solar radiation and wind speed), fuel price etc.

After determining the feasible solutions of the hybrid energy system, which meet the requirements under the specified conditions, the costs for installation, replacement, operation and maintenance, as well as salvage value of the system over the lifetime of the project have been estimated. Also, electricity and thermal energy production by each component, levelized cost of energy, renewable fraction, natural gas consumption, emissions of pollutants are some of the obtained output results that have been calculated. Conclusions for the obtained results of the realized analysis in the paper are presented in section 4.

REFERENCES

[1] *HOMER Software*, National Renewable Energy Laboratory (NREL), Colorado (available at: http://homerenergy.com/).

[2] Rinaldi, F., Moghaddampoor, F., Najafi, B., Marchesi, R. Economic feasibility analysis and optimization of hybrid renewable energy systems for rural electrification in Peru. *Clean Technologies and Environmental Policy*, ISSN 1618-9558, Vol. 23, 2021, pp.731–748, https://doi.org/10.1007/s10098-020-01906-y.

[3] Mubaarak, S., Zhang, D., Chen Y., Liu, J., Wang, L., Yuan, R., Wu, J., Zhang, Y., Li, M. Techno-economic analysis of grid-connected PV and fuel cell hybrid system using different PV tracking techniques. *Applied Sciences*, ISSN 2076-3417, Vol.10, No.23, 2020, pp. 1-26, https://doi.org/10.3390/app10238515.

[4] Hatata, A. Y., Osman, G., Aladl, M. M. Design and analysis of wind Turbine/PV/Fuel cell hybrid power system using HOMER and clonal selection algorithm. *International Middle - East Power Systems Conference,* 15-17 Dec 2015, Mansoura Egypt, pp. 1-11.

[5] Mohammed, O. H., Amirat, Y., Benbouzid, M., Elbast, Adel. Optimal design of a PV/Fuel cell hybrid power system for the city of Brest in France, *Proceedings of the IEEE International Conference on Green Energy*, March 2014, Sfax, Tunisia. pp.119-123. (available at: https://hal.archives-ouvertes.fr/hal-01023490).

[6] Luu, N.A., Tran, Q.T. Dynamic programming for optimal energy management of Hybrid Wind–PV–Diesel–Battery. *Energies*, ISSN 1996-1073, Vol. 11, No.11, 2018, pp.1-16, https://doi.org/10.3390/en11113039.

[7] Maatallah, T., Ghodhbane, N., Nasrallah, S.B. Assessment viability for hybrid energy system (PV/wind/diesel) with storage in the northernmost city in Africa, Bizerte, Tunisia. *Renewable and Sustainable Energy Reviews, Elsevier*, ISSN: 1364-0321, Vol. 59, 2016, pp.1639–1652, https://doi.org/10.1016/j.rser.2016.01.076.

[8] Ahadi, A., Kang, S.-K., Lee, J.-H. A novel approach for optimal combinations of wind, PV, and energy storage system in diesel-free isolated communities. *Applied Energy*, Elsevier, ISSN: 0306-2619, Vol. 170, 2016, pp. 101–115, https://doi.org/10.1016/j.apenergy.2016.02.110.

[9] N. Yimen, T. Tchotang, A. Kanmogne, I. A. Idriss, B. Musa, A. Aliyu, E.C. Okonkwo, S.I. Abba, D. Tata, L. Meva'a, O. Hamandjoda, M. Dagbasi. Optimal sizing and techno-economic analysis of Hybrid Renewable Energy Systems — A case study of a Photovoltaic/Wind/Battery/Diesel system in Fanisau, Northern Nigeria. *Processes,* ISSN: 2227-9717, Vol. 8, No.11, 2020, pp.1- 5, https://doi.org/10.3390/pr8111381.

[10] *HOMER User Manual*, 2016 (available at: http://homerenergy.com/).

[11] S. Nikolova-Poceva. Optimization of hybrid renewable energy system, *Journal of Electrical Engineering and Information Technologies*, ISSN 2545–4250, Vol. 6, No.1, 2021, pp. 5–11, https://doi.org/10.51466/JEEIT2161181005np.

[12] https://news.energysage.com/small-wind-turbines-overview/

[13] https://www.nrel.gov/docs/fy21osti/77324.pdf

[14] *NASA Surface Meteorology and Solar Energy Data Se*t, (available at: http://eosweb.larc.nasa.gov/).

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