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OPTIMIZATION OF HYBRID RENEWABLE ENERGY SYSTEM

Sofija Nikolova-Poceva

Faculty of Electrical Engineering and Information Technologies,
"Ss. Cyril and Methodius" University in Skopje, North Macedonia
nsofija@feit.ukim.edu.mk

Abstract: In this paper, an off-grid hybrid energy system consisting of micro run-of-river hydro-power plant, photovoltaic system, wind turbines, diesel generator as a back-up power source, batteries and converters is studied. The objective of this research is to obtain the cost effective configuration of the system, which will meet consumption demands, respecting the total net present costs. HOMER software is used to simulate the system and to determine the most appropriate combination of renewable energy resources. Sensitivity analysis is also performed in order to examine how the average annual wind speed, average annual solar radiation and the fuel price will affect the configuration of the system. At the end the emissions analysis of the verious types of the hybrid energy system is also carried out.

Key words: hybrid energy system; solar; wind; hydroenergy sources; optimization; net present cost

ОПТИМИЗАЦИЈА НА ХИБРИДЕН ЕНЕРГЕТСКИ СИСТЕМ СО ИНТЕГРИРАНИ ОБНОВЛИВИ ИЗВОРИ НА ЕНЕРГИЈА

Апстракт: Во трудот е проучуван изолиран хибриден енергетски систем составен од микропроточна хидроелектрична централа, фотоволтаичен систем, ветерни турбини, дизел-генератор како резервен извор на електрична енергија, акумулаторски батерии и конвертори. Целта на ова истражување е да се добие оптимална конфигурација на системот кој ќе ги задоволи потребите на потрошувачите и ќе биде оптимален од аспект на сегашните вкупни нето трошоци. Се користи софтверот HOMER за симулирање на системот и за утврдување на најсоодветната комбинација на обновливи извори на енергија. Исто така е спроведена сензитивна анализа за да се испита како просечната годишна брзина на ветерот, просечното годишно сончево зрачење и цената на горивото влијаат на конфигурацијата на системот. На крајот е извршена анализа на емисиите за различни типови хибридни енергетски системи.

Клучни зборови: хибриден енергетски систем; соларен; ветерен; хидроенергетски ресурс; оптимизација; сегашни нето трошоци

INTRODUCTION

Hybrid renewable energy system (HRES) is a combination of different power generation capacities that used renewable resources such as wind, hydro, solar, biomass, hydrogen fuel, with fossil fuel powered generator connected together to feed power to the local load/grid. One of the main problem is the stochastic nature of solar and wind energy resources. So, hybrid renewable energy system generally consists of a primary renewable power generation capacity(ies) working in parallel with a standby secondary non-renewable power generation component and storage units and in such configuration can alleviate the issues associated with renewable uncertainties and fluctuations. Hybrid energy systems with integrated renewable power generation capacities can be independent of large centralized power grids and can be used in remote areas.

Access to electricity is important concern for people without access to the electrical grid, the majority of which live in rural areas. Supply of electricity through grid is financially unviable or practically infeasible, particularly if the areas are remote and sparsely populated. One of the major challenges is to provide reliable and cost effective services. To select the site for hybrid power source, many factors are considered which are dependent on a combination of load demand, cost of energy storage, seasonal availability of energy sources, site topography and delivery, seasonal energy requirements etc. [5].

When designing hybrid energy system, off-grid 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.

When designing a HRES, we have to consider its components' performances. The main goal is to have a better performance with reduced costs.

Different objectives can be considered when optimizing a system's design. Optimization methods and techniques can help to solve complex problems.

The economic feasibility of standalone hybrid renewable energy system to meet the electrical load requirements has been investigated. In order to determine the configuration of the system that will meet the needs of consumers, and as a design solution that will meet the requirements of the investor, the software tool HOMER is used [10].

HOMER's optimization and sensitivity analysis algorithms make it easier to evaluate the many possible system configurations [11].

RELATED WORK

Much research has been done regarding the hybrid energy systems integrating capacities on renewable energy sources (e.g. wind turbines, photovoltaics, hydroturbines, fuel cells, etc.) with diesel generators and storage devices, and emits low carbon and other pollutant gases.

In [1], focus was given on hydrogen-based hybrid energy systems as an emerging technology for use in stand-alone applications in St John', Newfoundland. Various energy sources (wind, solar, and diesel generator) and storage systems (battery and electrolyzer–tank) were considered in this analysis. NREL's optimization tool HOMER was used in identifying probable hybrid configurations and their applicability. In [2], 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 study carried by [3] evaluated the energy costs of hybrid energy systems with different generator schedules in powering base transceiver stations in Nigeria. A load range of 4 kW to 8 kW was considered using: (i) an optimized generator schedule; (ii) forced-on generator schedule and (iii) the generator-only schedule. Gelma in [4] described the design information of solar PV and wind turbine hybrid energy system to provide electricity to a model community of 100 households and health clinic and elementary school. The study was started thru investigating solar and wind sources potentials of the area of interest. The optimal simulation result showed that PV/wind turbine/diesel generator/battery and convertor configured system.

The authors in [5] investigated the economic feasibility of hybrid energy systems (PV/wind/diesel/battery) to meet the load requirements of a village Perumal Kovilpathy in Coimbatore, minimizing the cost of energy and the CO_2 emission using HOMER. The analysis results show that, among three hybrid systems for supplying electrical requirements, the most economical is the PV-diesel-battery hybrid system. In [6] the authors present a techno-economic evaluation of standalone hybrid renewable energy system consisted of PV modules, wind turbines, diesel generator, inverter and batteries. The optimization design is worked out by reducing the unit cost of energy for different case studies and comparing the outcomes obtained by the use of HOMER-Pro software.

Bekele and Palm conducted a feasibility study, presented in [7], for a standalone solar/wind based hybrid energy system to supply electricity for rural areas in Ethiopia. This paper presented the simulation of PV/wind/diesel and battery system to supply electricity demand for 200 household's model community. The paper showed the most cost efficient combination from the hybridizing of diesel generator/battery and converter with no contribution of renewable sources fractions. It also presented other cost effective combinations of diesel generator/PV and converter. Nasser Yimen et al. [8] 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.

OPTIMIZATION OBJECTIVES FOR HRESS

Various criteria are considered for optimal design and component sizing of HRESs. These criteria can be broadly categorized as economic and technical. Economic criteria are used to minimize costs of HRESs. Technical criteria include reliability, efficiency and environmental objectives to supply the load demand of HRESs at desired reliability levels with maximum efficiency and minimum greenhouse gas emissions [9].

HRESs often times include higher capital costs and lower operation and maintenance (O&M) costs which require an optimization to determine the compromise solution between the costs and benefits. Cost optimization of HRESs includes minimizing energy cost, net present cost and any other costs associated with such systems.

Some studies investigated minimizing levelized cost of energy (COE) for HRESs. In paper [9] are summarized the related research works, their objective functions, techniques in use for optimization and their main findings.

Net present cost (NPC) of an HRES is defined as the total present value that includes the initial cost of the system components as well as the replacement and O&M cost within the project lifetime. The objective here is to minimize the NPC of HRESs. In paper [9] are summarized the related research works, their objective functions, techniques in use for optimization and their main findings.

Other cost-related optimizations include minimizing life cycle cost, levelized unit electricity cost, annualized cost of the system, capital cost of the hybrid system, total cost of the system and average generation cost. In paper [9] are summarized the related research works, their objective functions, techniques in use for optimization and their main findings.

Besides the cost optimization, technical objectives can be also optimized when designing an HRES. Technical objectives include, but are not limited to, satisfying desired reliability levels based on loss of power supply probability or loss of load probability, minimizing cost/efficiency ratio, minimizing carbon emissions and maximizing power availability. In paper [9] are summarized the related research works, their objective functions, techniques in use for optimization and their main findings.

METHODOLOGY

In this paper, the HOMER software was used to simulate an off-grid hybrid renewable energy system in order to obtain the optimal configuration of the system. Techno-economic and emissions analysis is carried out in the paper. The hybrid energy system that is analyzed integrates micro run-of-river hydropower plant, photovoltaic (PV) system, wind turbines, diesel generator as a back-up power source, batteries and converters. Sensitivity analysis is also performed in HOMER in order to examine how the average annual wind speed, average annual solar radiation and the fuel price will affect the configuration of the system.

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. If the emissions are analyzed then it is necessary to enter the appropriate input data.

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.

The total net present cost is calculated by the following relation [10]:

$$C_{NPC} = \frac{C_{ann,tot}}{CRF(i,R_{proj})}, \ \$ \qquad (1)$$

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

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

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 [10]:

$$S = C_{rep} \frac{R_{rem}}{R_{com}}, \ (\$) \qquad (3)$$

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:

$$R_{rem} = R_{com} - (R_{proj} - R_{rep}), \ (\text{yr}), \qquad (4)$$

where 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 [10]:

$$COE = \frac{C_{ann,tot} - c_{boiler} E_{thermal}}{E_{prim,AC} + E_{prim,DC} + E_{def} + E_{sales}}, \ (\$/\text{kWh}) \ (5)$$

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).

SYSTEM DESCRIPTION

Photovoltaic systems, wind turbines and hydro power plants may be integrated in the hybrid energy system in areas where there are favorable conditions for the use of wind, solar and hydroenergy resources. However, due to the stochastic nature of solar radiation and wind speed, diesel generators and batteries are usually included in the system to ensure a reliable supply to consumers. 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.

In this paper, an off-grid hybrid energy system (Figure) consisting of diesel generator, micro run-of-river hydro power plant, wind turbines, photovoltaic system, batteries and converters will be analyzed, which should satisfy the given load of electricity. Lifetime of the project is 25 years, while the interest rate is 6%. In the paper the emissions are also analyzed.

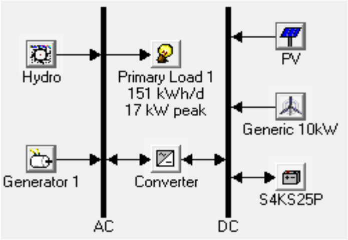


Fig. 1 - Schematic representation of the hybrid energy system under consideration

Load data

Figure 2 presents the average daily load profile in each month for the analyzed period.

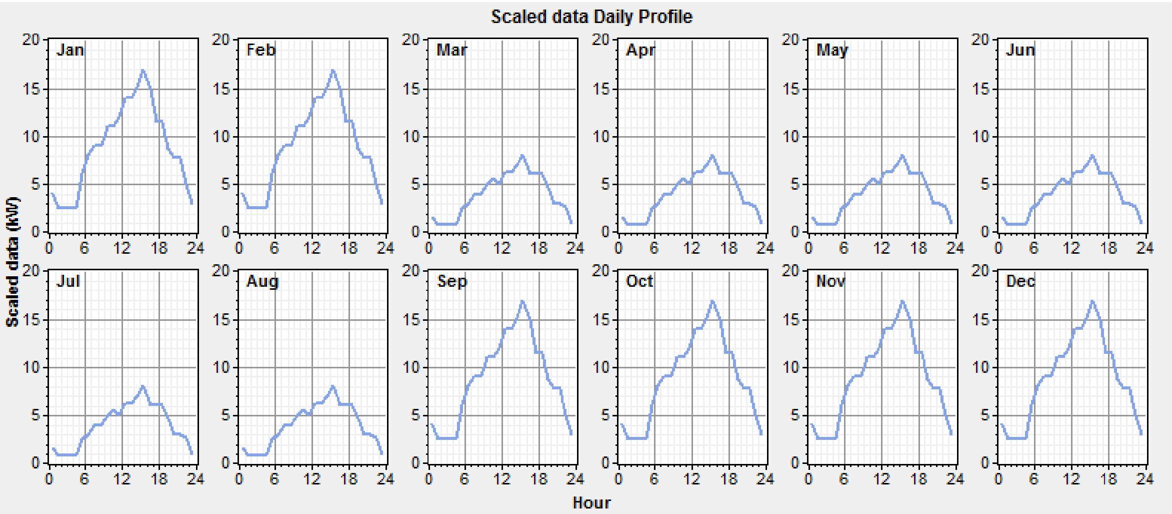


Fig. 2. Average daily load profile in each month

Characteristics of the components

PV system. The data of photovoltaic system costs: capital costs (C_c), replacement costs (C_R), operation and maintenance costs ($C_{O\&M}$) are presented in Table 1, [13]. 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.

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 3. Lifetime is set to be 20 years. The hub height is 15 m. The data of wind turbine costs are given in Table 1 [14].

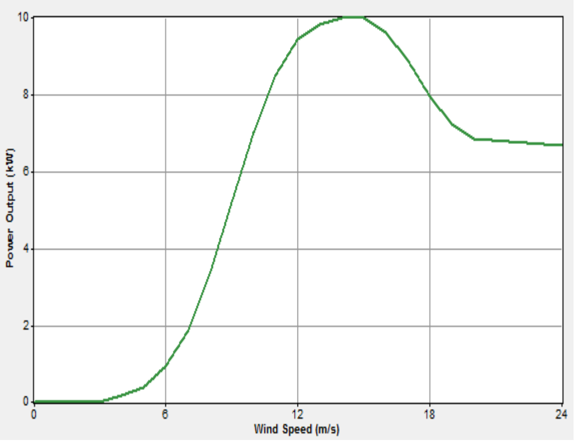


Fig. 3. Power curve of generic 10 kW wind turbine

Micro run-of-river hydro power plant

Nominal power of the power plant is 11.9 kW. Desigh flow rate is 30 l/s and the net head is 50 m. Lifetime is 30 years. The data of the hydro power plant costs are given in Table 1.

Diesel generator

There is a wide range of diesel generators that can be applied. Different manufacturers provide different information which makes their comparison difficult. The costs for this component are given in Table 1. Lifetime is 12000 hours. The fuel price is 1.1 $/l.

Batteries

There are 5 types of storage models in HOMER, [11]. For the considered system Surrette 4KS25P, a kinetic model of batteries, is chosen as the battery type. 20 units of these batteries are considered. Table 1 presents the costs for this type of batteries.

Converters

Due to the need to adjust the voltage in the system it is planned to have an inverter and a rectifier. The inverter and rectifier have efficiency 90% and 88%, respectively. The costs for the converters used are given in Table 1. 10 kW size of converter is considered.

Table 1.

Component costs

	Quantity/ Size (kW)	C_c ($)	C_R ($)	$C_{O\&M}$ ($/yr
PV	1 kW	2710	2300	54
Generic 10 kW	1	30000	25500	450
Micro HPP	11.9 kW	29750	16371	595
Diesel gen	1 kW	500	430	0.01
Battery	1	950	950	19
Converter	5 kW	1000	1000	15

Energy resources availability data

Solar energy as a resource is used for our location with latitude 41.2048 and longitude 22.5801. Data for solar radiation are taken from [12]. The average annual solar radiation for the selected location is 6.09 kWh/m^2/d. Figure 4 shows the profile of the average daily solar radiation in the individual months during a year.

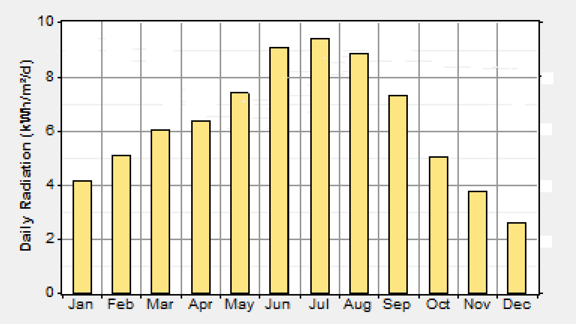


Fig. 4. Profile of the average daily solar radiation in the individual months

Figure 5 shows the average monthly wind speed over a year for this location. The data of wind speeds are measured at anemometer height 10 m. According to the entered data, the average annual wind speed in the considered case is 5.7 m/s. The parameters of the weibull distribution are k = 1.99 and c = 6.43 m/s. Figure 6 presents the Weibull distribution for the given input data of wind speeds.

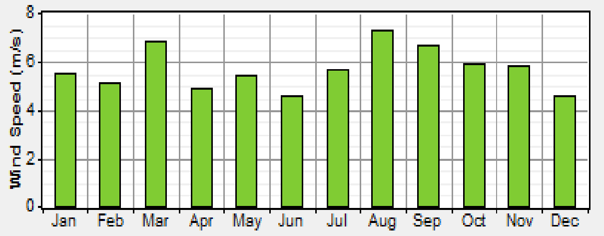


Fig. 5. Average monthly wind speed

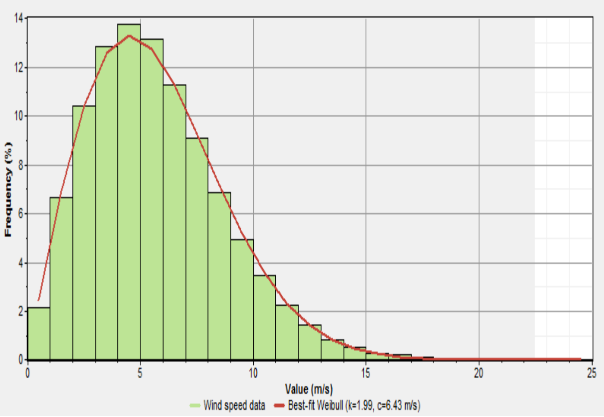


Fig. 6. Weibull distribution

The profile of the average monthly stream flow over a year for this location is presented in Figure 7. The average annual stream flow is 15.9 l/s.

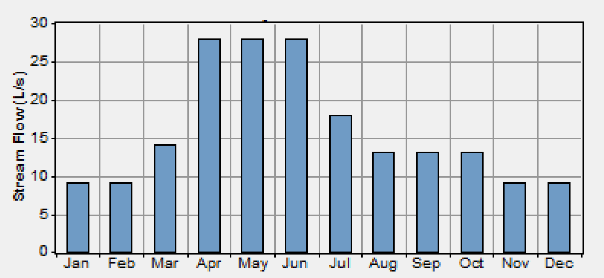


Fig. 7. Average monthly stream flow

RESULTS AND DISCUSSION

At first the basic electricity generation scenario, for an off-grid hybrid energy system consisting of 11.9 kW micro run-of-river hydro power plant, 1 wind turbine Generic 10 kW, 5 kW photovoltaic system, 17 kW diesel generator and 20 units of batteries, is considered. The net present cost by cost type and by component is presented in Figure 8 and Figure 9 respectively. The net present cost for the whole hybrid system is 228.427 $. Also the salvage value is presented on the figure (9,380 $). COE = 0.324 $/kWh. Monthly average electricity production is given in Figure 10. The renewable fraction is 0.831.

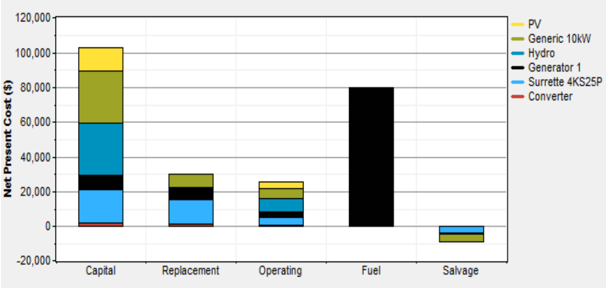


Fig. 8. Net present cost by cost type

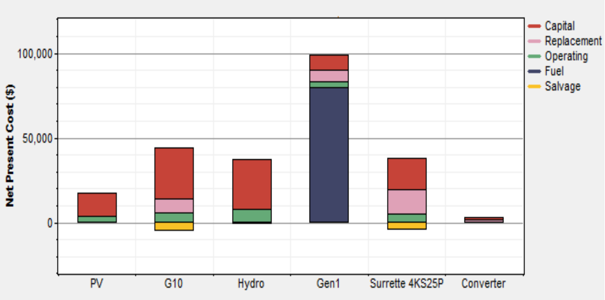


Fig. 9. Net present cost by component

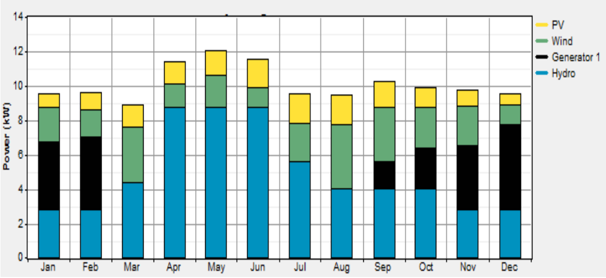
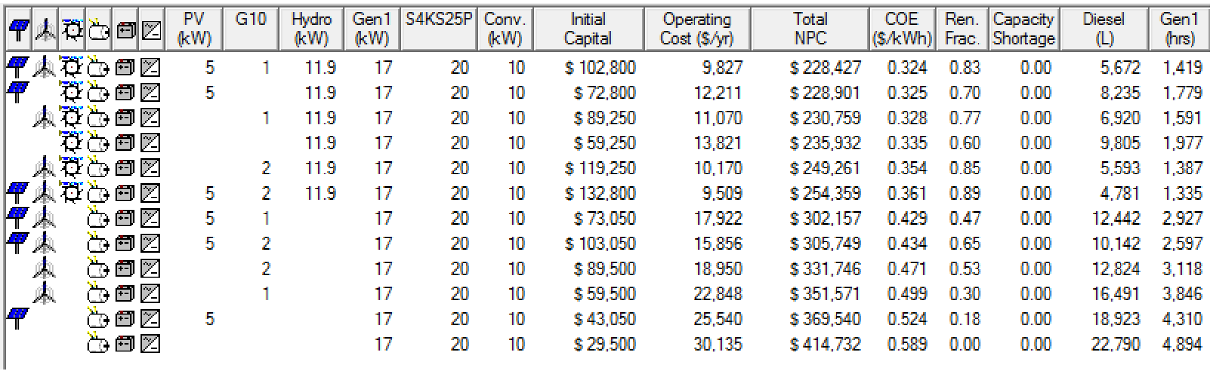


Fig. 10. Monthly average electricity production

Another case that is further analyzed is with the following inputs for the renewable components: size of photovoltaic system: 0 kW, 5 kW, generic 10 kW (0, 1, 2), and system with the presence and absence of the hydro power plant. The generated list of feasible solutions, sorted by total net present cost are given in Figure 11. The simulation results show that the optimal system is the same system of the basic electricity generation scenario (solar/wind/hydro/diesel/battery). The next is solar/hydro/diesel/battery system (total NPC 228,901 $).

Sensitivity analysis is also performed in HOMER in order to examine how the average annual wind speed, average annual solar radiation and the fuel price will affect the configuration of the system. Let the average annual wind speed (*Va*) change from 5 m/s; 5.7 m/s; 6 m/s and 6.5 m/s. the average annual solar radiation (*Sa*) change from 4kWh/m^2/d; 5.5 kWh/m^2/d; 6.09 kWh/m^2/d; and 6.5 kWh/m^2/d; and the price of diesel: 0.9 $ and 1/1 $/l. The Figures 12 and 13 present the optimal system type graph when diesel price is 0.9 $ and 1.1 $/l, respectively.

It is clear that the price of the fuel significantly affects costs. The conclusions for the obtained results and optimal system type graph, when diesel price is 0.9 $/L and 1.1 $/L, are presented in the next Table 2, where the cost effective combination of the system for various conditions is gives.



PV (kW)	G10	Hydro (kW)	Gen1 (kW)	S4KS25P	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Capacity Shortage	Diesel (L)	Gen1 (hrs)
5	1	11.9	17	20	10	$ 102,800	9,827	$ 228,427	0.324	0.83	0.00	5,672	1,419
5		11.9	17	20	10	$ 72,800	12,211	$ 228,901	0.325	0.70	0.00	8,235	1,779
	1	11.9	17	20	10	$ 89,250	11,070	$ 230,759	0.328	0.77	0.00	6,920	1,591
		11.9	17	20	10	$ 59,250	13,821	$ 235,932	0.335	0.60	0.00	9,805	1,977
	2	11.9	17	20	10	$ 119,250	10,170	$ 249,261	0.354	0.85	0.00	5,593	1,387
5	2	11.9	17	20	10	$ 132,800	9,509	$ 254,359	0.361	0.89	0.00	4,781	1,335
5	1		17	20	10	$ 73,050	17,922	$ 302,157	0.429	0.47	0.00	12,442	2,927
5	2		17	20	10	$ 103,050	15,856	$ 305,749	0.434	0.65	0.00	10,142	2,597
	2		17	20	10	$ 89,500	18,950	$ 331,746	0.471	0.53	0.00	12,824	3,118
	1		17	20	10	$ 59,500	22,848	$ 351,571	0.499	0.30	0.00	16,491	3,846
5			17	20	10	$ 43,050	25,540	$ 369,540	0.524	0.18	0.00	18,923	4,310
			17	20	10	$ 29,500	30,135	$ 414,732	0.589	0.00	0.00	22,790	4,894

Fig. 11. Generated list of feasible solutions for the second analyzed case

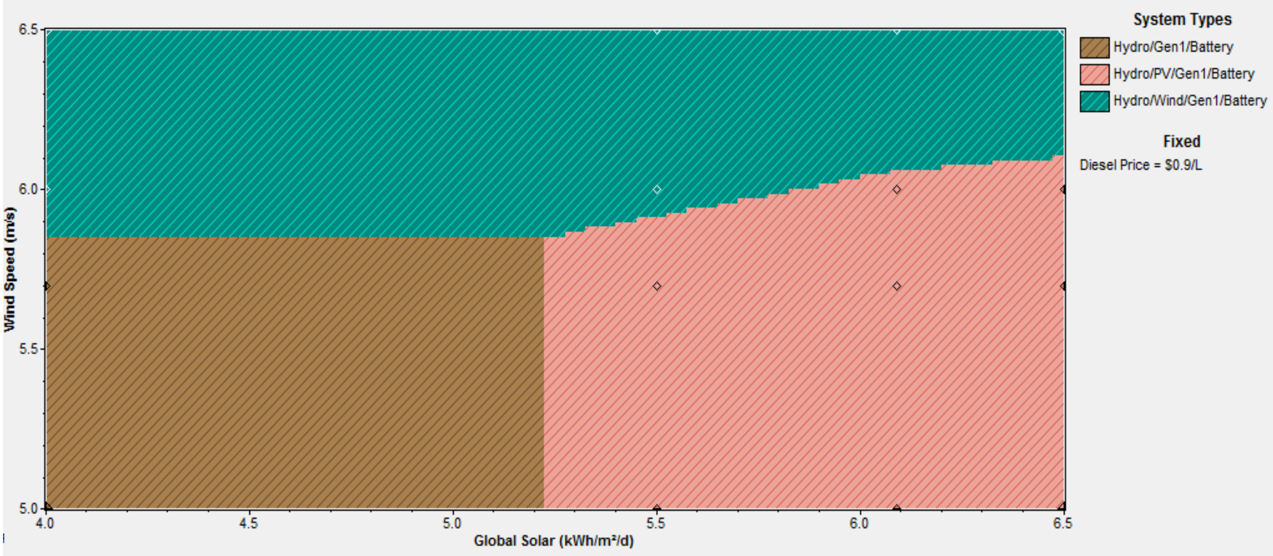


Fig. 12. Optimal system type graph when diesel price is 0.9 $

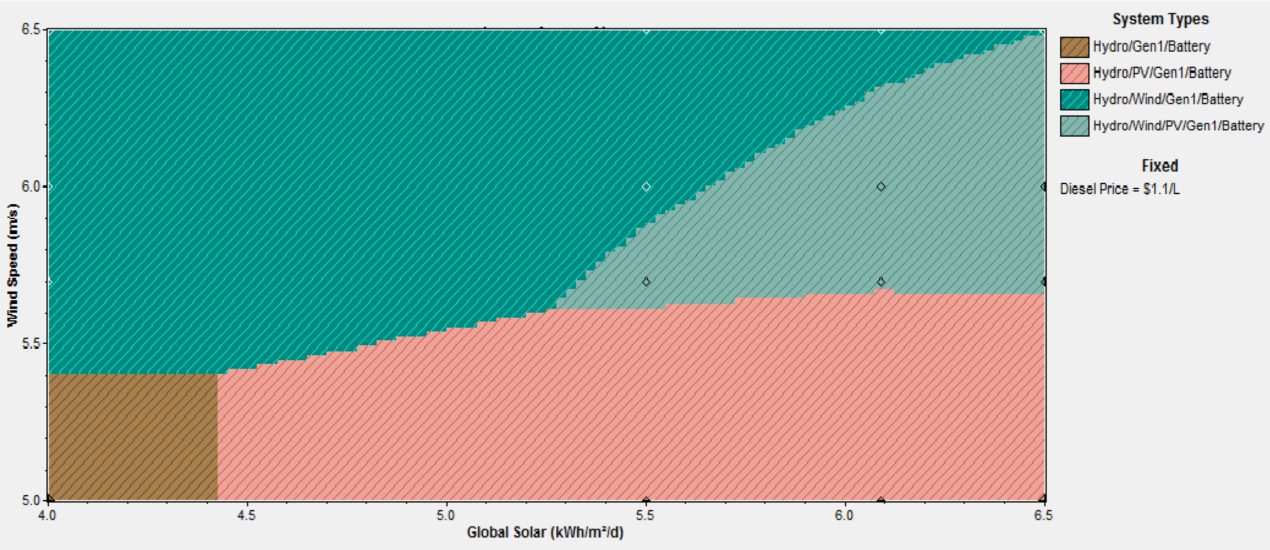


Fig. 13. Optimal system type graph when diesel price is 1.1 $/l

Table 2. Conclusions for the obtained results of the realized sensitivity analysis

If Va	If Sa	Cost effective combination of the system
Diesel price = 0.9 $		
$5 \text{ m/s} \le Va \le 5.85 \text{ m/s}$	$4 \text{ kWh/m}^2\text{/d} \le Sa \le 5.2 \text{ kWh/m}^2\text{/d}$	hydro/diesel/battery
$5 \text{ m/s} \le Va \le 5.85 \text{ m/s}$	$6.5 \text{ kWh/m}^2\text{/d} \le Sa \le 5.2 \text{ kWh/m}^2\text{/d}$	solar/hydro/diesel/battery
$Va = 6 \text{ m/s}$	a) $4 \text{ kWh/m}^2\text{/d} \le Sa \le 5.9 \text{ kWh/m}^2\text{/d}$	a) wind/hydro/diesel/battery
	b) $6.5 \text{ kWh/m}^2\text{/d} \le Sa \le 5.9 \text{ kWh/m}^2\text{/d}$	b) solar/hydro/diesel/battery
$Va = 6.5 \text{ m/s}$	$4 \text{ kWh/m}^2\text{/d} \le Sa \le 6.5 \text{ kWh/m}^2\text{/d}$	wind/hydro/diesel/battery
Diesel price = 1.1 $		
$5 \text{ m/s} \le Va \le 5.4 \text{ m/s}$	$4 \text{ kWh/m}^2\text{/d} \le Sa \le 4.4 \text{ kWh/m}^2\text{/d}$	hydro/diesel/battery
$Va \le 5.7 \text{ m/s}$	a) $4 \text{ kWh/m}^2\text{/d} \le Sa \le 5.2 \text{ kWh/m}^2\text{/d}$	a) wind/hydro/diesel/battery
	b) $6.5 \text{ kWh/m}^2\text{/d} \le Sa \le 5.1 \text{ kWh/m}^2\text{/d}$	b) solar/wind/hydro/diesel/battery
$Va = 6 \text{ m/s}$	a) $4 \text{ kWh/m}^2\text{/d} \le Sa \le 5.6 \text{ kWh/m}^2\text{/d}$	a) wind/hydro/diesel/battery
	b) $6.5 \text{ kWh/m}^2\text{/d} \le Sa \le 5.6 \text{ kWh/m}^2\text{/d}$	b) solar/wind/hydro/diesel/battery s
$Va \le 6.5 \text{ m/s}$	$4 \text{ kWh/m}^2\text{/d} \le Sa \le 6.5 \text{ kWh/m}^2\text{/d}$	wind/hydro/diesel/battery

The carbon dioxide emissions (kg/yr) for different system combinations are presented in Figure 14. The nitrogen oxides emissions (kg/yr) for different system combinations are presented in Figure 15. The carbon monoxide, unburned hydrocarbons, particulate matter and sulfur dioxide emissions (kg/yr) for different system combinations are presented in Figure 16.

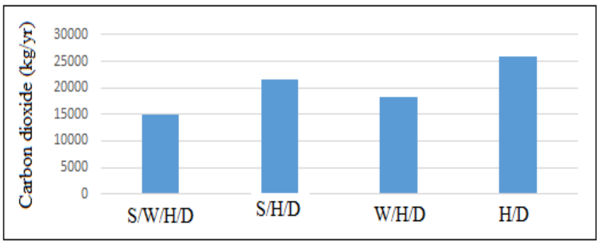


Fig. 14. Carbon dioxide emissions for different system combinations

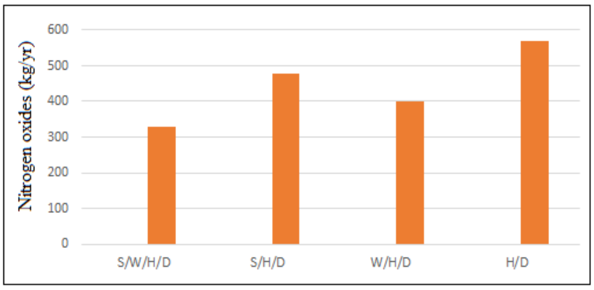


Fig. 15 . Nitrogen oxides emissions for different system combinations

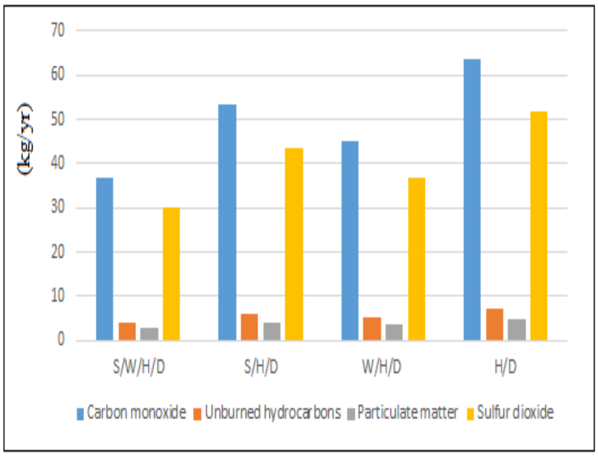


Fig 16. Carbon monoxide, unburned hydrocarbons, particulate matter and sulfur dioxide emissions for different system combinations

CONCLUSION

An off-grid hybrid energy system consisting of micro run-of-river hydro power plant, photovoltaic system, wind turbines, diesel generator as a back-up power source, batteries and converters has been investigated. In order to determine the most appropriate combination of renewable energy resources, the software tool HOMER has been applied. The software allows the comparison of different combinations of components, their different quantities and performance. Feasible solutions are listed and sorted by total net present cost. Emissions of the verious types of the system are presented too.

In the program, the simulations are realized based on the input data for the components that are modeled, data for the electrical load, data of the energy resources availability (in this case for stream flow, solar radiation and wind speed), fuel price, emissions iputs as well as the economic parameters for the project.

Sensitivity analysis is also performed in HOMER in order to examine how the average annual wind speed, average annual solar radiation and the fuel price will affect the configuration of the system.

The conducted analyses within the paper and the corresponding results and discussion are presented in section Results and dizcussion.

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