Designing the Optimal Stand alone Power System which uses Wind Power and Solar Radiation for Remote Area Object

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Abstract. The objective of this paper is to discuss both energetical and economical aspects of designing the optimal stand alone power system for remote area object. A smaller part of this research refers to investment expenses of connecting the remote area object to electrical grid, while the main part concerns the optimal configuration of hybrid stand alone power system which uses wind power and solar radiation. The research is conducted for various intervals of time when the object can be used. Computer model that is used in this research is HOMER. HOMER estimates the cost of installing and operating the system, and displays a list of optimal configurations. After the simulations have been made I have concluded that optimal configurations are dependable on location, renewable energy recourses and investment expenses of components. Computer models can perform feasibility analysis, while the actual performance of hybrid power systems can't be accurately predicted.

Keywords

Stand alone power system (SAPS). Photovoltaic (PV) modules. Small wind turbines. Hybrid wind/PV/diesel systems.

1. Introduction

Over last several decades demand for electrical energy on a world-wide level is growing rapidly. Energy services are considered as a driving force of economic development, and its sociological benefits cannot be neglected. However, current patterns of energy production are polluting and unsustainable, and are characterized by inequity in consumption and access. The challenge is to improve access of modern energy services, without increasing reliance on fossil fuels. Recent approaches meet this challenge with a focus on application of renewable energy recourses, such as wind, solar and hydro, which are especially suited for decentralized electricity generation [1]. However, application of renewable energy resources has two major problems, i.e. instable energy provision due to fluctuating nature of the resources and location dependency; therefore, there are no universal methods when developing renewable energy power system for a specific site.

The research that is presented in this paper is oriented towards application of renewable energy resources (wind and solar) in stand alone power systems (SAPS). Due to absence of respective guidelines, the analysis is performed with methodology that is developed for this research only.

The overall objective of this paper is to analyse both energetical and economical aspects of designing the optimal stand alone power system for remote area object. A smaller part of this research refers to investment expenses of connecting the remote area object to electrical grid, while the main part concerns the optimal configuration of hybrid stand alone power system which uses wind power and solar radiation.

The purpose of the paper is to present implications and solutions when designing hybrid photovoltaic/wind power systems.

The aim of the research is to determine the best ratio of investment and design with criterion of designing power system that is stable.

The approach that has been implemented in this study can result with quality solutions, and based on them; decision can be made concerning the feasibility of hybrid power system on a specific location.

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2. Project assignment

Project assignment is to determine the best power system for remote area object that is approximately 9 km away from conventional electric grid.

When calculating which power system is the most suitable for the object, one can choose between:

- connecting the remote area object to electrical grid,
- photovoltaic (PV) power system,
- wind power system (wind turbine, WT),
- fossil fuel generator,
- hybrid power system (PV/WT/Gen).

Object is a household, which consists of typical electrical appliances, such as: electric boiler, a water pump, washing machine, refrigerator, TV, PC, lights...

The research must be conducted for various time intervals when the object can be used; that is 1, 3, 6, 9 or 12 months. The object is located in Croatia, at the Island Vis (Hum hill).

3. Defining the basic parameters

Prior to any calculations and regardless of power system that remote area object will eventually be connected to, basic parameters must be determined. First and foremost parameter that needs to be determined is the average power consumption curve of the object. Based on the average (peak) load of the object, adequate power system is designed or implemented. If application of renewable energy power system is considered, input data, such as average wind speed and solar radiation for the specified location, must be obtained. Based on that input data, renewable energy potential is assessed, after which, conclusion on feasibility of the same is made.

4. Creating the average daily load profile

There are two ways to gather the power consumption data, i.e. average daily load profile. First, and the best way that power consumption data can be collected is through wattmeter and data logger on the object that has similar electrical appliances. Second way, and the way that average daily profile was created for the needs of the research, is through power consumption table.

When creating daily load profile through power consumption table, the first thing to do is to measure how many hours or minutes par day appliance is used. A precise measurement of operating minutes per hour has to be performed for appliances with large wattage ratings (electric boiler, water pump, microwave oven). Wattage information from the product labelling (or the manual) is then multiplied with loss factor (for AC appliances is around 1.4) and the time while the appliance is operating.

Creating the average daily profile through power consumption table deviates from the actual values. Those deviations are compensated when entering the daily load profile into a computer sizing model (HOMER [2]) by adding daily and hourly noise.

Table I shows power consumption table that was created with the methodology explained above.

TABLE I
DAILY POWER CONSUMPTION

Electric appliance	Pnom (VA)	Work hours (h/day)	Loss factor	Wh/day
El. boiler	2000	3.75	1.4	10500
Water pump	1100	1.8	1.4	2772
Lights (x10)	100	1.6	1.4	2240
TV set	100	9	1.4	1260
PC	90	6.5	1.4	819
Vacuum cleaner	600	0.5	1.4	420
Hair drier	1500	1	1.4	2100
Iron	1000	0.75	1.4	1050
Refrigerator	n.a.	24	1.4	720
Washing machine	n.a.	2	1.4	760
Total power need (Wh/day)				22641

Table I does not give the full perspective of the methodology, it rather presents a shorter version (summation) of the actual power consumption table. Due to its size and complexity, actual power consumption table that contains values measured through 24 hours cannot be shown in this paper. However, chart presented in figure 1 clearly illustrates the outcome of data acquisition methodology explained above.

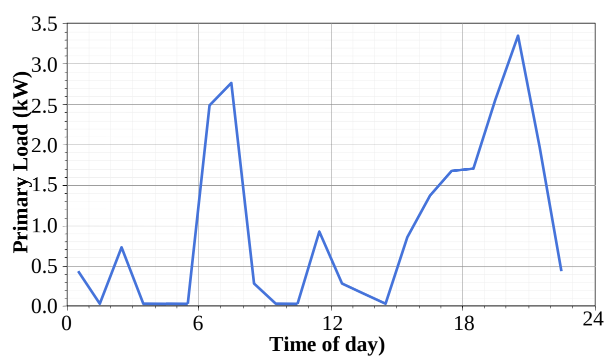

Fig. 1. Average daily load profile

5. Investment expenses of connecting the remote area object to electric grid

Technical solution and investment expenses of connecting the remote area object should be provided by local distributor (in Croatia). Prior to contacting local distributor, it is necessary to predict or calculate peak load. Since previously created average daily profile does not give accurate information about peak load values; peak load is calculated by adding daily (10%) and hourly (15%) noise in computer sizing model (HOMER). HOMER [2] has calculated that the peak load of the remote area object is 5.25 kW.

Since calculated peak load is 5.25kW, standardized solution provided by local distributor is a single-phase connection with the peak value of 5.75kW and current overload limitation at 25A. However, connecting the object to low voltage powerline (400V) is not feasible, since energy loss in the powerline is enormous.

Remote area object could be connected through medium-voltage powerline (10kV) and TS 10/0.4 kV. Investment expenses of connecting the remote area object are around 270 000€, which is obviously too expensive.

6. Estimating the renewable energy potential

It is well known that renewable energy potential depends on the specific location (micro location). In this research, as it is previously stated, object is located on the island Vis, at the Hum hill, on an altitude of 140m, with roof that is facing south, and it is assumed that are no obstacles to air flux in a nearby area.

In order to investigate feasibility of PV/WT application at given location, an estimate of wind and solar renewable energy potential is needed.

A. Estimating the wind energy potential

In order to conduct a quality analysis of wind energy potential for a specific location (micro location), speed and direction of winds should be measured through a certain number of years (at least 3 years). Besides that, terrains topography and proximity of air flux obstacles should also be considered . Also, accuracy of reference data is important for wind energy potential estimates, because small inaccuracies result in large errors when estimating the available power. Since power is proportional to the cube of wind speed, a 25% over-estimation of wind speed results in predicting twice as much power as is actually available. An estimate of average wind speed at a micro location may be determined by accessing reference data from Internet, global wind data maps, nearby airports or from the available studies. At the wider area of the Hum hill, wind speeds were measured for the needs of the National wind energy potential study. Since location Vis4 is the closest one to the location of the object, it is assumed that Vis4 wind data is suitable for wind energy potential estimate. Wind speeds on Vis4 location were measured from May of 1996 until April of 1997, with the outcome of average yearly wind speed of 5.5 m/s [3]. Although average yearly wind speed cannot directly be associated with the production of electric energy, it can serve as an indicator of wind presence.

Based on the fact that average yearly wind speed is 5.5 m/s, while the lower limit of the wind turbine application feasibility is between 4 and 5 m/s, it is safe to assume that location of remote area object is suitable for wind turbine application. Table II shows average monthly wind speeds for the given location.

TABLE II
AVERAGE MONTHLY WIND SPEEDS

Month	Wind speed (m/s)
January	6.5
February	6.5
March	5.7
April	5.2
May	4.6
June	4.4
July	4.2
August	4.7
September	5.6
October	6
November	6.2
December	6.5
Average wind speed	5.502

B. Estimating the solar energy potential

The average amount of sunshine must be estimated in order to predict how well photovoltaic (PV) cell will perform in a given location. The intensity of the Sun, or insolation, varies with global locations, season and time of day. The average hours of full sun at a site may be estimated by accessing reference data from Internet. Most commonly used databases are: NASA – surface meteorology and solar energy data base [4], Meteonom database and PVGIS – Photovoltaic geographical Information System [5]. Solar insolation data from those databases is not measured, but it is calculated from the extraterrestrial solar radiation measured at the edge of earth's atmosphere, therefore, not entirely accurate. Also, direct solar radiation which determines PV production depends on the weather (clearness index); hence, predicaments of PV production could never be entirely accurate.

Table III shows reference data that is essential for solar energy potential estimate and computer simulation of PV modules for the given location (island Vis, Hum hill).

TABLE III
SOLAR RESOURCE REFERENCE DATA

Month	NASA	PV - GIS	
	Global radiation at horizontal surface (kWh/m^2 daily)	Average daytime temperature (˚C)	Optimal PV inclination angle (˚)
January	1.680	8.7	65
February	2.330	9.0	57
March	3.450	10.5	45
April	4.560	14.6	30
May	5.610	20.7	16
June	6.460	25.0	9
July	6.780	26.7	13
August	5.960	27.1	25
September	4.410	21.8	41
October	2.770	18.8	54
November	1.840	14.1	62
December	1.470	9.9	66
Average value	3.952	17.2	36

Since island Vis has approximately 2700 sunny hours per year, and average insolation around $1.6MWh/m^2$ per year, it is safe to assume that given location is suitable application of photovoltaic (PV) application.

7. Stand alone power system design with HOMER simulation software

HOMER [2] or hybrid micro power optimization model, is a powerful software that simplifies the task of evaluating designs both off-grid and grid-connected power systems for a variety of applications. In order to use HOMER, user must provide model with inputs which describe technology options, component costs, and resource availability. HOMER uses those inputs to simulate different system configurations and generates results that user can view as a list of feasible configurations sorted by net present cost, so user can compare configurations and evaluate them on their economic and technical merits. HOMER also performs sensitivity analysis; if given sensitivity values that describe a range of resource availability and component costs. Results of a sensitivity analysis can identify the factors that have the greatest impact on the design and operation of the power system. The reason that HOMER is used in this research is simple; it combines both economical and electrical aspects of designing hybrid on-grid or off-grid power systems.

A. *Methodology of research with HOMER software*

Feasibility analysis is conducted for various intervals of time when the object can be used. Due to that fact, reference data which is needed for simulation of the power system, such as wind data, solar resource data, and component technical and economical data remains the same for all projects. The most important difference between the projects is the duration of the load, while minor difference is PV array inclination angle. For each project, HOMER compares feasibility of photovoltaic (PV), wind (WT) turbine, diesel generator power system and all possible combinations between them. Projects lifetime is set at 20 years, with interest rates of 6%.

Project 1 is presented in complete form, while other projects are presented in shorter, simplified form.

B. *Project 1: Stand alone power system which is set for permanent usage [t=12 months]*

HOMER simulates operation of the power system by calculating energy balance for 8760 hours per year. Based on previously defined daily load profile, with daily noise set at 10% and hourly noise set at 15%, HOMER synthesizes set of 8760 hourly values. With such, modified daily load profile, average consumption is 22.5kWh/daily, with peak load of 5.25kW. Monthly averages are presented with figure 2.

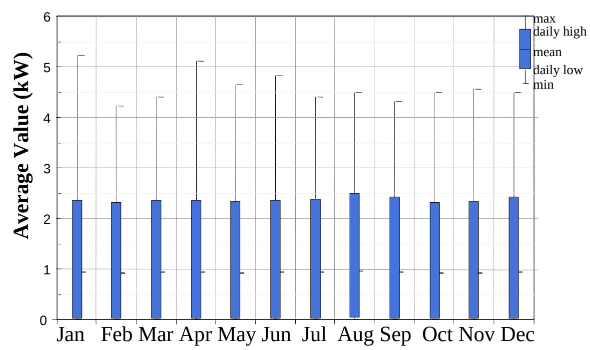

Fig. 2. Monthly average load profile of the object

Wind speed data is synthesized from monthly averages (Table II), thus creating 8760 hourly values, with average yearly speed of 5.5 m/s. Average monthly wind speed is presented with figure 3.

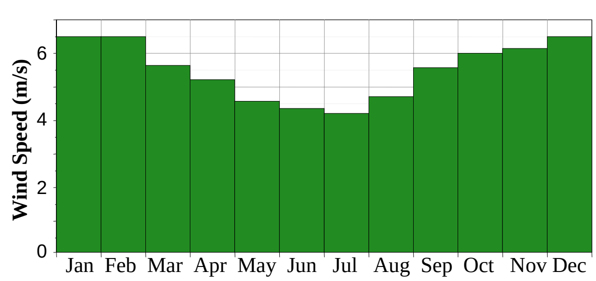

Fig. 3. Monthly average wind speed in Vis, Hum hill

Solar resource data is imported from NASA – surface meteorology and solar energy database. Importing solar resource data is simple, user needs to be connected to Internet and provide latitude (43° 2´ North), and longitude (16° 11´ South) of the object. Solar resource data, i.e. daily radiation and clearness index is presented with figure 4.

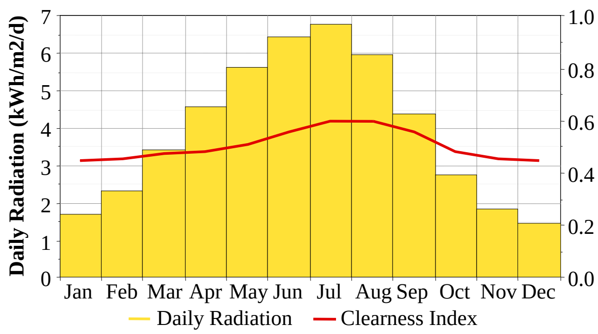

Fig. 4. Monthly average solar radiation at Vis, Hum hill

Wind turbine that was selected for simulation and possible implementation was 1kW DC Bergey BWC XL.1. It is considered to be the best one in its class, and it can be bought in Croatia [6]. Table IV shows overall costs of Bergey XL.1 wind turbine.

TABLE IV
BERGEY XL.1 OVERALL COSTS

P_{nom} (kW)	Investment expences ($)	Replacement costs ($)	O&M costs ($/yr)
1	6582	6582	50
2	12346	12346	100

In order to obtain hi-quality results, wind turbines investment expenses include the costs of wind generator, power centre with voltage regulator, breaker, wiring and costs of installing the wind turbine. Operation and maintenance costs are fairly difficult to calculate, they are approximately 0.005 $/kWh of wind turbine yearly energy output, plus safety added intermittent costs. Expected life of BWC XL.1 wind turbine is 20 years.

HOMER uses a very simple model of PV array output, which is fairly accurate if PV array is equipped with MPPT voltage regulator. However, HOMER does not consider the type of technology that PV cell is made of, given that mathematic modelling of PV cell is very complicated. PV module that was selected for simulation has a monocrystal Si structure [6]. That module is Hellios H 1500; 125 W_p/12V. It is important to include costs of voltage regulator into overall PV array costs, since HOMERs energy output calculation is fairly accurate if maximum power point regulator (MPPT). Overall costs are shown in table V.

TABLE V
PV ARRAY OVERALL COSTS

P_{nom} (kW)	Investment expences ($)	Replacement costs ($)	O&M costs ($/yr)
O.5	4418	4418	15
1	8895	8895	36
2	16972	16972	36

Because MPPT regulator has lifetime approximately 10 years, replacement of MPPT is included into O&M costs.

Fossil fuel generator that was selected for the simulation is Isuzu 400TS diesel generator with additional (automatic) equipment [6]. Its maximum output is 4.5kW; permanent output is 4kW, with lifetime set at 5000 operating hours. Operation and maintenance costs are difficult to predict, but they are usually 10% of overall investment costs. Table VI shows overall costs of Isuzu 400 TS diesel generator.

TABLE VI
ISUZU 400TS OVERALL COSTS

P_{nom} (kW)	Investment expences ($)	Replacement costs ($)	O&M costs ($/hr)
4.5	2890	1500	0.070

Power converters that were selected for the simulation are available at Croatian market [6]. Since power system can work if power converter is badly dimensioned, power converters vary in range from 1.6kW to 4kW. Those converters are bi-directional power converters (inverter/charger power converter), and all of them can endure 3xP_{nom} for at least 5 seconds. Table VII shows overall costs of bi-directional converters amongst which HOMER will chose the best one for the particular power system configuration.

TABLE VII
POWER CONVERTER OVERALL COSTS

P_{nom} (kW)	Type of bi-derectional power converter	Investment expences ($)	Replacement costs ($)
1.6	Studer XPC 220-24V	1576	1576
2.3	Studer C 2600-24V	2360	2360
3	Outback VFX 30- 24V	2803	2803
4	Studer HPC 4400-24V	4152	4152

Operation and maintenance costs are not listed, since they do not exist. Average lifetime of power converters is 10 years.

The batteries that were selected for the simulation are Trojan T-105 batteries; 225Ah; 6V; 845kWh [6]. Average lifetime of the batteries is mainly between 7 and 10 years. In the section sizes to consider quantity of batteries that HOMER will consider while simulating different power system configurations is from 2 to 46 batteries. Investment expenses must include the box that batteries are stored in, while O&M costs must include sporadic replacements of battery cells, cleaning the contacts etc. O&M costs are usually between 2 and 5% of investment expenses, for this type of batteries they are approximately 2%. Overall costs of T-105 batteries are shown in table VII.

TABLE VIII
T-105 BATTERIES OVERALL COSTS

P_{nom} (kW)	Investment expences ($)	Replacement costs ($)	O&M costs ($/yr)
2	225	225	5

Sensitivity variables that were chosen for the simulation are growth of industrial diesel prices (cheaper type of diesel) and variation of wind speed.

After the input data has been entered, and all the errors that HOMER has signalized are corrected, HOMER conducts simulation and presents list of the best power system configurations. Left double click on the optimal configuration opens full report of the specific configuration. The optimal configuration in selected with average wind speed at 5.5m/s and industrial diesel price at 0.78$/L.

Optimal system consists of: Bergey BWC XL.1 wind turbine, Isuzu 400TS 4.5kW diesel generator, 16 T-105 batteries, Studer 1.6 kVA power converter. Investment expenses are 12484$, while overall costs of the power system that are calculated for project lifetime of 20 years and interest rate of 6% are 40503$, or 3531$/year. The most important information is levelized cost of energy, which is 0.430 $/kWh. Figure 5 displays annual electric energy production of the power system.

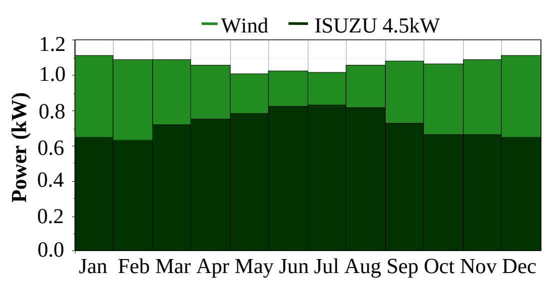

Fig. 5. Monthly average electric production [t=12 months]

As is visible in the figure 5, yearly production of electrical energy is divided between wind turbine and diesel generator. Diesel generator produces 68%, while wind turbine produces 32% of yearly energy output. The main reason for such ratio is that wind speed is not adequate for wind turbine maximum capacity production and the fact that wind turbine has only 1kW of installed capacity. In such power system configuration diesel generator cover almost all the load and transient peaks, while wind turbine serves as back up energy source. Power converter that has the maximum load set at 1.6kVA will cover the average load. When load demand is beyond 1.6kVA diesel generator will cover the load and charge the batteries. This strategy is called cycle charge strategy, and its characteristic is that diesel generator is always off; if renewable energy resources or batteries can follow the load. Cycle charging strategy can result with prolonged operating hours of diesel generator.

C. Project 2: Stand alone power system which is set for usage of 9 months per year [t=9 months]

Due to same location as in project 1, all reference input data is the same as in project 1. The only difference between projects is duration of the load (figure 6).

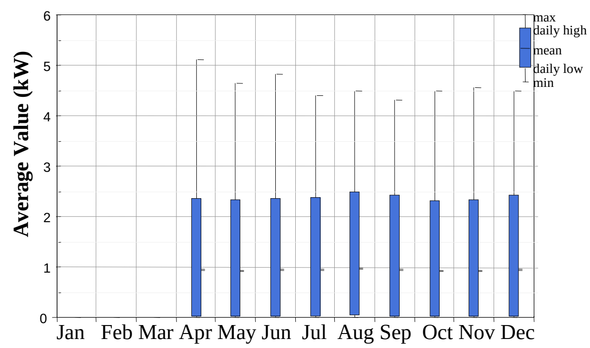

Fig. 6. Monthly average load profile [t=9 months]

In order to investigate cost effectiveness of PV array, duration of load which is shown in figure 6 is set on purpose (object is not used during the winter months). Average peak load is 5.25kW, while average daily load when the object is used is 22.5kWh. HOMER has indicted that daily load in this project is 17kWh, while peak load is 5.25kW. That is an obvious mistake of HOMERs algorithm, which displays those information's as average yearly values. However, HOMER calculates energy balance for every hour during the year; therefore, such mistakes do not have any impact on the modelling of the power system.

HOMER has calculated that optimal system consists of: Bergey BWC XL.1 wind turbine, Isuzu 400TS 4.5kW diesel generator, 16 T-105 batteries, Studer 1.6 kVA power converter. That optimal system is the same one as in project 1, which leads to the conclusion that PV array is still not cost effective.

Investment expenses are 12484$, while overall costs of power system that are calculated for project lifetime of 20 years and interest rate of 6% are 33824$, or 2949$/year. Levelized cost of energy, or cost of producing 1kWh is 0.478 $/kWh. Figure 7 displays annual electric energy production of the power system.

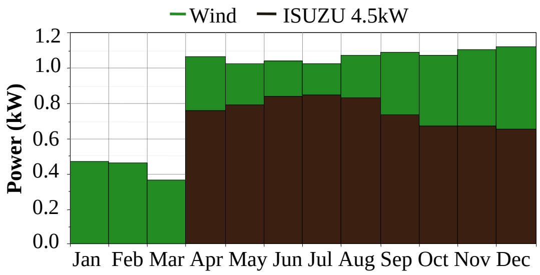

Fig. 7. Monthly average electric production [t=9 months]

It is obvious that calculated electrical production is the same as in project 1. Expected battery life and battery bank autonomy in this project is badly calculated. HOMER calculates those figures with a simple mathematical equation which involves average yearly values calculated for a 12 month period. That means that autonomy of the battery bank, expected battery life, average daily load and peak load are properly calculated only when duration of the load constant.

D. Project 3: Stand alone power system which is set for usage of 6 months per year [t=6 months]

The only difference between this project and previous projects is PV array inclination angle (43°), and duration of the load (figure 8).

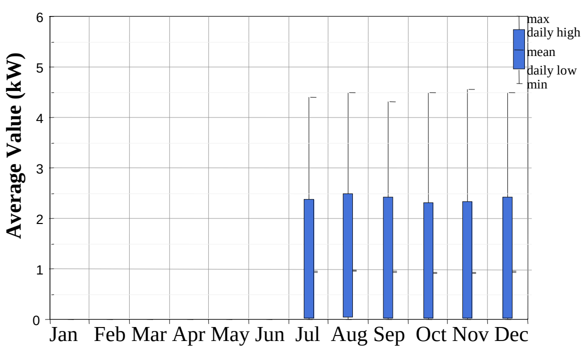

Fig. 8. Monthly average load profile [t=6 months]

The algorithm mistakes that are explained in project 2 are repeated again. However, those errors do not effect actual power system simulation and optimal system search; thus, the results are accurate, but badly presented.

HOMER has calculated that optimal system consists of: Isuzu 400TS 4.5kW diesel generator, 16 T-105 batteries, and Studer 1.6 kVA power converter. Investment expenses are 6266$, while overall costs of power system that are calculated for project lifetime of 20 years and interest rate of 6% are 24235$, or 2113$/year. Levelized cost of energy is 0.508 $/kWh.

Since optimal power system in this case does not include wind turbine or PV array, there is no point of displaying the systems electrical production. Due to the fact that there are no renewable energy resources, diesel generator will be in operating mode 1345 hours per year, or 7.5 hours per day when the object is used.

E. Project 4: Stand alone power system which is set for usage of 3 months per year [t=3 months]

This project refers to a typical summer home. PV array inclination is set at 20°. Figure 9 shows monthly average load profile.

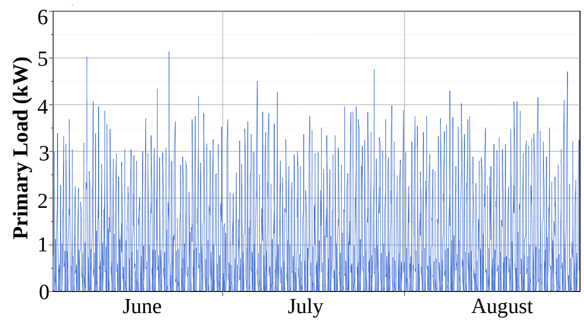

Fig. 9. Monthly average load profile [t=3 months]

HOMER has calculated that optimal system consists of: Isuzu 400TS 4.5kW diesel generator, 12 T-105 batteries, and Studer 1.6 kVA power converter. Investment expenses are 5816$, while overall costs of power system that are calculated for project lifetime of 20 years and interest rate of 6% are 15728$, or 1371$/year. Levelized cost of energy is 0.654 $/kWh. Despite of the small investment expenses, operating and maintenance costs and fuel costs are almost half of the overall yearly costs, that is 477$ per year.

F. Project 5: Stand alone power system which is set for usage of 1 month per year [t=1 months]

This time interval stands for any month during the summer. For this project, this month is July, since PV array production is expected to be at its maximum. PV inclination angle is set at 13°. Figure 10 shows monthly average load profile.

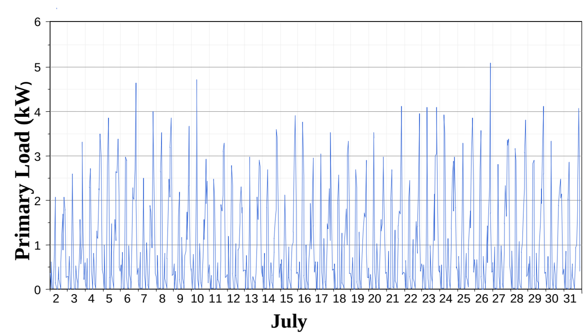

Fig. 10. Monthly average load profile [1=3 month]

HOMER is not designed for modelling the power system which is not constant. However, HOMER has calculated the optimal configuration, but it is hard to conclude if that is a correct calculation. Optimal configuration consists of 4.5kW diesel generator, 4 T-105 batteries and 1.6kVA power converter. Investment expenses are 4916$, while overall expenses are 9539$. Levelized cost of energy is 1.139$/kWh. Batteries in this configuration have almost no purpose. However, this power system most certainly can supply the users. Diesel generator will be in operating mode for 13.5 hours per day, which leads to a conclusion that generator will malfunction in a short period of time. Whether or not this power system can perform for a 30 days cannot be experimentally determined.

8. Summation of results

Table IX displays results of simulation with HOMER software.

TABLE IX
RESULTS OF SIMULATIONS CALCULATED BY HOMER

Duration of load (months)	Optimal power system	Investment expenses	Total NPC (20 y;6%)	COE
12	WT 1kW Isuzu gen. 16 T-105 St.1.6kVA	12 848$	40 503$	0.430 $/kWh
9	WT 1kW Isuzu gen. 16 T-105 St.1.6kVA	12 848$	33 824$	0.478 $/kWh
6	Isuzu gen. 16 T-105 St.1.6kVA	6 266$	24 235$	0.508 $/kWh
3	Isuzu gen. 12 T-105 St.1.6kVA	5 816$	15 782$	0.654 $/kWh
1	Isuzu gen. 4 T-105 St.1.6kVA	4 916$	9 539$	1.193 $/kWh

Since PV technology is too expensive and average wind speed on the objects location is relatively small, all the optimal power systems are based on diesel generator as a main source of electric energy.

9. Conclusion

Recent approaches when solving the problem of electrification requirements for isolated consumers rely on wind power and photovoltaic driven stand alone hybrid power systems. The research presented in this paper is a typical case-study of determining the appropriate energy power system for remote area object. Configuration of the power system depends on the electrical load and the location of the object. Based upon average (peak) load power system is dimensioned, while micro-location of the object determines availability of renewable resources. Since connecting the isolated object to conventional grid is too expensive, the only alternative is to design hybrid SAPS, which is designed with HOMER computer model. HOMER combines both economical and electrical aspects while searching for the optimal power system configuration. Since results of the power system simulation with HOMER software are highly dependable on the input data, a special attention was brought upon collecting the accurate technical sheets, while component prices are taken from the Croatian market. Although HOMER stands for reliable software, it has its limitations. Due to simplified mathematical algorithm, PV array output is not calculated accurately. When electrical load is not constant trough the year, HOMER will badly calculate and present peak load, autonomy of battery bank and expected battery life. Also, HOMER does not consider loses on the AC bus, and it optimises the operation of the fossil fuel generator. However, those limitations do not have any impact on the results of the simulation in this research, since power system has relatively small rated power.

When comparing optimal power system results, wind turbine is cost effective only if power system is used for 9 or 12 months. Cost of energy (COE) in those configurations is approximately 0.45 $/kWh, which leads to conclusion that such configurations would be cost effective even if they were grid-tried.

Due to the fluctuating nature of the renewable energy resources, and regardless of the input data accuracy, computer models can perform feasibility analysis, while the actual performance of hybrid power systems cannot be accurately predicted.

References

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