

TECHNO-ECONOMIC ANALYSIS OF STAND-ALONE PHOTOVOLTAIC/WIND/BATTERY/HYDROGEN SYSTEMS FOR VERY SMALL-SCALE APPLICATIONS

by

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The paper presents the results of a technical and economic analysis of three stand-alone hybrid power systems based on renewable energy sources which supply a specific group of low-power consumers. This particular case includes measuring sensors and obstacle lights on a meteorological mast for wind measurements requiring an uninterrupted power supply in cold climate conditions. Although these low-power (100 W) measuring sensors and obstacle lights use little energy, their energy consumption is not the same as the available solar energy obtained on a daily or seasonal basis. In the paper, complementarity of renewable energy sources was analysed, as well as one of short-term lead-acid battery-based storage and seasonal, hydrogen-based (electrolyser, H₂ tank, and fuel cells) storage. These relatively complex power systems were proposed earlier for high-power consumers only, while this study specifically highlights the role of the hydrogen system for supplying low-power consumers. The analysis employed a numerical simulation method using the HOMER software tool. The results of the analysis suggest that solar and wind-solar systems, which involve meteorological conditions as referred to in this paper, include a relatively large number of lead-acid batteries. Additionally, the analysis suggests that the use of hydrogen power systems for supplying low power-consumers is entirely justifiable, as it significantly reduces the number of batteries (two at minimum in this particular case). It was shown that the increase in costs induced by the hydrogen system is acceptable.

Key words: *photo-voltaic-wind-hydrogen hybrid system, proton exchange membrane fuel cell, stand-alone power system, meteorological mast, HOMER software, energy storage*

Introduction

Using renewable energy systems to supply power to remote areas has become commonplace worldwide. Connecting these areas to public distribution networks is often economically unjustifiable due to the large distances between consumers and the respective distribution network. Small- and medium-scale stand-alone applications include telecommunication stations, single homes, isolated military installations, medical institutions in developing countries, road lighting and signals, water supply systems, etc. These systems are based on photovoltaic (PV) modules and wind generators (WG) [1]. Despite being inexhaustible, affordable,

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and intermittent energy sources, solar and wind energy forms are highly unpredictable and generally governed by geographical position and local climate [1, 2]. Therefore, stand-alone systems are practically inconceivable without energy storing devices, *i. e.* batteries, used for short-term (up to several days) energy storage. For this purpose, lead acid batteries are mostly used. On the one hand, the advantages of the said batteries are numerous – high energy supply over a short period of time, energy efficiency (round trip efficiency up to 90%), and relatively low price. On the other hand, they include a number of drawbacks – complexity and a rather high maintenance cost, high carbon footprint, low capacity at winter temperatures (they are even prone to freezing), considerable size, and post-use inadequacy (unsafe and expensive to dispose of after use) [3]. Therefore, modern hybrid systems tend to reduce the required number of batteries as much as possible. However, the batteries are essential, as they mitigate transient processes in hybrid systems using fuel cells and renewable energy sources [4]. Using hydrogen as an energy form is an alternative method for storing electrical energy. The surplus of electricity generated can be converted into hydrogen using an electrolyser, whereas hydrogen can be converted into electrical energy using the fuel cell in cases when the energy obtained from renewable sources is insufficient to meet demand [4]. This mode of storing electrical energy is used only seasonally – hydrogen is produced when there is a surplus of renewable energy and is used in winter. However, the energy efficiency of such systems is low, as the system consists of electrolyser and the fuel cell. Vosen and Keller [4] shows that the most efficient hybrid combination is the one comprising a dual energy storage system – battery and hydrogen system (electrolyser, H₂ tank, and the fuel cell).

Results of analyses of the stand-alone PV/wind/hydrogen hybrid systems published in the literature so far primarily refer to supply systems for mobile base stations and residential buildings. In [5], the hybrid optimization model for electric renewable (HOMER) optimisation software [6] is used to analyze a small 356 W radio repeater station. Technical, economic, and environmental performance of fuel cell systems for telecom applications are analysed in [7]. These systems often serve as a *back-up* instead of a Diesel generator, the power of which ranges from 1.5 to 10 kW. Out of 900 fuel cell systems deployed worldwide, some 450 are located in Indonesia [7], whereas the majority of deployments are 2.5 kW systems at sites with an average electrical load of around 1 kW. Stand-alone PV/battery, PV/battery/Diesel generator, and PV/battery polymer electrolyte membrane (PEM) fuel cell systems have been analysed so as to meet the demand for mobile phone base stations of nearly constant power consumption ranging 400-500 W throughout the year [8]. Optimisation of the PV/battery/hydrogen supply system of a stand-alone remote-telecom application, with average and maximum consumption of 145 W and 197 W, respectively, is presented in [9]. The PV/hydrogen system was used to supply a meteorological station (weather station) characterised by a fluctuating pattern of power consumption which ranged from 780 W to 1500 W hourly [10]. As for the hybrid systems used for powering small residential buildings, the PV/wind/battery/hydrogen system was optimised to deliver a daily load of up to 160 W and 640 W by night [11]. Vosen and Keller [4] present two daily load diagrams whereby the load tends to change from 300 W by night to about 2,000 W by the day. Sizing optimisation of the stand-alone hybrid PV/wind/battery power supply system for small residential buildings, is shown in [12]. The hourly load profile shows 75 W consumer power at night, maximum power being 330 W.

Despite promising technical and economic characteristics of the hybrid PV/wind/battery/hydrogen stand-alone systems, little is known about their possible use in the field with power values below 100 W. In this paper, such applications are referred to as *very small applications*. This paper discusses some unique aspects relative to the available literature:

- Available literature is focused on analyses of systems with maximum power in excess of 300 W, while in our paper, only consumers with power consumption lower than 100 W were analysed.
- In this paper, we have analysed some specific, very low-power consumers who require a continuous power supply, which, in terms of stand-alone systems, significantly increases the need for storing electrical energy.
- In our study, there is a serious discrepancy between power consumption and possibilities of power production by the PV module. Power consuming items (such as safety lamps for air transport) require a power supply at night, whereas the PV module can generate power only during the day. The discrepancy is seasonal in character, *i. e.* electricity demand is higher in winter, given the insufficient sunlight over the season. Heating is essential because the measuring sensors of the analysed meteorological mast for wind measurements need to be heated so as to prevent freezing at low winter temperatures.

One of the low-power consumers is meteorological mast measurement equipment for measuring the wind velocity field, where continuous and long-term operation is a must [13]. The results of these measurements are used to assess the wind potential and plan both WG and entire wind parks, therefore the reliability of the measurement system is more important than the costs.

The main objective of this paper is to technically and economically analyse and compare the three hybrid power systems, *i. e.* PV/battery, PV/wind/battery, and PV/wind/battery/hydrogen systems, and to define the role of the hydrogen systems based on electrolysis and PEM fuel cells. The questions in need of answers are whether the hydrogen system can reduce the number and dimensions of the elements of the system, whether or not it is economically comparable to PV/battery and PV/wind/battery systems, and if not, how its equipment costs can be changed so as to make the hydrogen system comparable to the two systems.

It is for the first time that the analysis addresses very low-power consumers which, along with lead acid batteries, are likely to freeze due to low temperatures. Therefore the aim is to reduce the number of batteries using the hydrogen system.

This is a theoretical study aimed to optimise the hybrid power system for this particular situation, *i. e.* sensors of the meteorological mast for measuring wind speed and lead acid batteries subjected to very low winter temperatures are prone to freezing, electricity consumers are of very low power, and both daily and annual availability of energy is not in agreement with the consumers' needs.

Technical and economic analyses were performed using the National Renewable Energy Laboratory (NREL) HOMER software tool that facilitates optimum design of renewable hybrid systems. The HOMER simulates system operation during its entire lifetime, whereas required input data refer to capital expenses, operation and maintenance and replacement costs. Basic variables of the PV/wind/battery/hydrogen system that need to be determined are the number and size of the system elements in order to determine the exact configuration that meets technical restrictions and ensures optimal cost.

Description of the proposed systems

The first system for supplying power-consuming items of the meteorological mast for wind measurements and characterisation consists of non-predetermined total power of a solar module as well as an unidentified number of Trojan L16P lead-acid batteries. Overall sizes of the PV module to consider in the model defined by the HOMER software tool are 0.1 kW to 2 kW, with a step of 0.1 kW. The voltage of deep discharge lead-acid batteries used

in this analysis was rated at $U = 6$ V. Two batteries are serially connected in a single string in order to obtain the required voltage to operate the power-consuming items ($U = 12$ V).

A continuous power supply is indispensable, which implies that deliberate interruption of the electricity supply due to insufficient power from renewable sources is not allowed [13]. Another restriction relative to the determination of optimal system refers to costs. Of all equally important technical solutions that satisfy technical requirements, the one with the lowest cost of the produced kWh of energy is considered optimal [14].

Another analysed system consists of the PV module of total power of 0.1 kW to 2 kW (with a step of 0.1 kW), ten Trojan L16P batteries at maximum, and a single, low-power WG (Hummer 400) mounted at a height of 40 m. The configuration of the PV/wind/battery system is shown in fig. 1, whereas the PV/battery/system configuration is similar to the one in fig. 1, but without the WG.

Figure 2 shows a graph of the third analysed system comprising the PV/wind/battery system elements involving the hydrogen system – the electrolyser, a hydrogen tank, and the Ballard Fgen-1020ACS fuel cell.

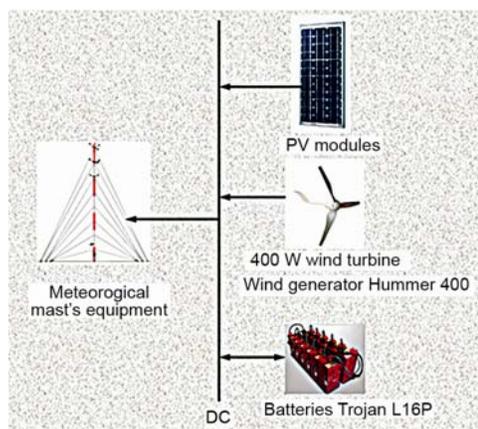


Figure 1. Schematic diagram PV/wind/battery power system

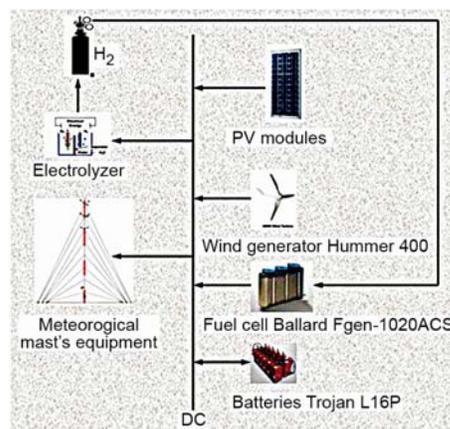


Figure 2. Schematic diagram of the PV/wind/battery/hydrogen power system

The operational reserve is 10% of the primary load in the current time step, along with 25% electricity each from the PV module and WG.

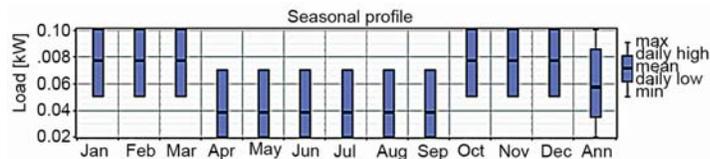
Characteristics of the system components

Power consumers

In this paper, we analysed supplying power to a meteorological mast on the Kopaonik mountain, Serbia, characterised by very low winter temperatures. The average annual temperature on Kopaonik in a typical meteorological year (used in the simulation model) is only 3.7 °C, while winter temperatures tend to fall as low as -15 °C. The principal power consumers in winter are anemometer heaters and a wind vane (manufacturer *Thies*) consuming up to 50 W, as well as red obstacle lights of equal power. For this reason, in the analysis, the typical assumed daily power consumed by the items of the meteorological mast during cold winter months (October-March) amounted daily to 50 W and 100 W by night. In months

with higher daily temperatures (late April-September), the consumed power amounts to 20 W and 70 W by day and night, respectively. In winter, street lights are on at 6 p. m. and off at 7 a. m., while in summer they are on at 8 p. m. and off at 5 a. m. The average annual power consumption amounts to 1.39 kWh per day, while the total annual power consumption is $365 \cdot 1.39 \text{ kWh} = 507 \text{ kWh}$. All consumers are DC in type therefore the power analysis does not include inverters. The graph in fig. 3 shows the load throughout the year.

Figure 3. Load diagram throughout the year



The PV module, battery, and WG

Ambient temperature during the typical meteorological year on Kopaonik was used to calculate the output power of the PV array. The input data for the simulation model applied involved the next parameters: 20 years lifetime of the module, 90% reduction in power production, 60° module slope, 0° azimuth, 20% ground reflectance, -0.5% temperature coefficient of power, and 47 °C nominal operating cell power. The assumed efficiency at standard test conditions was 19%.

In this analysis, we used the Trojan L16P deep discharge lead-acid batteries of 360 Ah capacity, 85% overall efficiency, and 30% minimum state of charge (SOC). Lifetime of the batteries is 10 years, and lifetime throughput is 1,075 kWh [6].

Freezing is the first problem relative to lead-acid batteries, as they are intended to operate at very low temperatures. According to the manufacturer's instructions, fully charged batteries cannot freeze owing to the presence of acid in the battery which prevents freezing at temperatures down to $-69\text{ }^{\circ}\text{C}$. However, if a battery is 40% discharged, freezing occurs at $-10\text{ }^{\circ}\text{C}$, which inevitably leads to battery destruction. Therefore, the manufacturer of batteries intended for operation at low winter temperatures ($0\text{ }^{\circ}\text{C}$ or below) recommends a 60% minimum SOC, which ensures a sufficient amount of acid in the battery solution. This highly unfavorable technical characteristic of the batteries provides space for the promotion of hydrogen as a storage medium. In this analysis, the lowest SOC is 60%. Another unfavorable feature of lead batteries, which cannot be simulated by the HOMER software tool, is the decrease in power at low temperatures. The curve of the available capacity of lead-acid batteries as a function of ambient temperature (provided at the producer's official website), shows that this type of battery preserves about 73% SOC at $0\text{ }^{\circ}\text{C}$, whereas at $-10\text{ }^{\circ}\text{C}$ it provides only about 60% of the SOC that a battery has at $27\text{ }^{\circ}\text{C}$. The subsequent power correction can be involved only if a battery of higher capacity than computed is introduced.

The output power curve (serving as a function of wind speed of the Hummer 400 WG) available at the manufacturer's website was included in the simulation model. The correlation between the wind speed and height was taken into account using the law degree coefficient being $\alpha = 0.18$ [6]. The WG mass is 5.5 kg.

Fuel cell, hydrogen tank, and electrolyser

For the analysis of power supply to a low-power consuming meteorological mast, it is possible to use a commercially available Ballard FCgen-1020ACS fuel cell. It is now used

for backup supply in base telecommunication stations. Its durability is up to 4000 hours, while its power ranges from 0.45 kW to 3.6 kW. It consists of 10-80 cells (45 W per cell). For our analysis, fuel cells of power 450-810 W, with a step of 90 W, were found to be suitable. As for the fuel (hydrogen), the lowest heating value was 120 MJ/kg and density 0.09 kg/m³. The fuel consumption did not exceed 0.06 kg/hkW.

The HOMER was used to identify hydrogen tank sizes as it allows determination of the optimal system. Sizes examined were 0.2-1 kg, with a step of 0.2 kg. Initial tank level at the beginning of the simulation was 10%.

In our case study, the efficiency of the electrolyser, energy content (based on a higher heating value) of the hydrogen produced, divided by the amount of electricity consumed was 76%. The power values of the electrolyser to be considered were 0.4 kW, 0.6 kW, 0.8 kW, and 1 kW.

Life-cycling costs (LCC) economic method

The parameters needed for the economic analysis by the method of LCC are presented in tab. 1. These were defined based on the analysis of references [4, 5, 7, 8, 11, 12, 15, 16] as well as market prices.

Table 1. Economic parameters of system elements

		Capital costs [\$]	Replacement [\$]	O&M costs	Lifetime
PV	1 kW	2000	2000	10 \$ per year	20 years
Battery L16P	1 piece	320	320	10 \$ per year	10 years
WG Hummer 4	1 piece	1000	1000	20 \$ per year	20 years
Fuel cell	1 kW	3000	800	0.020 \$/(hkW)	4000 hours
Electrolyser	1 kW	2000	1800	30 \$ per year	20 years
H ₂ tank	1 kg	500	500	10 \$ per year	20 years

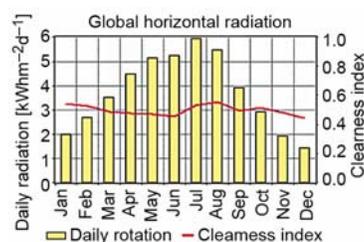


Figure 4. Daily global horizontal solar radiation on a monthly basis (columns) and clearness index (the line) at Kopaonik

Other economic parameters of the project are: annual real interest rate of 6%, duration: 20 years, and system fixed capital costs: \$500.

Results of numerical simulations

Solar and wind potential

The dynamic analysis of electricity generation by renewable sources was derived by using meteorological data for *typical meteorological year 2* [17]. Global solar radiation (GSR) recorded in a single year at Kopaonik was 1,366 kWh/m² per year, while GSR on a monthly basis, and clearness index, are shown in fig. 4. The mean annual wind speed at Kopaonik is 3.92 m/s. Figure 5

shows the mean monthly wind speed at Kopaonik used to calculate electricity generation using the Hummer 400 WG.

Techno-economic analysis of the solar system

The optimization procedure is:

- (1) the HOMER ranks the variants of power systems with different elements forces towards the lowest cost of energy (COE) and net present cost (NPC),
- (2) technical constraints of power decreasing lead batteries at low temperatures, which increases battery power by 50%, is being considered, and
- (3) batteries' SOC in the course of the year must not go below 60%, as this leads to freezing. It is the HOMER software tool that ensures this condition.

Finally, this method provides the cheapest solution that meets all the technical restrictions.

The HOMER works out initial solutions that meet power demand without including special technical restrictions, ranks them according to the total NPC and COE. Figure 6 shows the sequence of the first ten variant solutions, whereby the system with a 0.9 kW PV module and four Trojan L16P batteries is considered optimal. However, when technical restrictions are considered, *i. e.* the reduced battery power at low temperatures, the battery used should be of about 50% higher capacity, which implies that the system contains six instead of four batteries. The requirement that the battery capacity in the last hour of a year should be identical or slightly higher than the one in the first hour of an ensuing year suggests that the systems should not involve 0.8 kW and 0.9 kW PV modules. The simulations done suggest the PV module power should not be lower than 1 kW, *i. e.* the battery SOC at the end of a year is 65%, and 60% at the beginning of the ensuing year. Therefore, the first technically correct combination contains a 1 kW PV module and six Trojan L16P batteries. The NPC and COE of the system equal \$ 6,295 and \$ 1.082/kWh, respectively.

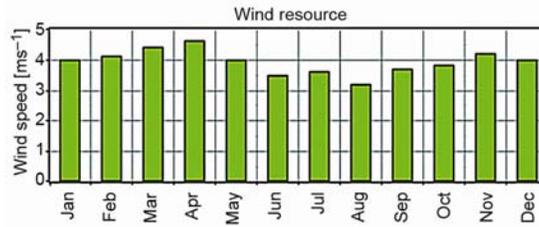


Figure 5. Mean monthly wind speed at Kopaonik

	PV (kW)	L16P	Initial capital	Operating cost [\$ per year]	Total NPC	COE [\$ per kWh]	Ren. frac.	Batt. lf. (year)
	0.9	4	\$3.580	111	\$4.857	0.835	1.00	10.0
	1.0	4	\$3.780	112	\$5.068	0.871	1.00	10.0
	1.1	4	\$3.980	113	\$5.280	0.907	1.00	10.0
	1.2	4	\$4.180	114	\$5.491	0.944	1.00	10.0
	1.3	4	\$4.380	115	\$5.703	0.980	1.00	10.0
	0.8	6	\$4.020	161	\$5.872	1.009	1.00	10.0
	1.4	4	\$4.580	116	\$5.914	1.016	1.00	10.0
	0.9	6	\$4.220	162	\$6.084	1.045	1.00	10.0
	1.5	4	\$4.780	117	\$6.126	1.053	1.00	10.0
	1.0	6	\$4.420	163	\$6.295	1.082	1.00	10.0

Figure 6. Overall optimisation results table showing system configurations sorted by NPC

Figure 7 shows the dependence of electricity generated by the PV system in January, November, and December, as well as total annual generation, on the module's slope. The results are in agreement with those in [1, 8] which infer that the greater the module's slope the higher the electricity generation in winter months and the lower overall annual electricity generation. In stand-alone systems, electricity generation is of greater importance in winter months hence the analysis performed in this paper included a 60° module slope. Additionally,

fig. 7 shows that the entire PV system is determined by December's conditions – the month with the lowest electricity generation due to minimum solar energy.

Electricity generation, energy consumption, and excess energy produced in each month are shown in fig. 8. Additionally, the figure shows that electricity generation drops rapidly in November and December, while substantial energy excess occurs particularly over the summer months. Total annual electricity generation, electricity consumption, and excess energy amount to 1,409 kWh per year, 507 kWh per year, and 835 kWh per year, respectively, accounting for 59.3% of total electricity generation. The electricity generated is 2.78 times higher than needed, whereas the levelled cost of the PV module is \$ 184/1,409 kWh = 0.131 \$/kWh, where \$ 184 stands for the annualised cost of the PV module. In other words, PV module-generated electricity is cheap, but also unusable for the most part. When the annualised cost of the entire system (\$ 549) is considered and divided by the consumer energy, the result is \$ 549/507 kWh = 1.082 \$/kWh, which is largely due to the cost of the six L16P batteries.

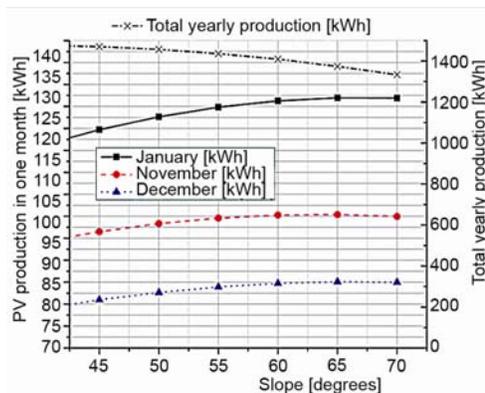


Figure 7. Electricity generation in January, November, and December, and total annual generation vs. PV module's slope

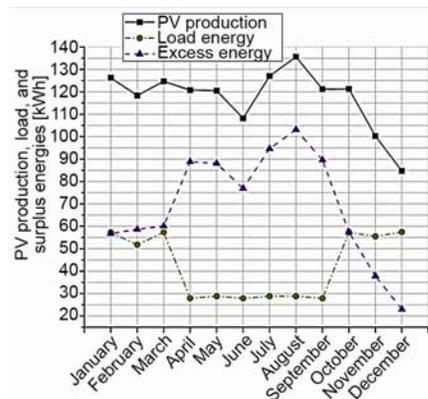


Figure 8. Monthly PV energy generation, load energy, and excess energy

It is necessary to check the technical restriction which requires that the battery SOC be above 60% to prevent freezing. The simulations confirmed the rather high SOC over the course of a year (above 80%), which is very convenient for battery life as it prevents freezing.

Techno-economic analysis of wind-solar system

Figure 9 shows the first twelve variant solutions to the wind-solar system. When technical restrictions are considered, as in the solar system, the option that could meet technical criteria is shown in the eleventh row (fig. 9). The variant comprises a PV module of 0.4 kW total output, a single Hummer 400 wind turbine, and six Trojan L16P batteries. The initial SOC should be in excess of 80%. The results given in fig. 9 apply to 80% SOC, whereby the batteries' capacity and the PV module power are correlated in such a way that the SOC of the batteries is maintained above 60% throughout the year.

Figure 9 shows that the NPC system and COE are \$ 6,256 and \$ 1.075/kWh, respectively, which is very similar to the values of the parameters in the solar system. The total

	PV (kW)	H400	L16P	Initial capital	Operating cost [\$ per year]	Total NPC	COE [\$ per kWh]	Ren. frac.
	0.4	1	4	\$3.580	126	\$5.029	0.864	1.00
	0.5	1	4	\$3.780	127	\$5.240	0.900	1.00
	0.6	1	4	\$3.980	128	\$5.452	0.937	1.00
	0.7	1	4	\$4.180	129	\$5.663	0.973	1.00
	1.3	1	2	\$4.740	84	\$5.705	0.981	1.00
	0.8	1	4	\$4.380	130	\$5.875	1.009	1.00
	1.4	1	2	\$4.940	85	\$5.917	1.017	1.00
	0.3	1	6	\$4.020	176	\$6.044	1.039	1.00
	0.9	1	4	\$4.580	131	\$6.086	1.046	1.00
	1.5	1	2	\$5.140	86	\$6.128	1.053	1.00
	0.4	1	6	\$4.220	177	\$6.256	1.075	1.00
	1.0	1	4	\$4.780	132	\$6.298	1.082	1.00

Figure 9. The sequence of first twelve variants of the wind-solar system by economic parameters

amount of electricity generated was 1,434 kWh per year, the PV module and Hummer WG 400 generating 564 kWh per year, and 870 kWh per year, respectively. The excess energy was 895 kWh per year (62.4%).

The electricity generated by the system was 2.83 times higher than the actual load (507 kWh). The levelled cost of the PV system was $\$ 74/564 \text{ kWh} = \$ 0.131 \text{ \$/kWh}$, where $\$ 74$ stands for the annualised costs of the PV system, and $\$ 564$ is the electricity generated by the PV module. The capacity factor of the PV module was 16.1%, which equals the percentage of the installed capacity of the PV module used in the course of the year. As for the WG system, the annualised COE was $\$ 107/870 \text{ kWh} = \$ 0.123/\text{kWh}$, which implies that, in terms of costs and technical parameters, the electricity generated by the WG was slightly lower than the one generated by the PV module. The capacity factor was 24.8%, which suggests that the installed capacity of the WG was more favourably utilized than the capacity of the PV module. With respect to the technical and economic parameters, it can be concluded that both PV/battery and PV/wind/battery systems are basically similar for the conditions of this study. In terms of electricity, the WG was equal to 0.6 kW of the PV module. Figure 10 shows the electricity generated by the PV module and WG on a monthly basis, as well as the excess energy. Figure 11 shows the change in SOC from January 5-11 and generated PV power. This SOC is at its lowest value in the year.

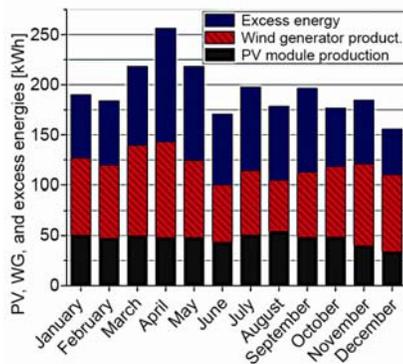


Figure 10. The PV module, WG, and excess energy for each month

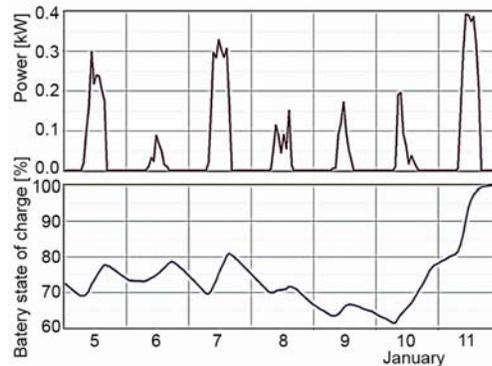


Figure 11. The SOC of batteries, and PV power from January 5-11

Figure 10 shows substantially more uniform electricity generation by the PV module on a monthly basis, and a decrease only in November and December. Power generation by WG is proportional to the wind speed and number of days in a month (fig. 4). Excess energy, recorded in all the months, was highest in summer. Figure 11 shows that although being at its lowest during the whole year, SOC is above 60% in January, which prevents the freezing of batteries. Charging and discharging of the battery is in agreement with PV power generated, but it also depends on the generation by WG.

Techno-economic analysis of the wind-solar-hydrogen system

In the PV/wind/battery/hydrogen power system, hours of operation of the fuel cell have a major impact on technical and economic parameters. The system depends greatly on the control algorithm. If electricity obtained from renewable energy sources (PV and WG) is insufficient, HOMER actuates a battery or the fuel cell, choosing the system that provides cheaper power. For this reason, a limiting power of the consumer is set to switch between the battery and the fuel cell depending on the power required. This limiting power markedly affects the number of operating hours of the fuel cell, which determines the frequency of fuel cell stack replacement, and the cost of the entire system. In this paper, the regulator sets the limiting power at 75 W, which implies that the fuel cell will supply consumers with electricity only at night during winter months, as the power required over the period amounts to 100 W. In this case, the fuel cell is operational 772 hours annually, within the cycle charging regime [6]. The FC stack has a 5.18 years lifespan, which implies replacements in the 6th, 11th, and 16th year.

The total annual electricity generation is 1,521 kWh, *i. e.* the PV array, WG, and FC generate 564 kWh (37%), 870 kWh (57%), and 88 kWh (6%), respectively. The load and electrolyser consume 507 kWh (63%) and 294 kWh (37%), respectively, the total consumption being 801 kWh, whereas the excess energy is 703 kWh (46.2% of total production). The lowest-cost system is comprised of a 0.4 kW PV module, a Hummer WG 400, 0.45 kW fuel cell, two Trojan L16P batteries, 0.4 kW electrolyser, and 0.6 kg H₂ tank. The simulations confirmed that two batteries are sufficient even in winter when there is no danger of freezing, given that the batteries' SOC is higher than 90%. Figure 12 presents the electricity generation by the PV module, WG, and fuel cell on a monthly basis. Figure 13 presents the electricity generation of the electrolyser on a monthly basis, and excess energy.

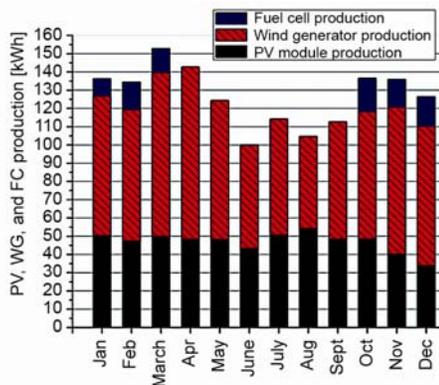


Figure 12. Electricity generation by the PV module, WG and fuel cell on a monthly basis

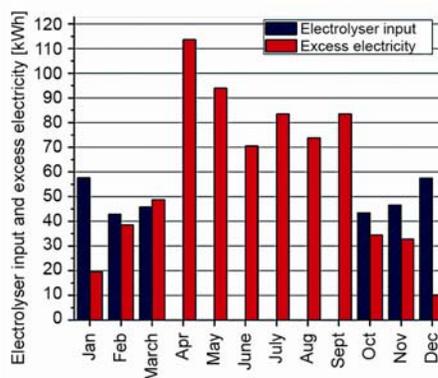


Figure 13. Monthly input electricity of the electrolyser and excess energy

Figure 12 shows that electricity generated by the PV module and WG is identical to that of the PV/wind/battery system comprising identical power elements. The figure also shows that the fuel cell generates electricity when it is most needed – only in winter, this is governed by the control algorithm. It is interesting to note that the electrolyser produces hydrogen (5.66 kg) only in winter months, whereas during summer, the H₂ tanks are full. Therefore, fig. 13 shows low energy excess in winter months, whereas during summer the energy excess is high because the electrolyser cannot use it up. In the course of a year, the fuel cell uses up some 5.27 kg of hydrogen to generate 88 kWh of electricity, which, in terms of efficiency of the hydrogen system, shows that 88 kWh/294 kWh = 30%, where 294 kWh stands for the surplus of renewable energy used by the electrolyser.

Figure 14 shows the level of H₂ in the tank on a monthly basis.

Figure 14. Level of H₂ in the tank on a monthly basis

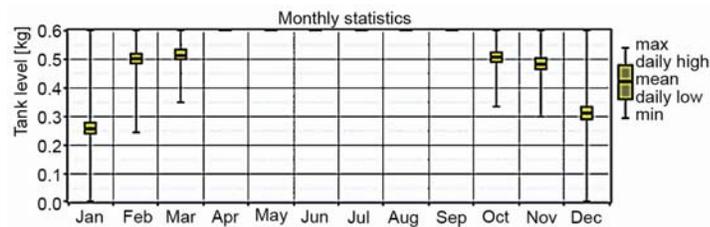


Figure 14 shows that the hydrogen tank is being filled over the first three months of winter, and emptied over the last three months of a year. The tank is full during summer, since, as set by the regulator, the electricity is generated over this period comes from renewable sources, not from the fuel cell. Accordingly, the electrolyser is not in operation during the summer (fig. 13). Some other control algorithm would lead to a different result and would have different economic outcomes as well.

Table 2 presents the economic parameters of the system.

Table 2. Net present and annualised costs of the PV/WG/battery/hydrogen system

Component	Net present costs [\$]				Annualised costs [\$]
	Capital [\$]	Replacement [\$]	O&M [\$]	Total [\$]	Total [\$]
PV	800	0	46	846	74
Hummer 400	1000	0	229	1229	107
Fuel cell	1350	1301	80	2731	238
Trojan L16P	640	357	229	1227	107
Electrolyser	800	0	138	938	82
H ₂ tank	300	0	69	369	32
Other	500	0	0	500	44
System	5390	1658	791	7840	684

In tab. 2, the NPC system is \$ 7,840, and the annualised value amounts to \$ 684. The price of the kWh generated is \$ 684/507 kWh = 1.35 \$/kWh. The cost of the PV/wind/battery/hydrogen system is about 25% higher than the cost of the PV/battery and PV/wind/battery systems where the number of batteries is drastically reduced, which is of great importance for system reliability. The largest share of costs, in terms of prices presented in this paper, is in-

curred by the fuel cell, given that the fuel cell stack needs to be replaced thrice. The fuel cell costs account for about 35% of total costs, and they contribute most to the high levelled cost of the energy hydrogen system which amounts to $(\$ 238 + \$ 82 + \$ 32)/88 \text{ kWh} = 4 \text{ \$/kWh}$. Using the annualised costs (tab. 2), we can calculate that the cost of the hydrogen system (electrolyser, H₂ tank, fuel cell system, and three fuel cell packs) should account for 60% of the costs presented in this paper, so as to equalise the prices of the PV/wind/battery/hydrogen and PV/wind/battery systems.

Conclusions

The paper presents the results of technical and economic analysis of three different stand-alone hybrid power systems based on renewable energy sources. In the paper, we analysed power-consuming items of the meteorological mast for wind measurements, which presuppose operation without interruption at very low temperatures and very low power (only 100 W), primarily with daily or seasonal discrepancy between consumption and electricity generation from renewable sources.

Simulations performed using the HOMER software showed that, regardless of the low energy consumption, the PV power system should include a PV module of relatively high power (1 kW). Additionally, due to the possible freezing of the batteries at low temperatures and substantial reduction in their capacity, accordingly the number of batteries required for the operation tends to become relatively large, which adversely affects system reliability. Also, batteries need to be replaced once in their life cycle, which increases the number of batteries required. When the hybrid system involves a low-power WG, in terms of energy, it replaces 0.6 kW power of the PV module, but the number of batteries remains the same as in the PV/battery system. As for the costs of the PV/battery system, they are approximate to the ones of the PV/wind/battery system, given the conditions presented in this paper. The hybrid PV/wind/battery/hydrogen system has significant technical advantages over the solar and solar-wind systems, as they require a minimum of two batteries necessary to mitigate the transient processes in the system. The hydrogen system uses 294 kWh of energy that would otherwise be unused, but owing to the relatively low efficiency of the hydrogen system, approximately 30% of this energy can be obtained by using the fuel cell. The costs of the PV/wind/battery/hydrogen system are about 25% higher than the costs of the other two systems. However, in this type of power consumer (meteorological mast), it is the reliability of the system that is of greater importance than the economic aspect, which is why the use of the hydrogen hybrid system is absolutely justifiable. Economic analysis shows that the high cost of the hydrogen system is the result of frequent replacements of the fuel cell stacks and a short period of operation before replacement. Lowering costs of the hydrogen system down to 60%, as presented in this paper, renders the NPC and COE equal to values of the PV and PV-wind systems. Our paper shows that a combined application of the hydrogen system and renewable sources is justifiable nowadays, even when used with extremely low-power consumers.

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