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Renewable Energy Supply for Remote Station Located in Antarctica – Simulations Based on Real Measured Data

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Abstract. Photovoltaic (PV) installation with energy control and energy storage systems (ESS) are becoming more popular to be used inside buildings. They can assure stable energy supply as well as energy savings. A proper system design is necessary to ensure optimal energy supply and cost savings. The present work describes current energy demands and sources of Johann Gregor Mendel Station operated by Masaryk University in Brno and suggests a new generation sources based on PV. The energy for the station is being provided by oil generators, PV system and wind turbines. Since the beginning of 2018 a new system for measuring detailed energy demand, irradiation and wind speed has been installed in that location. Thus, based on the in-site collected data, possible system sizes are suggested in order to make the station fully operating by means of renewable energy sources.

1. Introduction

Scientific stations in the Antarctica provide intensive research covering various fields of biology and earth sciences. It is of high importance to assure sufficient conditions of life for researchers with a minimal impact on the nature. Even if the potential of harvested power from renewable energy sources (RES) is important in that region. However, most of stations built in the Antarctica by different states are still generating energy by burning fossil fuels (oil) in order to fulfil their needs.

Antarctica has a large PV potential because of its high irradiation and low temperature [1]. The early attempts to introduce PV technology to Antarctic stations started in the 80-ies of the last century [2]. There is an intensive effort to build the new stations with respect to the environment. A holistic approach can be observed by designing the Belgian Princess Elisabeth Station combining new techniques of waste disposal, water treatment, energy generation utilizing RES and smart grid for effective energy supply [3].

In order to make the scientific stations in the Antarctica fully based on RES, a sophisticated design and sizing of the energy sources is required. Several research available in the literature presented different procedures for sizing standalone hybrid systems composed of wind turbine, PV system, battery energy storage and other RES [4], [5] and [6]. The sizing of the hybrid system mainly reposes on its function and the quantity of energy needed to satisfy the load demands.

An effective sizing is mainly based on the exact weather data of the location of the hybrid system. The present paper proposes a simple sizing methodology based on in-site measured data of solar irradiance and module temperature as well as the energy consumption of the station.

The remainder of the paper is organized as follow; the description of the Czech Antarctica research station as well as the installed system is given in section 2. Section 3 shows the methodology followed for sizing the hybrid system. Results and discussions are provided in section 4. Finally, conclusions are summarized in section 5.

2. Johann Gregor Mendel Czech station

Czech Antarctic Station of J.G. Mendel was completed in 2006. It consists of a main building based on construction using oriented strength board and polystyrene thermal isolation and a set of common marine containers used for storage and various technology purposes (water treatment, electrical energy unit…)[7]. Figure 1 depicts a simplified schematic of the Czech Antarctic station. The station is seasonal operated –the scientists together with technicians stay there usually in January and February. In this period (southern summer) the weather conditions enable intensive research activities on the base as well as taking one or more day expedition camps. From the very beginning, the energy system of the station was designed to utilize both fossil fuel and RES [7]. In the first stage several small scale wind generators were used together with Ni-Cd backup battery field. Unfortunately the hard climate conditions caused lot of damage to the wind generators, so at the present time, none of them is functioning. In 2015 a high power photovoltaic system was added to the energy concept with PV fields facing east, north and west to utilize the solar energy throughout the day.

There have been several problems with the PV system as well, the most serious was the damage of many modules during the first season –probably caused by water freezing behind the modules. Despite all the difficulties, the technical team together with partners (among them CTU UCEEB) try the most to further develop and improve the technical system of the station based on experiences and state-of-the-art components.
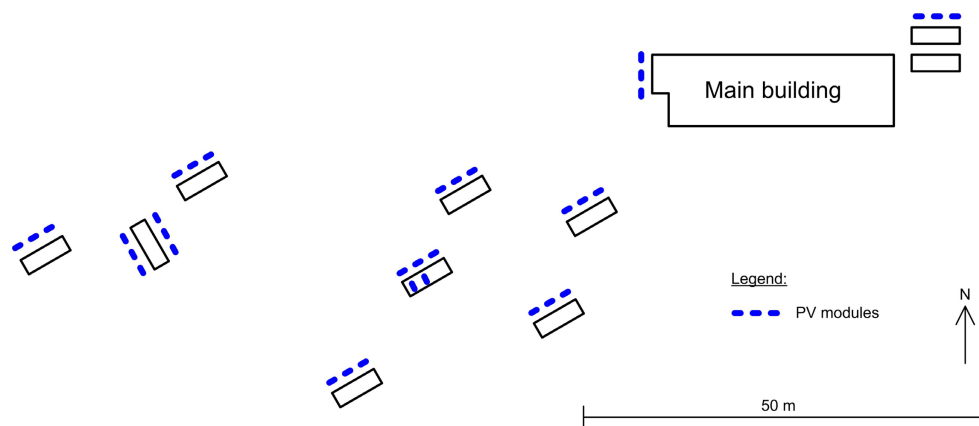

Figure 1. Layout of the technical containers and main building indicating the PV modules fields.

Simplified schematic of the electrical interconnection is shown in figure 2. The balance of energy is provided by three single-phase hybrid inverter units operating in master-slave concept forming a three-phase system. Diesel generator is being switched manually by a technician if the control system indicated lack of energy provided by RES and battery storage or a high demand on energy is expected (cooking, heating…). The PV modules as well as wind generators are being distributed and fixed to the skeleton of the containers as shown in figure 3. Automated start/stop control of the diesel generator is not implemented due to several technical and safety reasons. PV modules with overall power 21 kW$_p$ are facing east, north and west; this concept contributed to fit the energy generation to the load. The wind generator is based on small 1.5 kW wind turbines with horizontal axis. There are two diesel generators, each 22 kW peak power, one is being operated and the second is rather used as backup. The battery unit consists of serial and parallel interconnected cells based on Ni-Cd technology that is known for its reliability, robustness (resistant to overcharging or deep discharge) and possible operation at low temperature.
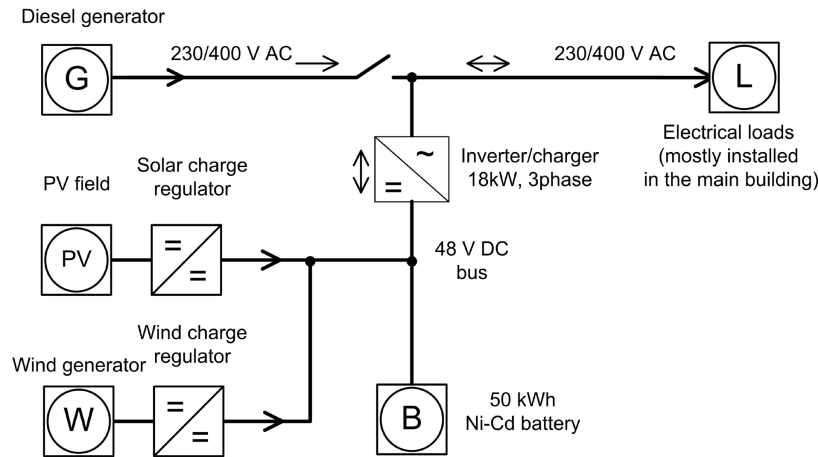
Figure 2. Simplified scheme of the electrical interconnection on the base.

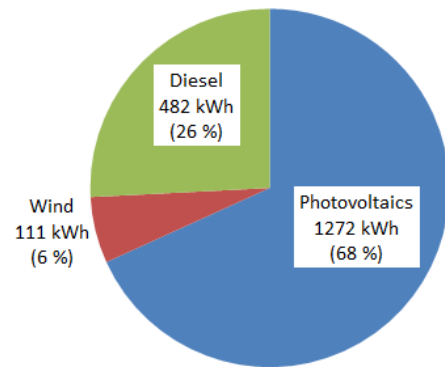**Figure 3.** View on the technical containers, PV modules and wind generators

Figure 4. Energy sources that covered the station loads in 2015

Since the PV system was installed, the RES covered a substantial part of the energy need for the station as it can be seen in figure 4. There is a high potential of wind energy generation and PV that can possibly in the future cover most of the energy provided now from diesel generator.

3. Methodology for sizing the system

This paper focuses on the simulation of energy sources to supply the above described station. It is based on previous experience and in-site measurement of solar irradiance (1 minute resolution), temperature (1 minute resolution) and the consumption (5 minute resolution). It seems to be possible to provide all the necessary energy from solar photovoltaic and cover the peaks and periods with low solar resources by batteries. To achieve this target, a sophisticated design has been proposed in the present work.

Real measured data of solar irradiance and temperature are obtained from calibrated silicon cells for the following orientations: north-east (-60°), north-west (30°) and south-west (60°) with the same inclination of 75°.

The expedition period to the Czech Antarctica station approximately lasts one month and half, thus the sizing of systems will be based on monitored data corresponding to that period.

The PV system output-power was modelled using a simplified mathematical model taking in consideration the available area, module efficiency, the monitored in-plane solar irradiance and module temperature [5]. The PV model is described by the following equations:

$$P_{PV} = G_{POA} N A_m \eta_g \qquad (1)$$

$$\eta_g = \eta_m \eta_{inv} \left[1 - \delta_p (T_m - T_{ref}) \right] \qquad (2)$$

where G_{POA} is the in-plane monitored irradiance. The number and the area of the PV modules are represented by N and A_m respectively. η_m is the module efficiency, η_{inv} is the inverter efficiency and δ_p is the power temperature coefficient of the PV panel. The module temperature (T_m) is supposed to be the same as the silicon sensor temperature and the T_{ref} is the reference temperature at standard test conditions equal to 25 ℃.

The methodology developed in this work for sizing the system is mainly based on the observation of the energy balance between generation sources and consumption evaluated along the monitored period using 5 minutes time step data. The procedure is mainly based on the equation below:

$$Balance = Energy_{Gen} - Energy_{Con} \qquad (3)$$

where, $Energy_{Gen}$ is the generated energy from RES in kWh, and $Energy_{Con}$ is the amount of energy consumed by the load in kWh.

The value of the *Balance* will define if the system is generating enough energy to feed the load or there is a need for a battery storage system. The integral of the *Balance* values obtained for a certain period of time will define how much energy is needed, this amount of energy is represented by the negative values of *Balance*. On the other hand, the excess of energy will be represented by the positive values of *Balance*.

4. Results and discussions

In order to make our system described previously in section 2 fully based on PV energy, the diesel generators as well as the broken wind turbine were omitted and the current PV system with the battery capacity must be resized.

Matlab® environment was used in the present work for the implementation of PV model and the developed methodology allowing the estimation of the battery size.

The current size of the already installed PV system has been evaluated by the proposed methodology in order to see how much battery storage is needed to be fully autonomous. In simulations, the PV outputs were estimated based on the described PV model using the monitored solar irradiance (G_{POA}) and module temperature (T_m). The module efficiency (η_m) has been considered 14 %, inverter efficiency (η_{inv}) is 95 %. Module area (A_m) is 1.6 m^2 and 81 of total number of PV panels ($N=81$) is considered. Different sizes were considered according to their orientations; 12.6 kW$_p$ is installed facing the north-west, 1.8 kW$_p$ facing the north-east and 1.8 kW$_p$ facing the south-west. The obtained result representing the actual system is shown is figure 5.

From figure 5 it can be seen that the balance values are negative, which means that there is a need of this amount of negative values in order to satisfy the consumption. For example, for the first 20 days, a battery size of 100 kWh is enough to satisfy the load. However, as the PV production is mainly affected by weather conditions, and the accumulation of bad weather conditions leads to the increased negative values of *Balance*. Thus, there is a need of a battery capacity of 550 kWh in order to be fully autonomous for the selected period of time using the same installed capacity of PV.

The sizing of the new PV system is based on the orientation of the PV panels and the analysis of the load profiles. The monitored data related to in-plane irradiances for north-east (NE), north-west (NW) and south-west (SW) are shown in figure 6. The monitored daily profile of the consumption along the analysed period is shown in figure 7.

From figure 6, it can be seen that the PV power profile can be made broader by putting PV panels in different orientations. By using the three different orientations, the load consumption can be covered from 6 h to 21 h, which means that more than 62 % of the daily consumption could be covered from PV in sunny days. Moreover, figure 7 shows that the load profiles match with the PV generation profiles, where, the consumption is higher during the day rather than night. The consumption during night-time is less than 4 kW, however during the daytime, the maximum peak consumption is around 18 kW. The daily energy consumption varies between maximum and minimum values corresponding to 95 kWh/day and 45 kWh/day respectively.
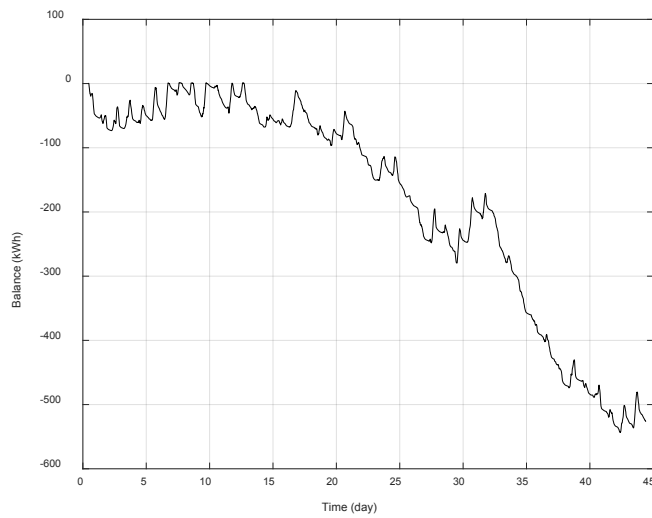
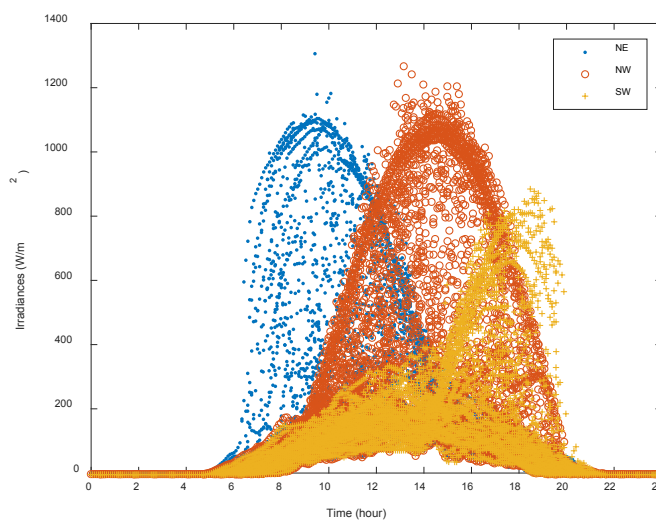**Figure 5.** Simulation of the real case considering the actual size of the PV system.

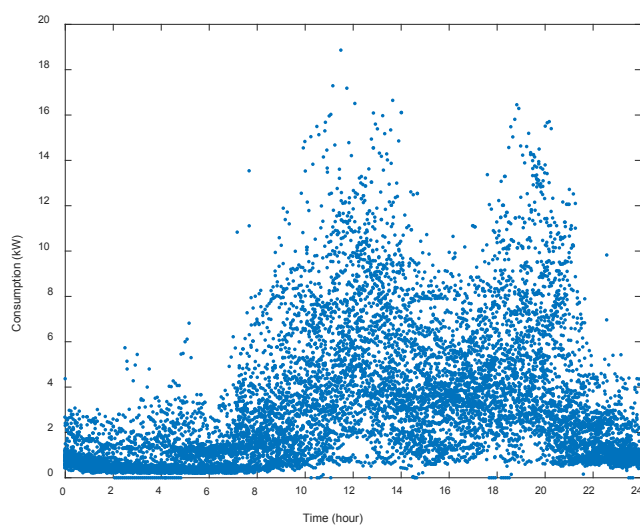**Figure 6.** Monitored irradiances for different orientations.

Figure 7. Monitored daily consumption profiles.

State-of-the-art PV module efficiency and technology were taken into account for designing the new PV system. The module efficiency (η_m) is set to 20 % according to nowadays mono-crystalline PV panel with the standard area of 1.6 m^2. The other parameters were kept the same except the number of PV panels (N) which will be changed according to the estimated PV size. Based on the monitored data of consumption, different configurations and orientations were simulated in order to meet the load. The optimization of the PV system size is carried out by considering the excess of energy and the battery capacity.

Table 1 summarizes the simulated scenarios considering different PV systems configurations, orientations, sizes and module efficiencies (η_m). Moreover, in table 1 it is shown the average daily excess of energy caused by each configuration and the percentage of that excess of energy regarding the maximum daily energy consumption. This percentage of excess of energy is used for determining the appropriate battery capacity. Finally, a maximum depth of discharge (DOD_{max}) equal to 80 % is already taken into account in the value of battery capacities listed in table 1.

Figure 8 shows some results obtained based on different sizes of PV systems. In figure 8 (a), the same size of the current PV system was considered but with mono-crystalline PV modules efficiency of 20 %. It can be seen that the negative value of *Balance* has been decreased from -550 kWh (see figure 5) to -220 kWh.

In figure 8 (b), the size of the PV system is almost the double of the previous case shown in (a). This increase of the size of the PV system showed a significant decrease in the negative value of *Balance*. In this case, a battery capacity of less than 100 kWh will be enough to cover the load for the whole simulated period of time.

Finally, figure 8 (c) depicts the case of oversizing the PV system. From that case (c), it can be concluded that increasing the PV system size to its maximum limit is not a good solution, and it will lead to high excess of energy without any significant decrease of the battery capacity. The average daily excess of energy for this case is of 328.2 kWh compared to the previous case (b) which is less than 65 kWh per day. In addition, there is still a need of a battery capacity of 50 kWh in order to cover the negative value of *Balance*.
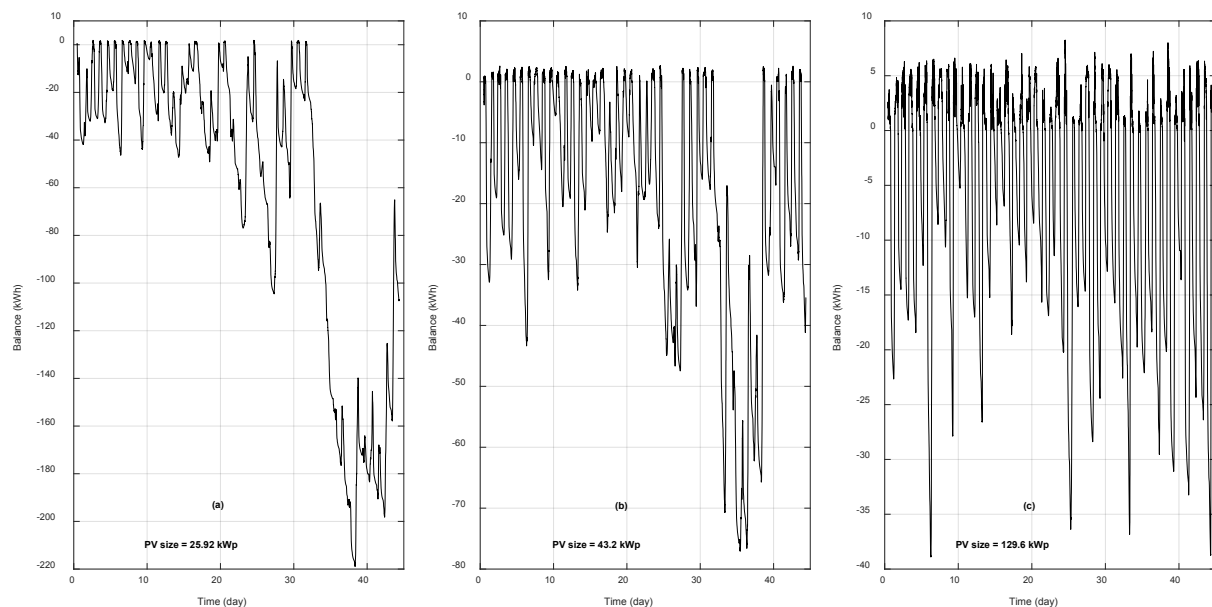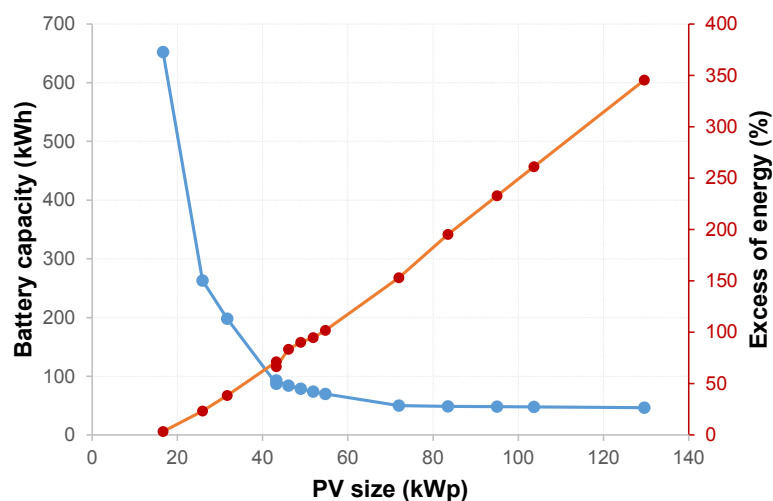

Figure 8. Comparison of different PV sizes and their impact on the battery storage.

Table 1. Estimation of the battery capacity considering different configurations and sizes of PV system.

Configuration of PV systems					Battery capacity (kWh)	Average daily excess (kWh)	Excess of energy (%)
NE (kW$_p$)	NW (kW$_p$)	SW (kW$_p$)	η_m (%)	Total PV size (kW$_p$)			
1.8	12.6	1.8	14	16.6	652	3.1	3.2
2.9	20.2	2.9	20	25.9	263	22.1	23.2
5.8	20.2	5.8	20	31.7	198	36.4	38.3
11.5	20.2	11.5	20	43.2	87	67.8	71.3
5.8	20.2	17.3	20	43.2	93	63.1	66.4
17.3	20.2	8.6	20	46.1	84	79.2	83.3
17.3	20.2	11.5	20	49	79	85.8	90.2
14.4	20.2	17.3	20	51.8	74	90.1	94.8
14.4	20.2	20.2	20	54.7	70	96.7	101.1
20.2	23	28.8	20	72	50	145.5	153.1
25.9	28.8	28.8	20	83.5	48.8	185.5	195.3
31.7	31.7	31.7	20	95	48.2	221.3	232.9
34.6	34.6	34.6	20	103.7	47.8	248	260.9
43.2	43.2	43.2	20	129.6	46.6	328.2	345.4

Based on the methodology developed in this work for sizing a standalone PV system, as well as the different simulated scenarios, a sizing curve has been drawn and it is presented in figure 9. In addition to the sizing characteristic, another parameter representing the percentage of daily excess of energy regarding the daily consumption is also presented in figure 9. The appropriate size of the system can be determined by combining these three parameters. For example, from the sizing characteristic it can be seen that the adequate PV size is between 38 and 45 kW$_p$ resulting in a daily excess of energy less than 60 %. Thus, the optimal capacity of the battery ranges from 90 to 120 kWh. However, the last decision of the system sizes will mainly depends on the economical side and especially on the battery price. Moreover, the amount of daily excess of energy could be reduced by increasing the battery capacity.

Figure 9. Variation of the battery capacity with respect to the PV size.

5. Conclusion

The present paper a study the possibilities to make the Czech Antarctic Station of J.G. Mendel fully independent of fossil fuel for electricity generation in order to ensure sufficient conditions of life for researchers. Based on experiences gained from previous expeditions, and the damage of wind turbines after short time of deployment under the harsh environment of the location, it has been decided that the appropriate RES is PV combined with battery energy storage system.

A simple and effective methodology based on energy balance has been developed for the sizing of the standalone PV system. The methodology uses in-site measurements of solar irradiance, temperature and consumption in order to determine the appropriate size of PV and the best battery capacity.

Finally as a result, a sizing characteristic was created from different simulated scenarios based on different PV module efficiency, orientations and sizes.

Acknowledgments

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