

ANALYSIS OF EXPERIMENTAL DATA FROM HOUSEHOLD OFF-GRID SYSTEM IN LATVIA

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Autonomous off-grid systems might be seen as a favourable option when it comes to high grid connection fees and for a sustainable electric system in transition to a low-carbon, renewable-based decentralized system. To ensure such a system, accurate analysis of different scenarios is required to determine the optimal energy source mix and sizing of the off-grid system. Software computing techniques or mathematical models can help solve this task, but, unfortunately, it is unpredictable how actually such systems will perform in real life. There are not so many publications, where the real data and off-grid systems are analysed and compared to simulation results. Thus, this paper examines an experimental stand-alone electrical off-grid solution in Latvia. The operational data of real autonomous off-grid system are obtained for the off-grid system performance and control strategy analysis, which is highly relevant for the planning and dimensioning of affordable renewable off-grid systems.

Keywords: *Equipment sizing, experimental off-grid system, power flow control based on battery voltage level.*

1. INTRODUCTION

In scientific literature, self-sustaining microgrid systems that are built for different consumers are analysed. For example, [1] examines the technical feasibility (including system dimensioning) for a single-family house off-grid energy system in Finland's northern climate with short-term battery and seasonal hydrogen storage. While in [2] comparative analysis between an off-grid hybrid power supply for different consumption levels (1825, 3650 and 5475 kWh) and a newly built grid connection for domestic consumers was performed in different regions of Estonia. In another paper [3], the configuration of off-grid systems in Estonia, which includes photovoltaics, wind turbines, a diesel generator, and batteries, is studied.

The validity of the results presented in literature, however, degrade the further to the south, to Latvia, for example, due to increased PV power generation, or less windy days which depend on specific climatic conditions. Moreover, according to the location, in scientific literature there is little information about real autonomous off-grid systems implemented in life, their technical characteristics, data acquisition and monitoring, as well as data analysis of such electrical systems in general.

In this article, an autonomous off-grid system is assumed as a set of interconnected controllable and uncontrollable rural household loads, decentralized energy sources, and energy storage that is not connected to the power grid. This means the cluster of equipment, which operates in the independent environment, island mode. Overall, there are several benefits for such an autonomous off-grid system:

1. useful development of project is possible in places where there are relatively high

investments needed for the grid connection to the distribution networks [4];

2. due to reduced costs of new renewable energy technologies and fluctuating fossil fuel prices, a simplified off-grid system for household electricity supply in remote regions may be an efficient and cost-effective electrification way to the fight against climate change and to reach the European Union (EU) decarbonization targets [5]–[7];
3. to protect against electricity supply quality problems and overall reliability due to increased variable generation or decreasing conventional generation in the grid [8].

Considering the mentioned benefits, such an experimental system was implemented for rural household located 30 km away from Jelgava city in Latvia. The autonomous off-grid system is capable to operate with 16–25 amps (A) within single phase connection at a voltage of 230 volts (V) and frequency of 50 hertz (Hz).

By installing electricity generation devices, batteries, and system control equipment, the analysis is planned for the off-grid performance and possibilities to increase the availability of such electricity supply in Latvia and expand the use of local renewable and zero-emission energy resources. It will be useful to find out the possible costs of an optimized solution, commercialization possibilities, their contributing factors, problems, as well as the efficiency of the use of the overall and individual elements of the off-grid solution.

Initially, a special mathematical model was created to select energy sources, to size equipment and to further test the operation of this off-grid system in the Latvian cli-

matic conditions. Thus, in this article not only we focus on evaluation of this real autonomous off-grid system performance, but also discuss aspects related to software computing techniques and mathematical models versus a real operational off-grid system.

As it is stated in [9], to ensure optimal design and that such renewable systems are affordable, careful planning preferably with high-resolution data on electricity generation and consumption is necessary. As it is one of research gaps identified in litera-

ture, and not delivered in a clear way, the objective of the article is to further increase knowledge of such system performance, planning and dimensioning in climatic conditions like it is in Latvia. It is expected to validate approaches which could be used in future and easily replicated for configurations that are more complex.

The study provides a reference for interested parties, including policy makers, foreseeing the landscape for off-grid energy system development.

2. MATERIALS AND METHODS

2.1. Setup of Off-grid System

An electric off-grid system (see Fig. 1) is installed for autonomous power supply of the individual household located near Jelgava city in Latvia. Electric off-grid system consists of:

1. micro wind turbines and solar panels;
2. diesel generator;
3. battery electric storage system;
4. all of it is set up in or around a standard

sea container (3.0 x 2.5 m, 2.5 m high) with other necessary equipment (sensors, cables, etc.) for the operation of the off-grid system.

The off-grid system is modular and can be moved relatively easily. It is designed for installation with minimal compliance requirements.

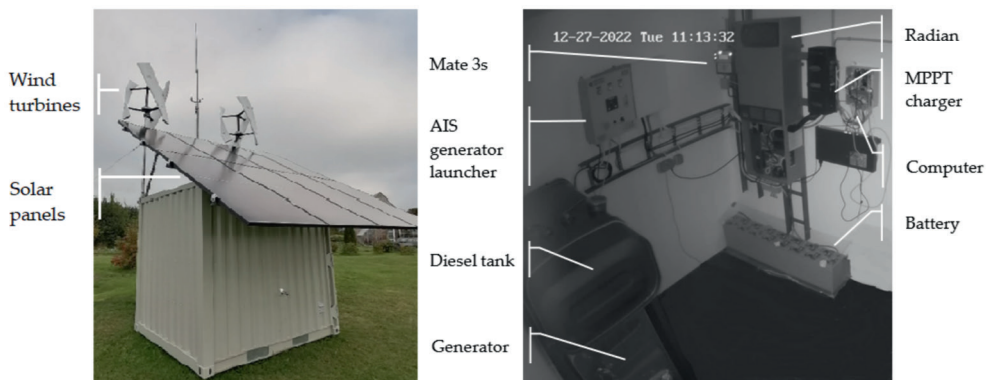
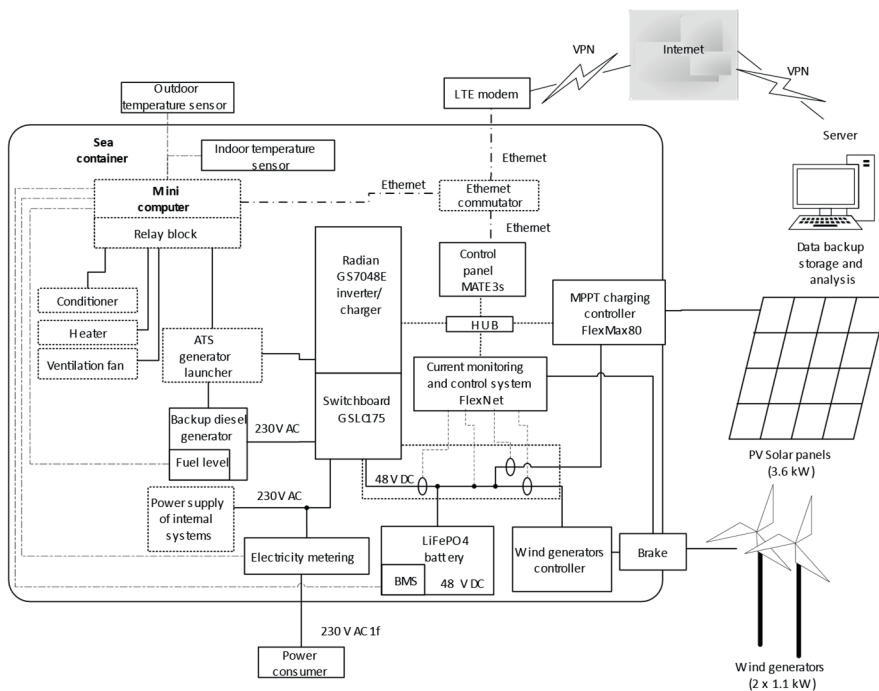


Fig. 1. Experimental autonomous off-grid system.

The basis of the off-grid system is a set of equipment manufactured by OutBack Power for microgrid imple-

mentation. System includes Radian GS7048E inverter/charger, system control equipment, panel MATE3, battery

monitoring equipment FlexNetDC and solar panel (3.6 kW) charging controller FlexMax80. Separate charge controllers are used to transfer the electricity produced by micro wind turbines (2 x 1.1 kW) to the off-grid network, which are connected with the help of power relays depending on the battery charge level. In case of unavailability of renewable resources, a backup diesel generator is provided with automatic start-up according to the battery charge level. A



After the implementation of the off-grid system, it is expected that the quality of the electricity supplied to the household will meet the Latvian distribution system operator network connection requirements according to LVS EN 50160 standard. For research in the future, it is planned to upgrade the experimental system also with a fuel cell system.

for the entire year was created and used as an input in the Homer Pro software to evaluate the optimal energy source mix and siz-

ing of the off-grid system. The equipment survey results are summarised in Table 1.

Table 1. The Current and Planned Electricity Equipment in Household

Consumer	Approximate electrical power, W	Number of units	Duration of use per day, h
Before off-grid system implementation			
LED bulbs	5	10	4 (depending on the season)
Refrigerator	200	1	2 (compressor activation depending on temperature)
Kettle	2000	1	0.5
Water Pump	400	1	0.5
Phone charger	7	2	4
Portable computer	100	1	3
TV	200	1	5
Electric tools	300-1000	3	0.5
After off-grid system implementation			
LED bulbs	5	15	4
Refrigerator	200	1	2 (compressor activation depending on temperature)
Kettle	2000	1	0.5
Water Pump	400	1	0.5
Water Pump	7	2	8
Portable computer	100	1	4
Washing machine	200–1500	1	2
Dishwasher	300	1	2.5
TV	200	1	6
Vacuum cleaner	1500	1	0.1
Fan	200	1	5
Conditioner	1000	1	5
Electric tools	300–1000	3	0.5

As it can be seen in Table 1, before the creation of the off-grid system, household electricity was mainly used for lighting, powering computers, and for other household equipment. The average daily electricity demand for the household was 4 kWh, totalling 1,460 MWh per year before the construction of the off-grid system. Consumer relied on a diesel-powered generator, connection with a capacity of up to 1 kW from the neighbour and a couple of solar panels; however, there were periods when

the household had limited access to electricity.

After the construction of the off-grid system, the household owner was able to increase their power consumption, for example, by using an air conditioner as desired. Electricity consumption was forecast to be 12 kWh per day, considering the use of an air conditioner during the summer season. This would result in a total annual consumption of 4,380 MWh, which would be provided by the created off-grid system.

2.2. Setup of the Off-grid System

The operational modes and quantitative setting values are selected in such a way as to control the charging of the battery pack and ensure the supply of electricity to the load. The main parameter, according to which the control takes place, is the charge level of the batteries.

Fig. 3 shows the off-grid system control principle, which is summarised based on the above configuration.

The principle of power flow control in the off-grid system is based on voltage levels of the battery. Battery is charged from three sources using a two-phase charging method. During the first stage, constant current bulk charge is up to 0.5 C-rate or limited by resource availability, terminated at 58.4 V; and constant voltage absorption charge is terminated at return amps 0.03

C-rate. PV charger and AC charger using diesel generator are managed by a central system controller and obey rules described before. Wind turbine controller is a discrete device and, therefore, needs to be connected to DC bus if necessary, using power relay. If the voltage of the battery reduces below 52.0 V and solar energy is available, bulk constant current charging is started. In case solar energy is not available and voltage drops down to 57.6 V, wind turbines start to generate by connecting wind chargers to DC bus. If both wind and solar sources are insufficient or unavailable and voltage is below 52.8 V, a diesel generator shall take over the control and charge battery in that way avoiding power supply interruption. The operation of the diesel generator is set at 50 V.

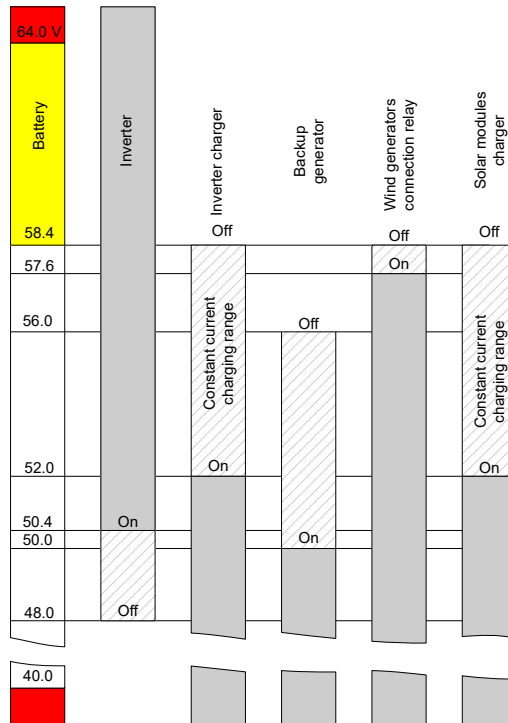


Fig. 3. Principle of power flow control based on a battery voltage level, source and power converter operating voltage ranges: red – voltage when battery damage occurs; yellow – charged battery voltage; grey – the device is working; dashed grey – switch-on or special charging mode.

When multiple sources are running simultaneously, priority is given to the source with the highest resource availability, i.e., for a charge controller that has a higher voltage and a proportionally larger amount of energy available from the renewable source. For example, if it is sunny with moderate wind,

then due to higher installed capacity of the solar panels, charging will take place from them, the wind charge controllers will give a minimum current. In darker and windier weather, the situation will be the opposite. If the backup diesel generator is running, it will be able to charge battery at all times.

2.3. Data Collection

Accumulation of the off-grid operation data is organised both in a local database in a minicomputer installed in a container (Raspberry PI), and remotely as a backup copy. The main monitoring data sources are listed below (see Fig. 2).

1. OutBack power MATE3 control panel – collects data from devices connected to OutBack Hub - FlexMax80, FlexNetDC and Radian GS7048E. Connected to a

minicomputer via an Ethernet network.

2. The battery management system (BMS) has its own output data flow through the serial port to the minicomputer.
3. Power network analyser EM21 – Modbus RTU device connected to a minicomputer via RS485 network.
4. Minicomputer – collects information from connected sensors and analogue and digital inputs and outputs.

2.4. Data Analysis Method

Data analysis is made by using Python language in Jupyter notebook, which is a web-based interactive computing platform. The graph codes were written in Python using libraries like pandas, numpy, matplotlib, seaborn. A 31-day dataset from an off-grid system was collected between 18 October and 21 November 2022, with a minute-by-minute sampling frequency. The analysed dataset includes 37 input signals

and high granularity data with a total of 48,301 data points.

The obtained dataset reflects only one time of the year. To create a more accurate analysis, it is desirable to use historical data to estimate the change taking into account the change of all seasons.

Various statistical methods are used in the present research – time series analysis, cumulative columns, and histograms.

3. RESULTS

The data analysis of the off-grid system was performed according to the previous sections. The off-grid system operating data are important and necessary to detect failures or faults of the system, especially

in the initial stage of such off-grid system implementation. The results provide an insight for further studies and an indication of the importance of data availability and resolution.

3.1. Data Analysis Method

Figures 4–6 present daily and hourly production data curves of the off-grid system electricity between October 2022 and

November 2022. The cumulative generation of electricity from solar, wind and diesel generator is covered.



(a)



(b)

Fig. 4. Generation of electricity from solar modules: (a) daily cross section profile; (b) cumulative hourly profile.

Figure 4 shows that solar power is generated on a relatively large scale and with a distinct tendency to take place from 6

a.m. to 3 p.m. Solar kilowatt hours (kWh) are calculated using data obtained from FlexnetDC.



(a)



(b)

Fig. 5. Generation of electricity from wind generators: (a) daily cross section profile; (b) cumulative hourly profile.

Figure 5 shows that wind power is generated on a relatively small scale and with no distinct tendency during the days. Also,

wind kilowatt hours (kWh) are calculated using data obtained from FlexnetDC.



(a)



(b)

Fig. 6. Generation of electricity from diesel generator: (a) daily cross section profile; (b) cumulative hourly profile.

Figure 6 shows that diesel generator power is generated almost every day – roughly the same amount (7–12 kWh). In comparison with solar and wind, the generator operates also in the early morning and late evening hours. Diesel generator

kilowatt hours (kWh) are calculated using data obtained from inverter RadianGS.

Looking at the minute-by-minute data, Fig. 7 shows how electricity generation profiles differ from sources.

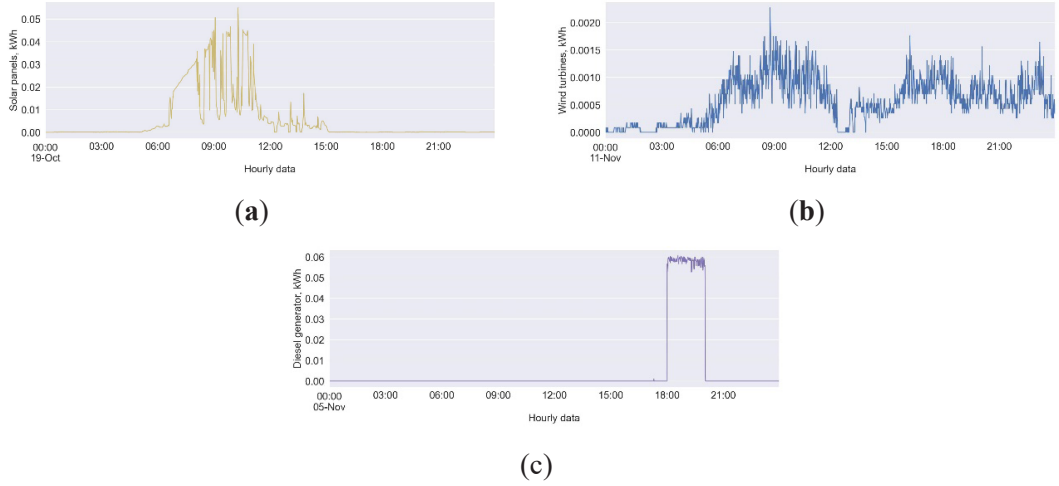


Fig. 7. Electricity generation profiles: (a) from solar source; (b) from wind and (c) from diesel source.

The data were taken on 19 October 19, 5 and 11 November. Thanks to the high granularity of the data, trend of each generation source can be seen in Fig. 7. It can

be seen that renewable sources in these days show a lot of variability, while the diesel generator has been working for a specific period with a certain capacity.

3.2. Amount of Generated Electricity by Source Type

During 31 days of observation (see Fig. 8), most electricity was generated by the diesel generator (152 kWh), followed by solar (104 kWh) and wind generation (7 kWh). Later on, it was discovered that low output of wind generation was associ-

ated not only with insignificant wind velocity during the investigation period, but also due to inadequate operation of wind charger control logics. This is the challenge to be addressed during the course of experimental activity.

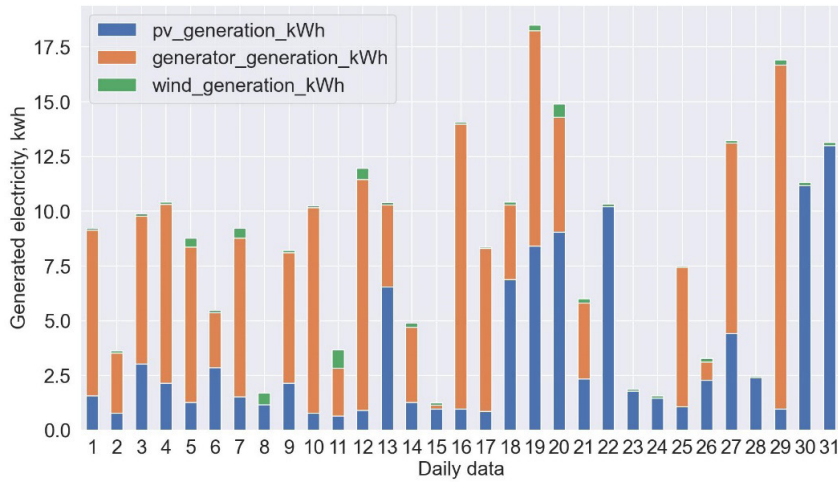


Fig. 8. Cumulative electricity generation by source type.

The analysis of the off-grid system operation throughout the experiment indicated that the off-grid system works suffi-

ciently during this time. However, during some period of time, missing data were observed.

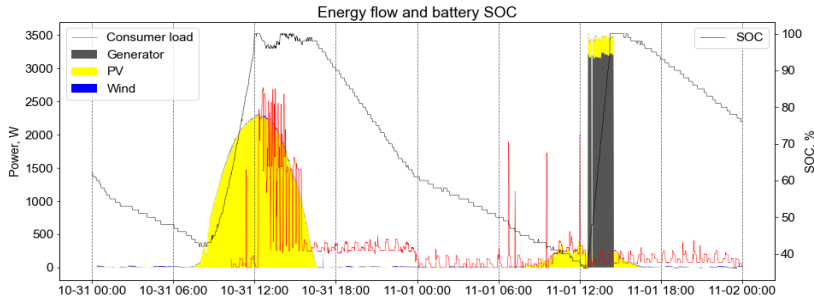


Fig. 9. Off-grid system characteristics during a sunny day at the end of October.

For example, Fig. 9 shows two sunny days at the end of October and at the beginning of November. During this time, the demand consumption was not logged in the

beginning, indicating that the acquisition of data should be checked to ensure data continuity.

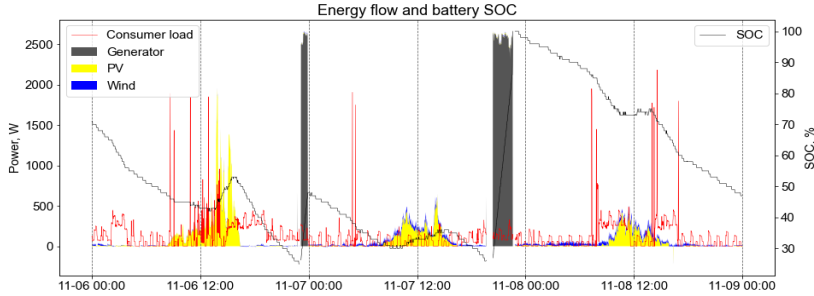


Fig. 10. Off-grid system characteristics during a sunny day at the beginning of November.

In Fig. 9 and Fig. 10, one can see the total contribution from each source. If the load capacity is greater than the total source contribution, the state of charge (SOC) of

the battery falls, if less – battery charging occurs. When the generator is on, the SOC level climbs rapidly.

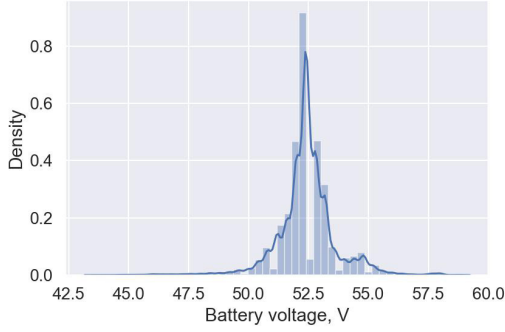
3.3. Electrotechnical Data: Voltage, SOC, Frequency

It was also important to observe electro-technical data in the experiment. Figures 11 and 12 show the four histograms. A histo-

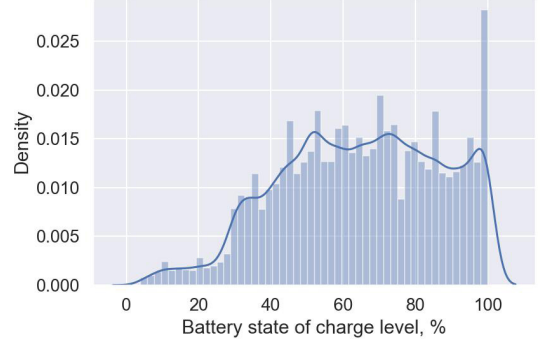
gram divides the variable into bins, counts the data points in each bin, and shows the bins on the x-axis and the counts on the

y-axis. In our case, we used Python library seaborn, which turns the y-axis as a density plot, which is the probability density function for the kernel density estimation. Density plot is a value only for relative com-

parisons. The y-axis is in terms of density, and the histogram is normalized by default, so that it has the same y-scale as the density plot [10].



(a)

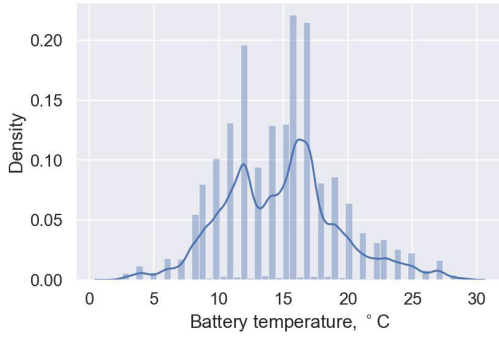


(b)

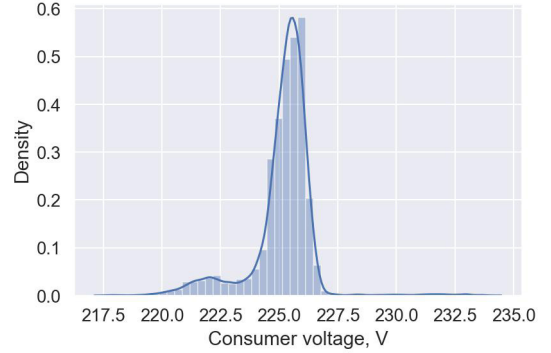
Fig. 11. Electrotechnical data analyses: (a) for battery voltage; (b) battery SOC level.

According to the electrotechnical data shown in Fig. 11, it can be noticed whether the battery has any overvoltage or the bat-

tery is operated in the most efficient way to reduce the risks of degradation.



(a)



(b)

Fig. 12. Electrotechnical data analyses: (a) for battery temperature; (b) for consumer frequency.

It is important to monitor what happens to the battery temperature and whether the electricity consumer is provided with the appropriate voltage quality of electricity supply (see Fig. 12). Battery voltage data

were obtained from inverter RadianGS, SOC and battery temperature data from system monitoring – FlexnetDC device, while consumer voltage from power network analyser – Carlo Gavazzi EM21.

3.4. Analysis of Climatic Data (Wind Speed, Temperature)

During observations, the internal temperature of the off-grid container and the outside air temperature are monitored.

Sensor DS1280 is used to determine both parameters. Results are shown in Fig. 13.

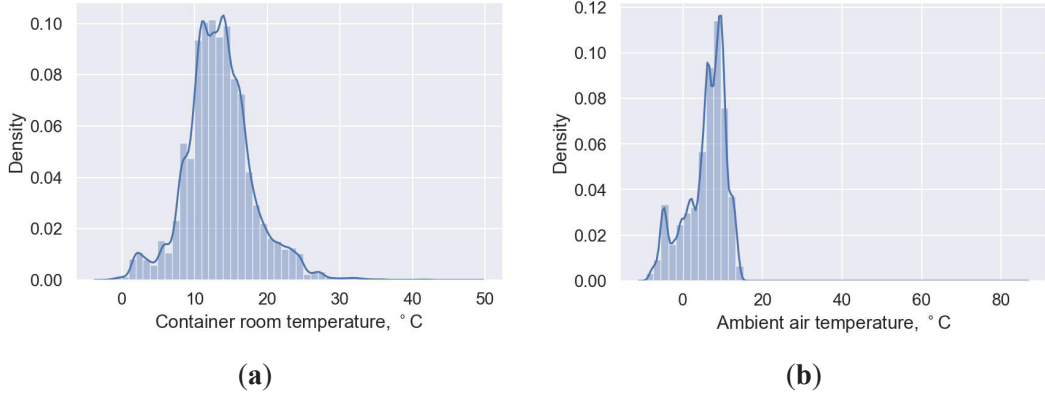


Fig. 13. Air temperature analyses: (a) for container room temperature; (b) for ambient air temperature.

In the climatic conditions of the country of Latvia, it is important that the container is warm enough during the winter period (from November to December), while in the summer period (from June to August) it is the opposite, so that the container room does not overheat. During the observation period, container room temperatures were observed above 0 °C, despite the fact that the outside air temperature dropped below

zero degrees Celsius.

In parallel, much attention is paid to the wind speed observations. Wind generation during the off-grid observation is not as originally planned. This is also shown in the data (see), which shows that the wind speed is not particularly high, but it does not explain why wind generator output is so low. Correlation between wind power output and wind speed can be seen in *b*.

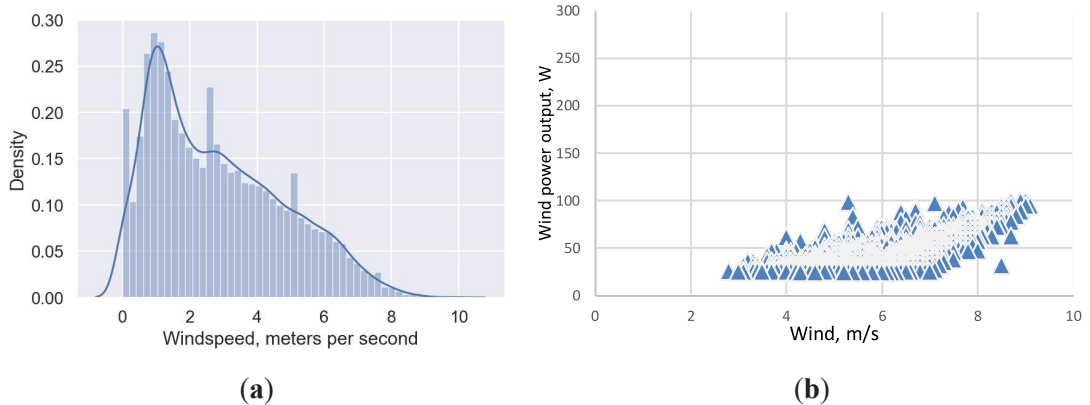


Fig. 14. Wind speed data: (a) using histogram; (b) using time scatter analysis. It should be admitted that wind data were obtained for only half of observation time.

All the previous weather conditions were measured every minute at the site.

Wind speed data were obtained from the anemometer above the sea container.

4. MODELLING TOOLS VERSUS REALITY

To understand accuracy and validate off-grid modelling tools and mathematical models, initially a comparison analysis for this study was planned. The idea was to compare results from modelling tools and mathematical models versus real experimental off-grid system. The aim was to determine how applicable the selected energy source mix and equipment sizing are in real life regarding what was proposed by modelling tools and models. However, it was later concluded that it was not clear how to do it due to the following reasons:

1. to obtain life data it would be required to test experimental off-grid system for at least 1-year period;
2. the off-grid system operation should be tested using more than one dispatch strategy (longer analysis than a 1-year period would be needed);
3. to obtain data to be later used in com-

puter tools and mathematical models more measuring devices as planned before would be required, for example, regarding solar radiation;

4. as the off-grid project is still implemented, its true costs can only be clarified after a longer time period than now.

Having a data array for a comparatively short period, it is difficult to make reasonable conclusions about the adequacy operation of the off-grid system. Nevertheless, from the available data it was possible to draw the conclusion that simulation results in certain aspects deviated from the real operation of the off-grid system.

The authors of this publication consider to obtain data for a longer period and to carry out a more comprehensive comparison of simulation data versus real measurements.

5. DISCUSSION AND CONCLUSIONS

The publication presents an experimental stand-alone electrical off-grid solution in Latvia. For the off-grid system discussed in this publication, the most important goals are the maximum use of all local renewable energy sources and reliability of electricity supply. The experimental system in Latvia showed that it was not feasible to power an off-grid system solely with renewable sources. A backup generator, such as a diesel or fuel cell system, is necessary to meet off-grid consumer demand. Theoretically, this might only be achieved by incorporating oversized solar, wind, and battery systems.

Real autonomous off-grid system operational data were analysed, and the following was concluded:

1. more attention should be paid to improve the operation of the off-grid wind turbines. The electricity from the wind is relatively small part from total consumption. On the other hand, the data show that the wind speed in the site is not high;
2. attention could be paid to setting the SOC level of the battery. For the battery to be able to accommodate the rapidly changing renewable generation, the battery should not be charged fully, but to a cer-

tain level. Also, in order not to degrade the battery, it should not be completely discharged;

3. the high granularity operating data (in minutes resolution) from the off-grid system are essential for troubleshooting and assessing the performance of such a system;
4. Such an analysis showed that it was important to gather data on off-grid performance in a timely manner in order to later analyse the results obtained from the operating system.

High-quality power supply off-grid and microgrid systems will have to solve the same main tasks that are solved by large energy systems. The project developers must always have a complete understanding of the probable consumers' load values and appropriate combination of the energy generating sources. It is necessary to ensure protection of systems from accidents, short circuits,

overvoltage and other factors of environmental impact on energy equipment, as well as that batteries and electronic devices operate at their appropriate preferable temperature (microclimate). The safe and efficient operation of the system must be ensured both when connected to the public power grid if there is such a connection and when it operates autonomously. The integration of different power conversion equipment, often supplied by different standards and different times, must be achieved, ensuring a continuous power supply of electric system for all time equipment that operates in all provided regimes.

In the future, the authors plan to continue evaluating the performance of the autonomous off-grid system, considering a longer observation period, adding a comprehensive comparison of simulation data versus real measurements, as well as adding a fuel cell system to maintain system operation in a more environmentally sustainable manner.

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