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RIGA TECHNICAL UNIVERSITY

Kārlis Gičevskis

FLEXIBLE POWER SUPPLY SOLUTIONS: MODELLING METHODS AND INNOVATIVE APPROACHES TOWARDS SUSTAINABLE ENERGY TRANSFORMATION

Summary of the Doctoral Thesis

RTU Press
Riga 2024

RIGA TECHNICAL UNIVERSITY
Faculty of Computer Science, Information Technology and Energy
Institute of Power Engineering

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RTU Press
Riga 2024

Gičevskis, K. Flexible Power Supply Solutions: Modelling Methods and Innovative Approaches Towards Sustainable Energy Transformation. Summary of the Doctoral Thesis. Riga: RTU Press, 2024. 60 p.

Published in accordance with the decision of the Promotion Council “RTU P-05” of 26 March 2024, decision No. 98/24.

The Doctoral Thesis was developed thanks to support from Riga Technical University's Doctoral Grant programme and the European Social Fund within Project No. 8.2.2.0/20/I/008, “Strengthening of PhD students and academic personnel of Riga Technical University and BA School of Business and Finance in the strategic fields of specialization” of the Specific Objective 8.2.2, “To Strengthen Academic Staff of Higher Education Institutions in Strategic Specialization Areas of the Operational Programme Growth and Employment”.

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https://doi.org/10.7250/9789934370540
ISBN 978-9934-37-054-0 (pdf)

DOCTORAL THESIS PROPOSED TO RIGA TECHNICAL UNIVERSITY FOR PROMOTION TO THE SCIENTIFIC DEGREE OF DOCTOR OF SCIENCE

To be granted the scientific degree of Doctor of Science (Ph. D.), the present Doctoral Thesis has been submitted for defence at the open meeting of RTU Promotion Council on June 20, 2024, at the Faculty of Computer Science, Information Technology and Energy of Riga Technical University, 12/1 Āzenes Street, Room 306.

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DECLARATION OF ACADEMIC INTEGRITY

I hereby declare that the Doctoral Thesis submitted for review to Riga Technical University for promotion to the scientific degree of Doctor of Science (Ph. D) is my own. I confirm that this Doctoral Thesis has not been submitted to any other university for promotion to a scientific degree.

Kārlis Gičevskis ……………………………. (signature)

Date: ………………………

The Doctoral Thesis has been written in English. It consists of an introduction, 5 chapters, conclusions, 69 figures, 23 tables, and 10 appendices; the total number of pages is 121, not including appendices. The Bibliography contains 97 titles.

ACKNOWLEDGEMENTS

I would like to express my deepest gratitude to the corresponding members of the Latvian Academy of Sciences, Professor Antans Sauļus Sauhats and Professor Oļegs Linkevičs for their guidance and encouragement in my scientific work.

I'm grateful to Edgars Groza and Santa Ķiene from RTU for helping me through tough technical challenges and assistance during the preparation of the Thesis. I want to thank Professor Vitālijs Osadčuks and Aldis Pecka from the Latvian University of Biosciences and Technologies for their helpful advice. I also appreciate the financial support provided by my employer, "Latvenergo AS", for the experimental research on the off-grid power supply system, which was crucial for my Thesis.

I also appreciate the support and motivating talks from my colleagues Edijs Vesperis, Kaspars Karlsons, Poļina Grebeša, Jānis Andersons, Māris Balodis, Ilmārs Stuklis and Kaspars Cikmačs at "Latvenergo AS", as well as other young professionals in the energy sector, who were part of the "Future Energy Leaders in Latvia" program (2022) initiated by the Latvian Committee of the World Energy Council.

My sincerest thanks go to my family, parents, and grandparents for their constant support throughout my research journey.

CONTENTS

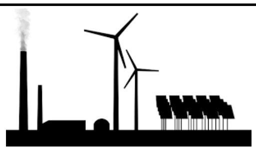
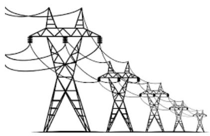
INTRODUCTION

Topicality of the research

Climate change poses a serious risk to our planet, with widespread effects observed globally. In response, nations and regions have set ambitious climate neutrality objectives. Internationally, agreements like the Paris Agreement strive to limit global warming to below 2 degrees Celsius, with efforts to pursue even more stringent targets. The European Union (EU) has committed to achieving climate neutrality by 2050, aiming for zero net greenhouse gas emissions. Latvia, among other EU countries, has joined in this endeavour, recognizing the pressing need for collaborative action. These commitments reflect a collective resolve to address climate change, foster energy innovations, and progress towards a sustainable future [1].

Understanding why we are innovating and why it is necessary to transform the energy system is very important for success. The answer to the question "Why do we need to innovate?" can help to define what success would look like, what kind of innovations we are aiming for, and ultimately, how best to organize and implement innovations to help transform the energy system. It is important to note that innovation and energy system transformation can mean many different things (see Table 1.1).

Table 1.1. Innovations for Transforming the Energy System [2]

		
Generation	**Transmission & distribution**	**Consumption**
Hybrid energy systems. Flexible generation. Conversion of electricity into different substances, incl. hydrogen, (P2X). Energy storage. Virtual power plants. Digital twins. Power-to-heat. Microgrids.	Real-time monitoring and control. Grid automation. Advanced analytics. AI-based control centres. Smart asset management. Simulation tools for hybrid AC/DC systems. Transparency and market platforms.	Electrification of end-use sectors. Electric vehicles, smart charging and vehicle-to-grid (V2G). Empowered consumers. Energy communities. Peer-to-peer electricity trading. Demand response and flexibility. Aggregators.

However, for the most part, innovations are almost always aimed at objectives: new activities that would provide real profits for one or more stakeholders, mitigate environmental impact, or enhance energy security. The nature of these new activities and how they are implemented is where many ideas come from, including from stakeholders who use the energy system in their daily lives.

The need for innovation can generally be broken down into a smaller set of reasons. Here are just a few of them:

1. Competitive pressure from more innovative companies.
2. Trends that are transforming an industry and changing the positions of market players.
3. Direct changes in the demand for products or services.
4. Economic recession (for example, which many companies began with the pandemic).
5. Changes in customer needs (for example, in connection with new technologies).
6. Stagnating or shrinking core markets.
7. Exploring new market opportunities.
8. Opportunities created by new technologies, such as in the context of digitalization and artificial intelligence.

There are various measures and innovations to accelerate the transition from fossil fuels to environmentally neutral technologies. New modelling techniques, simulation tools and innovative approaches are needed to find a sustainable, technically and economically efficient mix of solutions and their parameters for a safe and sustainable energy transformation. Therefore, in the Doctoral Thesis, the author focuses on innovative methodologies and mathematical models to address several key aspects in this field, together with an experimental approach:

1. The development of an evaluation framework for off-grid (which is not connected to the electricity grid) and microgrid systems. This includes optimizing equipment parameters, considering the impact of various operating modes, and creating mathematical models to enhance the effectiveness of these systems.
2. A systematic assessment of current legislation and the economic viability of diverse decentralized power supply solutions. This aims to provide valuable insights into the regulatory landscape and financial feasibility associated with various, decentralized energy systems.
3. The formulation of an evaluation and optimization model specifically tailored for large-capacity electricity storage systems.
4. The design of an algorithm for technical and economic justification, along with increased flexibility using an electrode boiler. This is intended for active participation in balancing markets, contributing to both technical efficiency and economic viability.

The developments were used to simulate the technologies in the conditions of Latvia and its energy system.

Hypothesis, objective and tasks of the Thesis

Hypothesis

Prioritizing the efficient planning and operation of decentralized power supply solutions can lead to a more flexible, sustainable, and balanced energy landscape. Decentralized power supply solutions can effectively address challenges related to intermittent generation, enhance system flexibility, lower energy prices, and improve overall energy infrastructure efficiency.

Thus, it is important to find an efficient combination of solutions and to determine the optimal parameters of this system, which can be done with innovative simulation tools.

Objective

The aim of the Doctoral Thesis is to propose new modelling methods, simulation tools and innovative approaches for the selection and evaluation of decentralized power supply solutions and their performance optimization (improvement) under changing operating conditions.

Tasks

To achieve the aim of the Thesis, the following tasks have been set:

1. Conduct an in-depth exploration of off-grid and microgrid systems, emphasizing the development of an evaluation framework that incorporates consumer habits, with a focus on optimizing equipment parameters, assessing the impact of different operating modes, and formulating mathematical models to increase the overall effectiveness of these systems.
2. Undertake a systematic assessment of existing legislation and evaluate the economic viability of diverse, decentralized power supply solutions. Provide insights into the regulatory landscape and financial feasibility across different scenarios.
3. Develop an evaluation and optimization model tailored specifically for large-capacity electricity storage systems used to provide system services (frequency regulation). This task involves synthesizing methodologies to enhance the efficiency and performance of these storage systems following the synchronisation of the Baltic power system with the Central European Synchronous Area (CESA).
4. Design an algorithm for technical and economic justification with a primary emphasis on flexibility enhancement through the integration of an electrode boiler. This algorithm aims to facilitate active participation in balancing markets, thereby contributing to both technical efficiency and economic viability.

Scientific novelty

Detailed mathematical descriptions and specialized algorithms were developed to evaluate the technical and economic aspects of various technologies, aiming to enhance their performance under different conditions. The goal was to make them better in different situations and speed up the switch to cleaner energy, thereby accelerating the energy transition. Offering to quickly and accurately determine the optimal composition of systems or other parameters, including comparison with existing commercial modeling tools. These approaches have been tailored to these main technologies: off-grid and microgrid systems, photovoltaics, electricity energy storage systems, and electric boiler, resulting in the development of four distinct methodologies designed for each specific technology.

The mathematical descriptions of those technologies, the algorithms used for evaluation of technical and economic aspects, and the legislative system have all been scrutinized within the context of Latvia and its energy system.

Practical significance of the research

The algorithms developed through research are designed to allow adaptation by other developers. These algorithms have tangible, real-world applications planning off-grid and microgrid systems, selecting equipment composition and parameters, and improving their performance.

These algorithms have found practical applications, notably in the technical and economic evaluation of projects undertaken by "Latvenergo AS". Among these projects are the installation of an off-grid system, battery energy storage system (BESS) at Riga hydroelectric power plant, and an electric boiler at the Riga thermal power stations. The experimental off-grid system has been successfully installed and is presently in operation in the Bauska region. Demonstration and further development of the system is ongoing.

Moreover, the developed algorithms were instrumental in creating the feasibility study for both the BESS and electric boiler projects. These studies are set to be submitted for European Union co-financing in the near future. At present, a procurement procedure is underway to select a suitable candidate to serve as the BESS contractor, who will be responsible for the development of the technical design and construction of the BESS system.

The results of the Doctoral Thesis can be used by "Latvenergo AS" to evaluate different options for the improvement of those technologies. Moreover, the obtained results can be used as input data by the policy makers, developers, and researchers of Riga Technical University.

During the preparation of the Thesis, the author participated in the development of the lecture materials for students of Riga Technical University. The results of the research have been used in the following lectures:

1. Microgrids, their basic elements, control systems and modelling (EES708, Electrical stations and substations, for master's level students).
2. Research and Development, Innovation in Energy (EES731, Introduction to the specialization and research in the field, for bachelor's level students).
3. Electric vehicle charging infrastructure, smart solutions (EES731, Introduction to the speciality and industry research, for bachelor's level students).

Publications and conferences

The results of the research have been presented in scientific journals in Latvia and abroad. Articles in scientific journals.

1. **Gicevskis K.** and Linkevics O., "The Role of Decentralized Electrode Boiler in Ancillary Services and District Heating: a Feasibility Assessment", Latvian Journal of Physics and Technical Sciences, vol. 60, no. 5, 2023, pp. 32–42, https://doi.org/10.2478/lpts-2023-0029.
2. **Gicevskis K.,** Linkevics O., and Karlsons K., "Transitioning to decentralized renewable energy in Latvia: a comprehensive payback analysis", Latvian Journal of Physics and Technical Sciences, vol. 60, no. 6, 2023, pp. 19–34, https://doi.org/10.2478/lpts-2023-0034.

3. Groza E., Kiene S., Linkevics O., and **Gicevskis K.**, “Modelling of Battery Energy Storage System Providing FCR in Baltic Power System after Synchronization with the Continental Synchronous Area”, Energies, 2022, vol. 15(11), doi:10.3390/en15113977.

4. Groza E., **Gicevskis K.**, Linkevics O. and Kiene S., “Mathematical Model for Household Off-Grid Simulation (Off-Grid System Sizing)”, Latvian Journal of Physics and Technical Sciences, 2022, vol. 59 (4), pp. 3–18, doi: 10.2478/lpts-2022-0029.

5. Linkevics O., Vesperis E., **Gicevskis K.**, Osadcuks V., Pecka A. and Galins A., “Analysis of Experimental Data from Household Off–Grid System in Latvia”, Latvian Journal of Physics and Technical Sciences, vol. 60, no. 3, pp. 3–17, https://doi.org/10.2478/lpts-2023-0014.

The research results presented in the doctoral thesis were discussed at two international scientific conferences, where topical energy sector problems were also discussed.

1. **Gicevskis K.**, Linkevics O., Groza E. and Kiene S., “Multiple Scenario and Criteria Approach for Optimal Solution and Sizing of Household Off-grid System”, in 2020 IEEE 8th Workshop on Advances in Information, Electronic and Electrical Engineering (AIEEE), 2021, pp. 1–7, doi: 10.1109/AIEEE51419.2021.9435627.

2. **Gicevskis K.**, Groza E., Karpovica I., Smiltans E., “The Energy Trilemma Index as a tool to support national security of energy system towards climate neutrality”, in the 80th International Scientific Conference of the University of Latvia, Latvia, Riga, 18 March 2022, pp. 5–5, https://dspace.lu.lv/dspace/bitstream/handle/7/61077/book-of-abstracts_18-03-2022.pdf?sequence=1.

The research results have been published as an article in a book and in articles in other journals.

1. Groza E., **Gicevskis K.**, Smiltans E., Karpovica I., Valdmanis G., “Latvia’s Energy Supply and Security”, Towards Climate Neutrality: Economic Impacts, Opportunities and Risks: reviewed monograph. Riga, University of Latvia Press, 2023, pp. 135–150, doi:10.22364/tcn.23.

2. Groza E., Smiltans E., **Gicevskis K.**, Karpovica I., “Pasaules enerģētikas trilemmas indekss: globālā pieredze lokālu risinājumu meklējumos”, Enerģija un pasaule, 2022, vol. 1, no. 132, pp. 58–63, URL: http://www.energijaunpasaule.lv/wp-content/uploads/2022/02/EP_132_2-3lpp_SATURS.pdf.

3. **Gicevskis K.**, Linkevics O., Groza E., “Jauni elektroenerģijas tirgus dalībnieki un tehnoloģijas–regulatīvie izaicinājumi”, Jurista vārds, 2022, vol. 1247, no. 33, pp. 30–35.

Author's personal contribution

During the development of the Doctoral Thesis, the author participated in several cooperation projects, working together with “Latvenergo AS”, Riga Technical University, Latvian University of Biosciences and Technologies, and other researchers. The overall concept of the Doctoral Thesis was developed by the author in close cooperation with Professor Dr. sc.

ing. Oļegs Linkevičs, under the leadership of Professor Dr. habil. sc. ing. Antans Sauļus Sauhats. The author contributed to all stages of the work, especially data processing, evaluations and calculations, working on case studies and analysing their results.

Volume and structure of the Thesis

The Thesis is written in English. It is composed of an introduction, five main chapters, conclusions, and bibliography with 97 references. The Thesis contains 69 figures, and 23 tables and consists of 121 pages.

The **Introduction** provides information regarding the topicality of the research, formulating the hypothesis, objective, and tasks of the Thesis. It also presents the scientific novelty and practical significance of the research, along with a listing of the author's scientific work.

Chapter 1 introduces the methodology for simulating off-grid systems and determining the optimal mix and sizing of household off-grid systems using various scenarios. It considers three different off-grid technological alternatives, three dispatch strategies, restrictions on some component operations, and sensitivity analysis. The chapter concludes with the advantages and disadvantages of the employed method and proposes improvements for future research.

Chapter 2 delves into a comprehensive overview of various methods and indicators that could be considered in the evaluation process of off-grid equipment. It introduces a novel multi-objective simulation tool that serves as an assessment tool for determining off-grid and microgrid equipment sizing. The developed model is validated against the calculations performed in Chapter 1 using Homer Pro software and real-world off-grid system data presented in Chapter 3.

Chapter 3 presents an experimental standalone electrical off-grid solution in Latvia. Operational data from a real autonomous off-grid system was collected for the analysis of system performance and control strategy. This information holds high relevance for planning and sizing cost-effective renewable off-grid systems. For example, simulations may deviate from real system operation in certain aspects. The findings from the first three chapters also indicated that off-grid and microgrid systems encounter similar challenges as large energy systems. Therefore, in the following chapters, decentralized technologies with an impact on the overall energy system are discussed.

Chapter 4 introduces a broader perspective on decentralized energy resources and emerging participants in the energy field. It examines trends in the electricity markets, the regulatory framework, and their impact on potential savings from innovative solutions in various scenarios within the context of Latvia. The chapter puts forward recommendations for legislative changes and findings that could serve as additional motivation for investing in energy transition.

Chapter 5 outlines the development of an algorithm to assess the technical feasibility of providing a frequency containment reserve (FCR) with a battery energy storage system (BESS). It also includes the development of a methodology and calculations for the provision of a manual frequency restoration reserve (also called mFRR) using an electrode boiler.

Conclusions of the Thesis provide a summary of the main findings.

1. METHODOLOGY FOR DETERMINING THE PARAMETERS OF THE HOUSEHOLD OFF-GRID ELECTRICITY SUPPLY SYSTEM

1.1. Motivation and background

Electrification may be a cost-effective way to fight against climate change and reach the EU decarbonisation targets [3]. Among other things, electrification can be counted not only as connecting electricity users to the grid but also to off-grid systems. Although there is no common definition of an off-grid system in the world, the following definition will be used in the Thesis:

- *an off-grid system is a collection of interconnected electricity consumers, controllable loads, decentralized energy sources and energy storage disconnected from the low-voltage grid. The cluster shall operate as an independent, controllable power supply system and shall be capable of operating in an independent, island mode.*

Where such a cluster is connected to a low-voltage grid and can operate in synchrony with the distribution system operator's network, such a system is also called a microgrid (see Fig. 1.1).

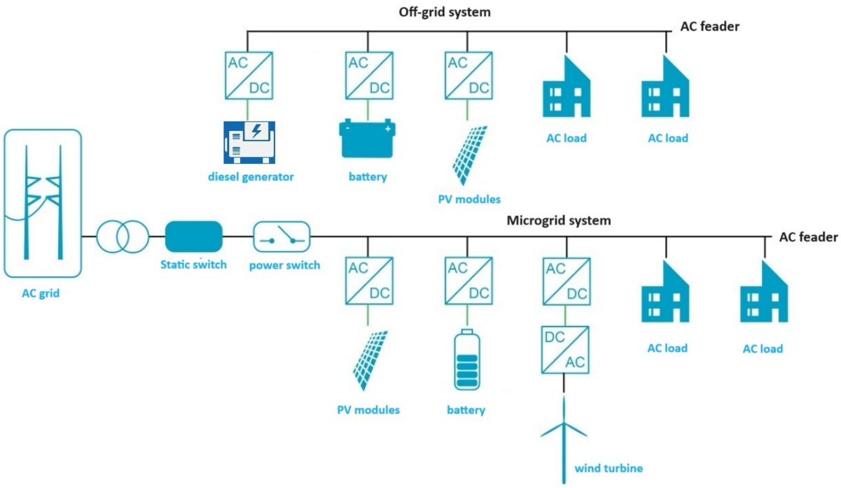


Fig. 1.1. Off-grid and microgrid power supply systems.

For users and electricity service providers, an off-grid or microgrid system can offer several benefits, such as reduced energy consumption (and thus costs), reduced environmental impact, improved reliability of electricity, reduced losses in distribution networks, reduced probability of overloading, improved voltage quality, etc. [4]. Off-grid or microgrid power supply solutions could have a positive impact on rural development in Latvia, e.g. in rural areas with long distribution lines or in areas without existing electricity supply (see Fig. 1.2).

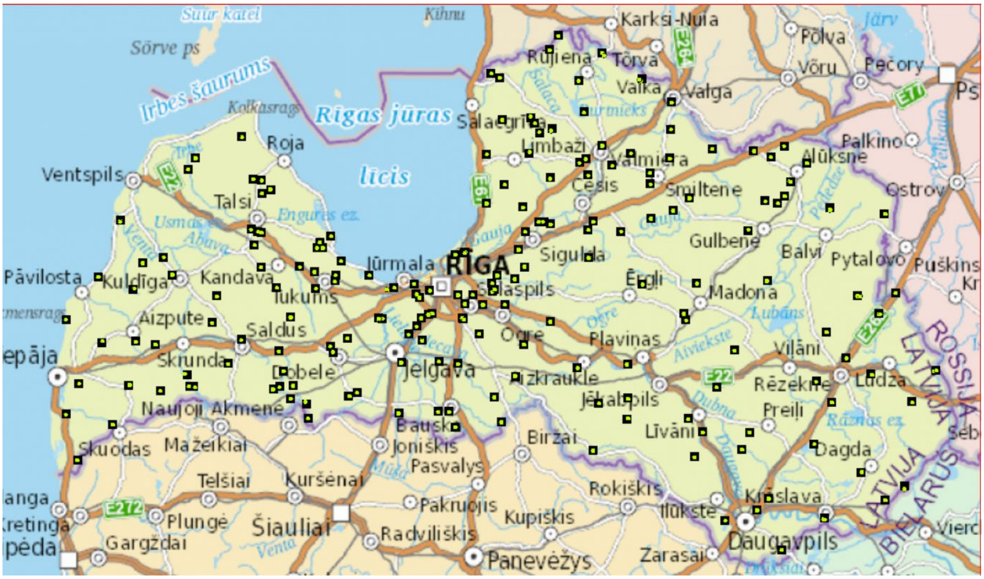


Fig. 1.2. Potential locations for off-grid or microgrid power supply solutions to customers in Latvia [5].

In many parts of the world, off-grid and microgrid technologies are seen as the future of electricity distribution networks. Across the residential sector outside urban areas, off-grid electricity systems are starting to become more recognized. However, planning of such systems from an economic and technical point of view still raises a series of questions and issues. Often, they are either oversized or undersized to fulfil the energy demand [6], [7].

1.1.1. Simulation using software tool

HOMER (abbr. for Hybrid Optimization of Multiple Energy Resources) Pro software[1] is an economic optimization tool for the simulation and optimization of off-grid and grid connected hybrid energy systems. The software can be used for decision making on choosing the optimal mix of resources, system configuration, or analysing capital and operating costs for energy system planning. The Homer Pro operation process could be described in three simple steps: 1) setting up the project, 2) analysis, and 3) results (see Fig. 1.3).

[1] https://homerenergy.com/products/pro/index.html

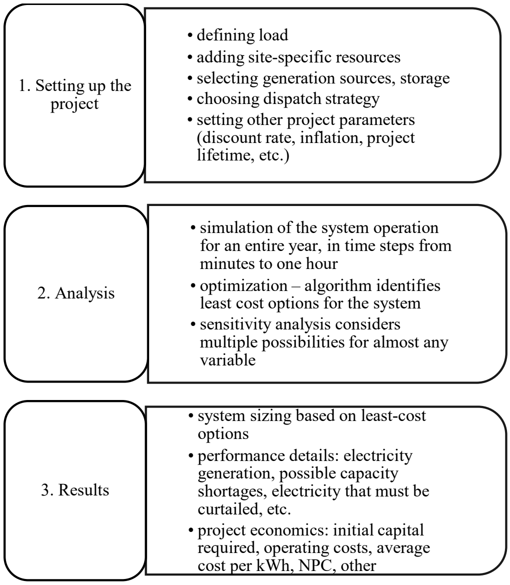


Fig. 1.3. Homer Pro process diagram.

The objective function of HOMER Pro is used for minimization of the total Net Present Cost (NPC-also known as the cost of the system over its lifetime). The NPC includes capital costs, replacement costs, operation and maintenance (O&M) costs, fuel costs, emissions penalties, and the costs of buying power from the grid (the last two will not apply to the case study in this paper). The NPC is the main economic output and a value by which HOMER Pro ranks all system configurations in the optimization results. To calculate the total net present cost (EUR), the software uses the following equation.

$$C_{\mathrm{NPC}}=\frac{C_{\mathrm{ann,\ tot}}}{CRF(i,\ N_{proj})}, \tag{1.1}$$

where $C_{\mathrm{ann,tot}}$ is the total annualized cost (EUR), i is the annual real discount rate (%), N_{proj} is the project lifetime (years), and $CRF(i, N)$ is a function returning the capital recovery factor, which is calculated with the equation:

$$CRF(i,\ N)=\frac{i(1+i)^N}{i(1+i)^N-1}, \tag{1.2}$$

where i is the real discount rate and N is the number of years. The i is calculated using the following equation:

$$i=\frac{i'-f}{1+f}, \tag{1.3}$$

where i' is the nominal discount rate (the rate at which you could borrow money) and f is the expected inflation rate. For example, if the nominal discount rate is 8 % and the expected inflation rate is 3.5 %, the annual real discount rate is 4.35 %. By defining the real discount rate in this way, inflation is factored out of the economic analysis [8].

While setting up the project, the software user must choose a dispatch strategy to determine how generation can provide the load. A dispatch strategy can be defined as a set of rules that pertain to energy flows among off-grid components. The software provides various dispatch strategies, like cycle charging, load following, and combined dispatch. Each dispatch strategy has its own operating principles.

1. Load following (LF) – when a generator is needed, it produces only enough power to meet the demand. It tries not to charge the battery with a backup diesel generator unless it reaches the minimum power of the generator. Load following tends to be more optimal in off-grid systems with a lot of renewable power that sometimes exceeds the load.
2. Cycle charging (CC) – whenever a backup generator is required, it operates at full capacity, and surplus power charges the battery bank. It stops charging the battery at the setpoint of the battery state of charge. Cycle charging tends to be more optimal in off-grid systems with little or no renewable power.
3. Combined charging dispatch strategy (CS) – intelligently switches between the load-following and cycle charging strategies. That way, it can improve performance over the cycle charging and load-following dispatch strategies by making more efficient use of the backup generator [8].

1.2. Methodology

In this case, we consider a household electricity consumer who has no access to the electric grid and faces high connection costs. Fig. 1.4 shows a block scheme of the case study.

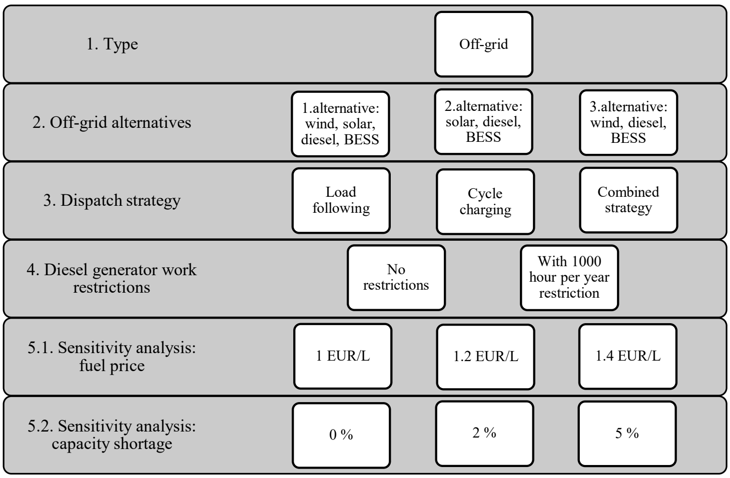


Fig. 1.4. Block scheme of the case study.

Various off-grid alternatives are compared to determine the most optimal solution for the selected household. Great attention is paid to ensure the following criteria: the highest use of RES, the smallest excess electricity, and the lowest cost of the system. Depending on the energy sources, three off-grid alternatives are assumed. The first alternative includes a wind turbine, solar panels, a backup diesel generator and battery energy storage system (BESS; lithium-ion type). The second alternative has solar panels, a backup diesel generator and BESS. The third alternative comprises a wind turbine, backup diesel generator and BESS. By considering the location of the household, the relevant default nature resource data are obtained. All off-grid equipment components and costs of all alternatives through three different dispatch strategies with and without certain restrictions of backup diesel generator operation were analysed. The restriction of the generator operation time is set to 1000 h per year (to extend the generator's lifetime, to ensure environment and comfort factors). In addition, diesel generator fuel consumption and initial required investments for the alternatives are analysed with the sensitivity analysis, where fuel price changes and different capacity shortage levels have been tested.

Using input data described in Fig. 1.4. and in the following sections, all off-grid alternatives with respective scenarios (totalling 162 simulations) were analysed.

1.2.1. Site location and household load

The location of the off-grid is in Latvia, near the capital city of Riga. Modelling input data of solar radiation, temperature, and wind resources for the selected location is obtained from Homer Pro software databases. For the proposed location, the maximum solar radiation is 5.5 (kWh/m2/day) in June, while the minimum solar radiation is 0.42 (kWh/m^2/day) in December, and the annual average solar radiation is 2.87 (kWh/m^2/day). Regarding temperature, the maximum temperature is 17.61 °C in July, while the minimum temperature is –5.56 °C in February, and the annual average temperature is 5.79 °C. While the maximum wind speed at a 50 m reference height is 7.68 m/s in January, the minimum wind speed is 5.4 m/s in July, and the annual average wind speed is 6.54 m/s. The wind speed for the location of the household is obtained at the reference height of 50 m, while the defined hub height for the household's wind turbine is 10 m. For extrapolating the wind speed at the hub height, the wind speed logarithmic profile in Homer Pro was used. For this case study, real household hourly load data are collected, integrated into the software, and used in simulations. The households' average daily electricity demand is 30.27 kWh, which reaches 11 049 MWh on an annual basis. The household consists of 2 persons. A heat pump, which is used for heat and hot water supply, and an electric vehicle for transport needs can be considered as the biggest consumers of electricity in this household. This type of household matches with aims for electrification, which has a critical role to play in achieving European Union decarbonisation policy targets.

1.2.2. Off-grid power supply system parameters

For the case study, basic project economic characteristic assumptions are 10 years project lifetime, 8 % discount rate, and 2 % expected inflation rate. Equipment capital expenditures (CAPEX), including installation, operation, and maintenance costs (OPEX), together with other technical aspects, were obtained from market research and discussions with experts (see Table 1.2).

Table 1.2. Input Data of Off-grid Components

Equipment	CAPEX, incl. installation	OPEX (EUR/year)	Service life	Other specific conditions
Solar panels	1250 EUR/kW	10	25 years	Derating factor – 10 %
Wind turbine	3500 EUR/kW	70	20 years	Wind turbine height – 10 m
Backup diesel generator	600 EUR/kW	0.03 (EUR/ op.hr)	15 thousand hours	Minimum load ratio – 25 %, diesel generator work restriction – 2172 litres of diesel fuel (which is around 1000 hours when nominal generator output capacity is 6.6 kW)
BESS	540 EUR/kW and EUR/ kWh	10	15 years	Minimum state of charge (SoC) – 20 %, at start SoC – 100 %, electricity throughput (kWh) – 3000
Converter	750 EUR/kW	0	15 years	Efficiency of inverter (DC–AC) – 95 %, efficiency of rectifier (AC–DC) – 85 %, rectifier capacity – 75 %
Controller	1300 EUR/kW	0	25 years	The setpoint state of charge – 80 %.

1.3. Results from simulations conducted for three alternative scenarios

System equipment dimensions (in kW and kWh) or the possible sizing parameters of off-grid equipment components are determined considering all dispatch strategies, the scenarios with and without diesel generator restriction, and considering different fuel prices and permissible capacity shortages levels.

Table 1.3 shows the average equipment values for each alternative. The biggest differences can be observed regarding the BESS storage capacity. The second alternative would require the biggest storage capacity, while the smallest would be required for the third alternative. The first alternative would need fewer solar panels and wind turbine capacities compared with the second and third alternatives.

Table 1.3. Average Equipment Size for All Alternatives

System equipment	Alternative 1	Alternative 2	Alternative 3
Solar panels (kW)	4.0	9.4	0
Wind (kW)	3.0	0	4.0
Diesel generator (kW)	11.0	11.0	11.0
BESS energy capacity (kWh)	22.0	28.3	17.8
Converter (kW)	4.7	5.0	5.0

In this case study, during the 10-year lifetime, NPC costs include capital costs, O&M costs, and diesel fuel costs. Fig. 1.5 shows the NPC results depending on three different dispatch strategies with and without diesel generator operating restrictions.

The NPC for the first alternative is within the 44 863–52 066 EUR range. The first alternative with a combined charging dispatch strategy (CS) and with diesel generator operating restrictions has proven to be the most cost-effective (lowest NPC value) than all other scenarios. Fig. 1.5 also shows that the impact of dispatch strategy can be more important than fuel restrictions. At the same time, it cannot be denied that those scenarios with generator restrictions do have an impact on the NPC values. There is an effect, and it can be seen in the NPC values which, in some cases, are extended both ways. If correctly applied, generator restrictions can reduce NPC.

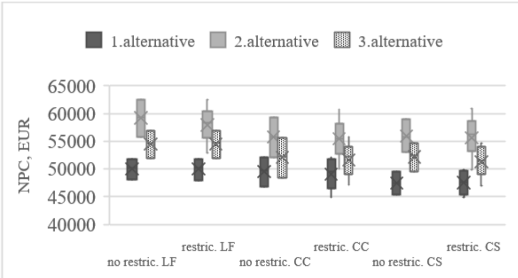


Fig. 1.5. NPC results depending on different dispatch strategies.

The NPC for the third alternative is within the 46 968–56 947 EUR range, while the second alternative is within the 49 783–62 506 EUR range. From the NPC perspective, it can be observed that cycle charging (CC) and combined charging dispatch strategy (CS) could be more suitable for the second and third alternatives because they are both relatively better than the load-following dispatch strategy.

Performing sensitivity analysis, Fig. 1.6 shows how fuel price impacts fuel consumption of the backup diesel generator. With a price increase from 1 EUR/L to 1.4 EUR/L, the mean value of fuel consumption for the first alternative is reduced from 1806 litres to 1386 litres per year.

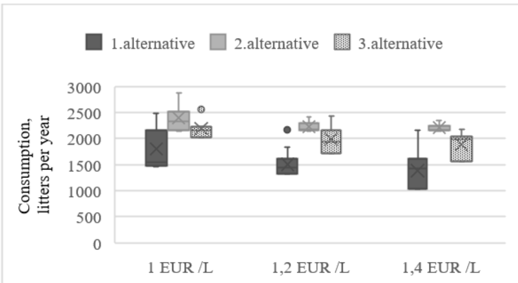


Fig. 1.6. Generator fuel consumption depending on fuel price.

One–year consumption for all off-grid alternatives is compared. Firstly, the sensitivity analysis shows that as soon as the price of fuel increases, the consumption of fuel tends to decrease. Secondly, the choice of dispatch strategy, generator restriction and capacity shortage level can affect required fuel on a relatively large scale, even within a single off-grid alternative level. In some cases, it can be more than thousands of litres per year. By comparing the initial off-grid investment costs according to capacity shortage levels in Fig. 1.7, it is possible to assess the capacity shortage impact.

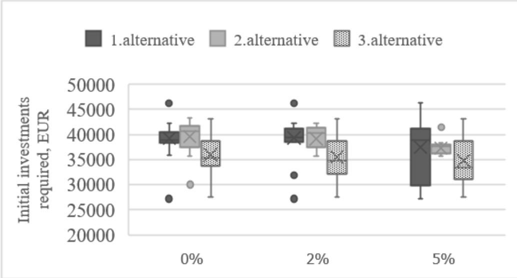


Fig. 1.7. Initial off-grid investment costs depending on capacity shortage.

A higher capacity shortage (5 %) will most likely mean that fewer initial investments might be required to develop an off-grid system. At the same time, Fig. 1.7 shows that there is practically no difference between a no capacity shortage (0 %) and a relatively small capacity shortage level (2 %).

In addition to all analyses before, so-called “excess electricity” is analysed. Excess electricity occurs when surplus power in off-grid is produced (either by the diesel generator or by renewable sources) and the batteries are unable to take all electricity. Excess electricity as the percentage (%) from a total generation for 6 simulations of three off-grid alternatives and three different dispatch strategies with and without diesel generator operating restrictions is shown in Fig. 1.8.

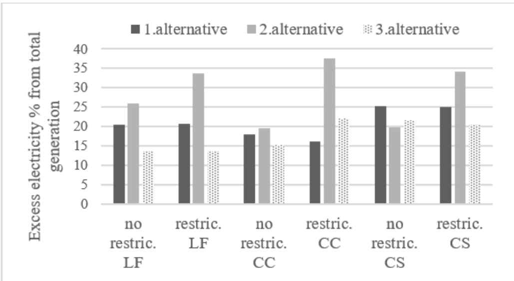


Fig. 1.8. Excess electricity in the all off-grid alternatives.

On average, the smallest “excess electricity” resulted in the third alternative – 17.68 % (which is around 2670 kWh per year). The next, with 20.9 % (or 3235 kWh), is the first alternative, while the greatest “excess electricity” resulted in the second alternative – 28.41 % (or 5108 kWh). Here, it is concluded that if the off-grid consists of PV panels, then it is crucial to correctly size their capacity and match it with adequate storage capacity.

2. NEW MATHEMATICAL MODEL FOR OFF-GRID SIMULATION

2.1. Motivation and background

The main aim of this chapter is to introduce a new multi-objective simulation tool to evaluate the performance of several off-grid cases under different dispatch approaches, which would further increase knowledge of such systems and the flexibility of already existing simulation tools. The developed tool is used to justify a composition and improve the capability of an off-grid system equipment for the real pilot project, which is discussed in the next chapter. Also, the motivation for developing a new multi-objective simulation tool is to create a tool that can be used to test equipment parameters for very specific cases and to visualise system performance for specific days. It can also be used to validate the results of existing software tools.

2.2. Methodology

2.2.1. Model for the household off-grid simulation

The simulation model described in this section was developed for the real-case evaluation. Before exploring the experimental off-grid system (see next chapter), the information for sizing the system was rather insufficient. The model determined necessary generation and storage equipment capacities, helped assess the payback of the off-grid project, and allowed visualising operating conditions.

The model has been applied to an off-grid system composed of solar PV, wind turbine, battery energy storage system (BESS) and backup power generator. The model presented in this chapter is designed as a set of algorithms that determine the operation of the off-grid solution according to the load and supply power balances indicated in Table 2.1 and Fig. 2.1.

Table 2.1. Abbreviations for terminology

Parameter	Abbr.	Parameter	Abbr.	Parameter	Abbr.
Load (kW)	P_l	Max amount of energy of the battery (kWh)	$E_{b\max}$	Power of PV modules (kW)	$P_{g\mathrm{PV}}$
Generation power (kW)	P_g	Min amount of energy of the battery (kWh)	$E_{b\min}$	Power of wind generators (kW)	$P_{g\mathrm{W}}$
Other generation capacities (kW)	P_n	State of charge of the battery (%)	SOC	Power of backup generator (kW)	P_r
Rated power of the battery (kW)	P_{br}	Max state of charge for the battery (%)	$SOC_{\max}$	Minimal power of backup generator	$P_{r\min}$
Rated capacity of the battery (kWh)	E_{br}	Min state of charge for the battery (%)	$SOC_{\min}$	Levelized costs of electricity, EUR/kWh	$LCOE$

The model has been developed to provide the highest (close to 100 %) electricity availability, considering that the electricity generation sources (PV, wind, etc.) connected to the off-grid are stochastic. Thus, energy storage and a backup generator are needed.

Fig. 2.1 shows a block scheme within the sequence of operations of the described off-grid system.

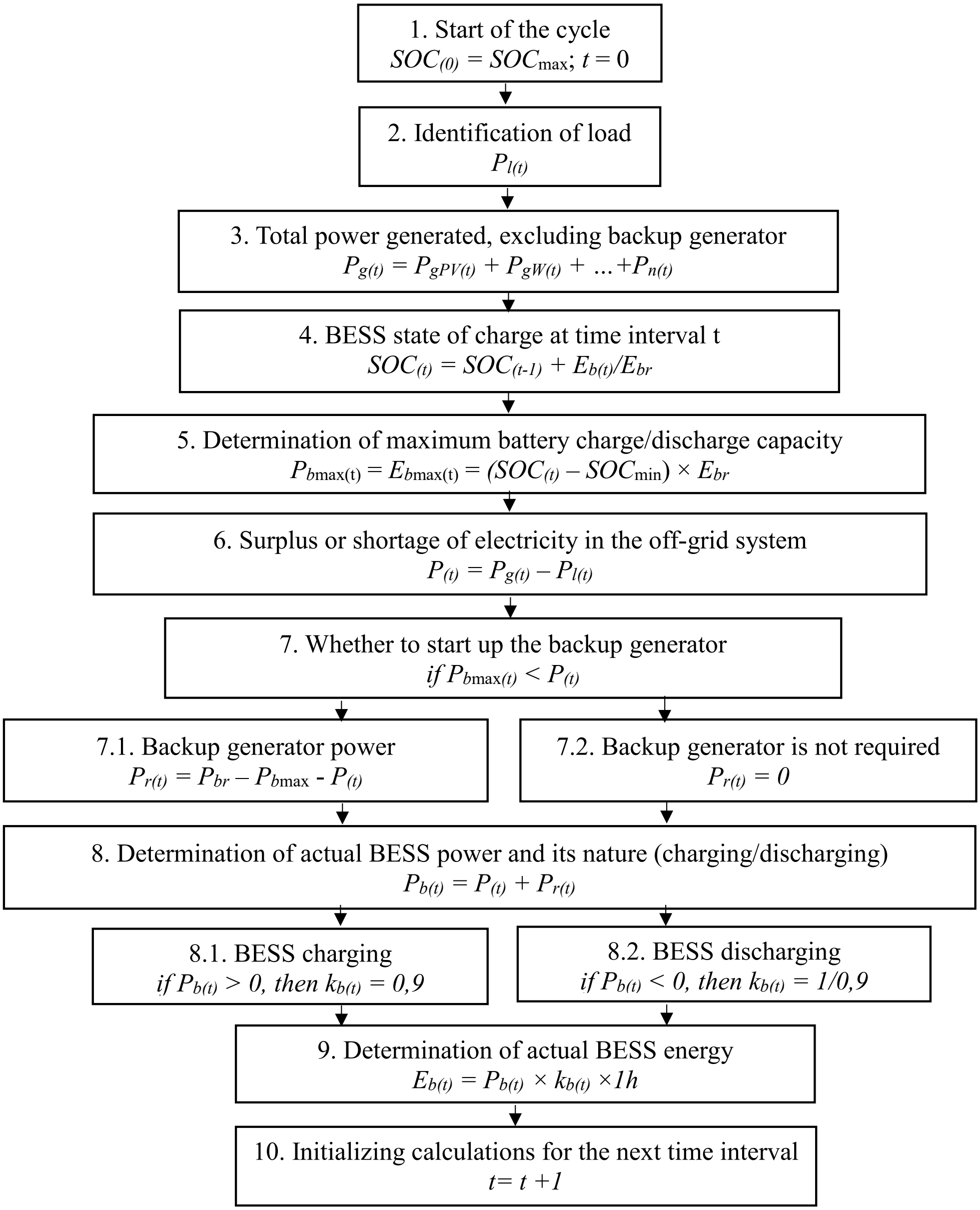


Fig. 2.1. Operational principles of the model of offgrid system.

The annual costs and levelized cost of electricity (*LCOE*) of the off-grid system are determined in a separate algorithm. Before using the algorithm, the model must be configured to set up the required dispatching strategy and input data.

2.3. Case study

For the case study, real household hourly load data are collected, which was mentioned also in Section 1.2.1.

Fig. 2.2 shows the typical daily load curve (for a 24-hour period) of this household, with a heat pump and electric vehicle charging. The largest amount of electricity is consumed at nighttime while an electrical vehicle is charging. For this case, it is highly important to choose the appropriate generation and storage solutions. When the readings were taken, the household was connected to the distribution system operator grid; thus, the energy availability was not an issue and always corresponded with the demand. Nonetheless, the connection allows the household not to consider load shifting.

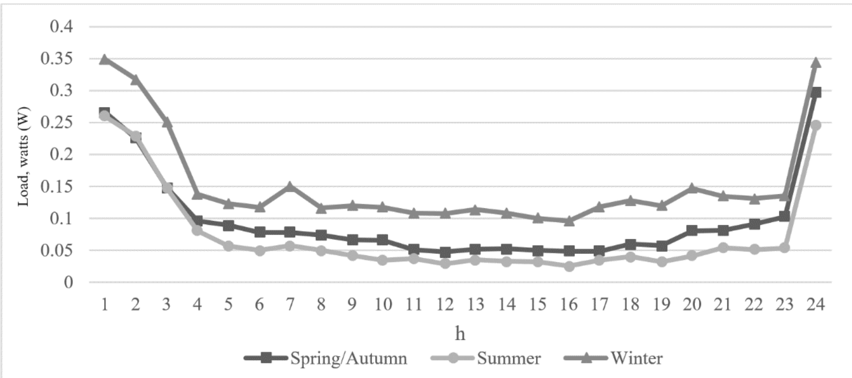


Fig. 2.2. Load curve in relative values for three seasons.

As shown in Table. 2.2, five equipment sizing alternatives were evaluated. The first three sizing alternatives are taken from the previous chapter on microgrid sizing with Homer software. The capacity of the backup generator is at least 11 kW, considering that the system must cover the maximum daily load (which is around 9 kW), thus ensuring higher security of supply [9]. Two additional sizing options were developed to find the most sustainable and economically efficient solution.

Table 2.2. Average Equipment Size for All Alternatives

System equipment	1.alternative	2.alternative	3.alternative	4.alternative	5.alternative
BESS (kW)	4.7	5	5	8.2	8.2
BESS (kWh)	22	28.3	17.8	30	16
Solar panels (kW)	4	9.4	0	6.2	3
Wind (kW)	3	0	4	2	2
Backup generator (kW)	11	11	11	13	13

In this case study, the results are displayed for the following alternatives: three dispatch strategies, different sizing options, power sources PV, wind, BESS, and the backup generator. The dispatch strategy is combined, and there is no capacity shortage.

2.4. Results

Table 2.3 shows the results for all five equipment sizing alternatives considering three different dispatch strategies.

Table 2.3. Results of Simulations

Alternative	**1st**	**2nd**	**3rd**	**4th**	**5th**
Combined charging dispatch strategy (CCDS)					
Backup gen. operating hours	1277	1234	1448	778	953
Excess renewable energy, kWh	1290	3990	71	2083	1029
Excess vs total renew. generation, %	18 %	40 %	2 %	26 %	20 %
***LCOE*, EUR/kWh**	0.71	0.73	0.73	0.79	0.70
Load following strategy (LFS)					
Backup gen. hours	2249	2276	2804	1923	2333
Excess renewable energy, kWh	1073	3646	46	1870	676
Excess vs total renew. generation, %	13 %	33 %	1 %	21 %	10 %
***LCOE*, EUR/kWh**	0.81	0.83	0.87	0.91	0.85
Cycle charging strategy (CCS)					
Backup gen. hours	1406	1355	1561	949	1248
Excess renewable energy, kWh	2273	5336	293	2999	1408
Excess vs total renew.generation, %	32 %	52 %	7 %	37 %	26 %
***LCOE*, EUR/kWh**	0.78	0.80	0.80	0.87	0.83

Like Homer Pro software, while setting up the project, a simulation tool can be used to configure dispatch strategies and determine the operating principles of how generation can provide the load.

1. The combined charging dispatch strategy (CCDS) intelligently switches between load-following and cycle charging strategyies. That way, it can improve performance over the cycle

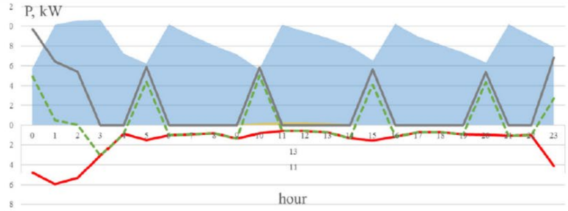
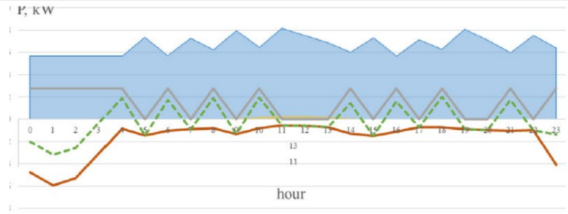
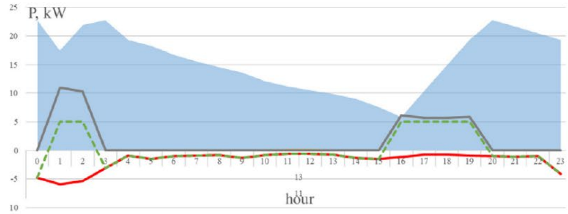
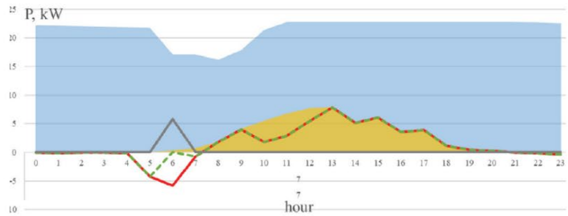
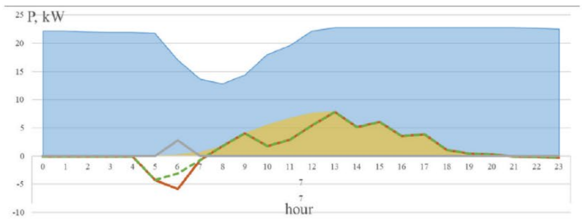
charging and load-following dispatch strategies by making more efficient use of the back-up generator. It is equivalent to the Combined Charging (CS) dispatching strategy in the previous chapter.

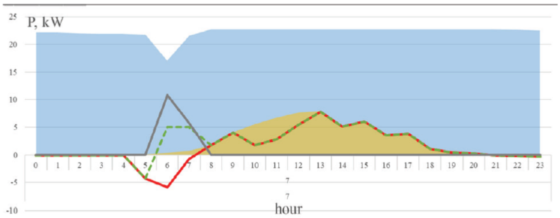
2. Load-following strategy (LFS): When a generator is needed, it produces only enough power to meet the demand. It tries not to charge the battery with a backup diesel generator unless it reaches the minimum power of the generator. Load-following tends to be more optimal in off-grid systems with a lot of renewable power that sometimes exceeds the load. It is equivalent to the Load Following (LF) strategy in the previous chapter.

3. Cycle charging strategy (CCS): Whenever a back-up generator is required, it operates at full capacity, and surplus power charges the battery bank. It stops charging the battery at the setpoint of the battery state of charge. Cycle charging tends to be more optimal in off-grid systems with little or no renewable power. It is equivalent to the Cycle Charging (CC) strategy in the previous chapter.

To better understand how different dispatch strategies impact the operation of generating sources and BESS charging/discharging, the visualization of off-grid operation in summer and winter days for one equipment sizing alternative and three dispatch strategies is provided in Table 2.4. The graphs show the power source and amount of generation, energy storage capacity, load and its nature, battery power and its nature, and backup generator power. The dates were chosen to represent the extreme situations where there was a surplus or deficiency of renewable generation. During the observation period, there was low wind output on the 7th of July and low PV output on the 13th of November. By considering the 2nd lternative, it is clearly visible that the microgrid benefits of diversified generation sources allow minimizing the backup generators' workload and maximizing the share of renewables. Dispatch strategies pose the most impact on *LCOE*.

Table 2.4. Off-grid Operation Visualization: 2nd alternative and Dispatch Strategies

2nd alternative: BESS power 5 kW, capacity 28.3 kWh, solar power 9.4 kW, wind power 0 kW, diesel gen. 11 kW	
Date	13th November
Combined charging CCDS	
Load following LFS	
Cycle charging CCS	
Date	7th July
Combined charging CCDS	
Load following LFS	

Cycle charging CCS	
LEGEND	

In addition to the analysis before, the next three figures compare results between the new simulation tool and Homer Pro software.

Firstly, backup generator operating hours are analysed. As it is necessary to avoid the use of electricity produced by the backup generator when renewable energy can be used instead, it is necessary to pay attention to the operating hours of the backup generator. As shown in Fig. 2.3, in all alternatives and dispatching strategies, the new tool displays more backup generator hours than Homer Pro software. The largest difference is observed in the load-following strategy (LFS). Nevertheless, both tools show that the generator hours will be the smallest for the 1st alternative in combined charging dispatch strategy (CCDS).

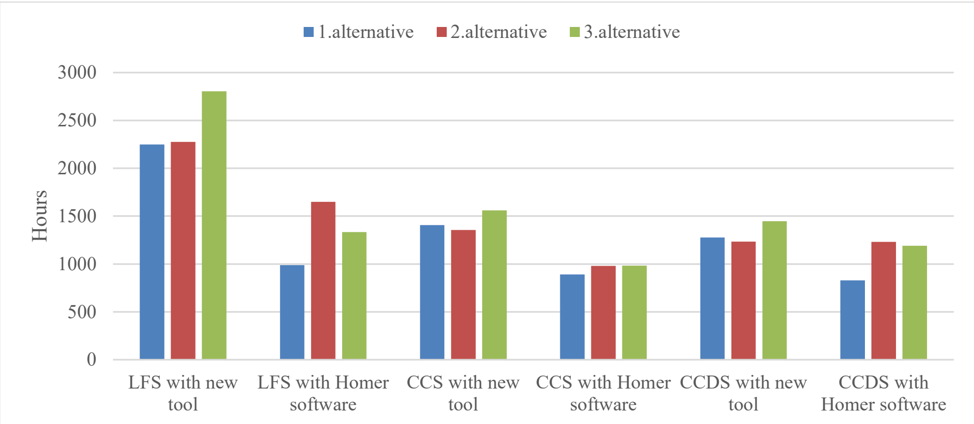


Fig. 2.3. Backup generator operating hours.

Secondly, "excess electricity" is analysed. Excess electricity occurs when surplus power in off-grid is produced (either by the backup generator or by renewable sources) and the battery or load is unable to take all the electricity. Excess electricity as a percentage (%) of the total generation of three off-grid alternatives and three different dispatch strategies is shown in Fig. 2.4.

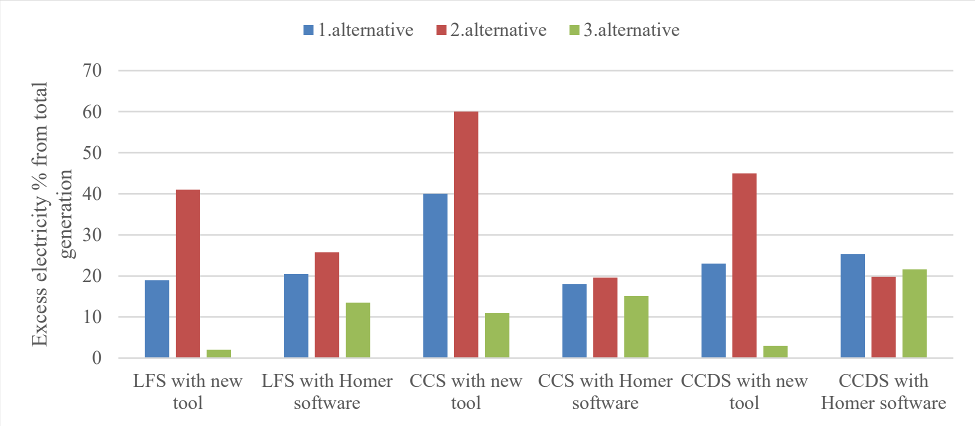


Fig. 2.4. Excess electricity in all off-grid alternatives.

On average, for both tools, the smallest "excess electricity" was shown by the third alternative –10.03 %, followed by the first alternative (21.13 %) and the second alternative (31.7 %). Despite excess electricity (%) differences between the tools (especially for an alternative that includes wind), the overall trend is the same, and it shows that if the off-grid system consists of PV panels, then it is crucial to correctly size its capacity and match it with adequate storage capacity.

Finally, in Fig. 2.5, we compare three alternatives regarding the levelized cost of electricity as the average cost per kWh of useful electrical energy produced by the system. The LCOE was not covered in previous chapter, but the gained results are being utilized this time.

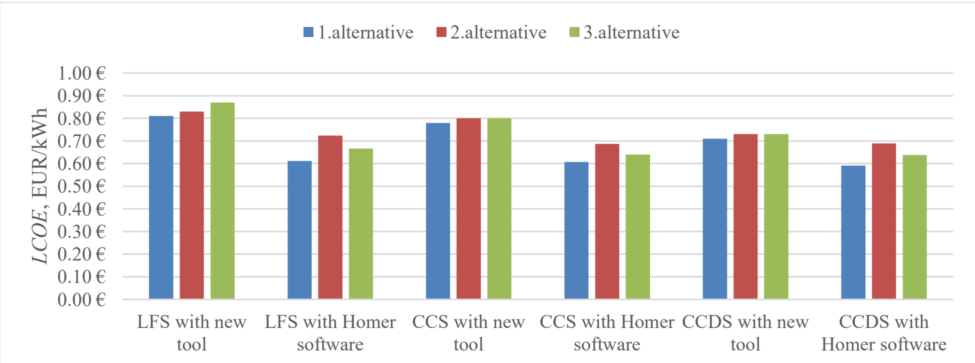


Fig. 2.5. Levelized cost of energy for all off-grid alternatives.

As shown in Fig. 2.5, for the new tool, average costs are between 0.72 EUR/kWh and 0.84 EUR/kWh, while in the case of Homer Pro software, they range from 0.64 EUR/kWh to 0.67 EUR/kWh. The results differ due to the emission cost implemented in the new tool and differences in the models themselves. In general, both simulation tools show similar trends, which confirms and validates their accuracy.

3. ANALYSIS OF THE REAL OFF-GRID SYSTEM PROJECT IN LATVIA

3.1. Motivation and background

In this chapter, an autonomous off-grid system is assumed to be 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.

Initially, a special mathematical model was created to select energy sources, size equipment and further test the operation of this off-grid system in Latvian climatic conditions. Thus, in this chapter, focus is on evaluating of this real autonomous off-grid system performance.

3.2. Materials and methods

3.2.1. Setup of the off-grid system

An electric off-grid system (see Fig. 3.1), which was installed in the summer of 2022, is adapted for the individual household located near Jelgava city in Latvia. The electric off-grid system consists of:

1. Micro wind turbines and solar panels.
2. Diesel generator.
3. Battery electric storage system; all of it is set up in or around a standard sea container (3.0 × 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.

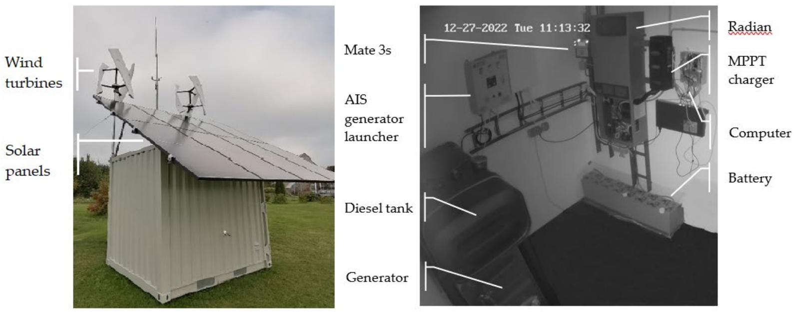


Fig. 3.1. Experimental autonomous off-grid system.

The basis of the off-grid system is a set of equipment manufactured by OutBack Power for microgrid implementation. The system includes a 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 × 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 startup according to the battery charge level. A $LiFePO_4$ battery with a nominal voltage of 52.8 V (3.3 V per cell) is used to store electricity, with a total capacity of 160 Ah (7 kWh). The electricity supply of the electricity consumer (the household participating in the experiment) is mainly from a battery.

The container, which hosts batteries, inverters, and other electronic devices sensitive to temperature, was insulated and equipped with devices for maintaining the necessary microclimate: a heater, conditioner, and ventilation. The conceptual diagram of the off-grid system is given in Fig. 3.2.

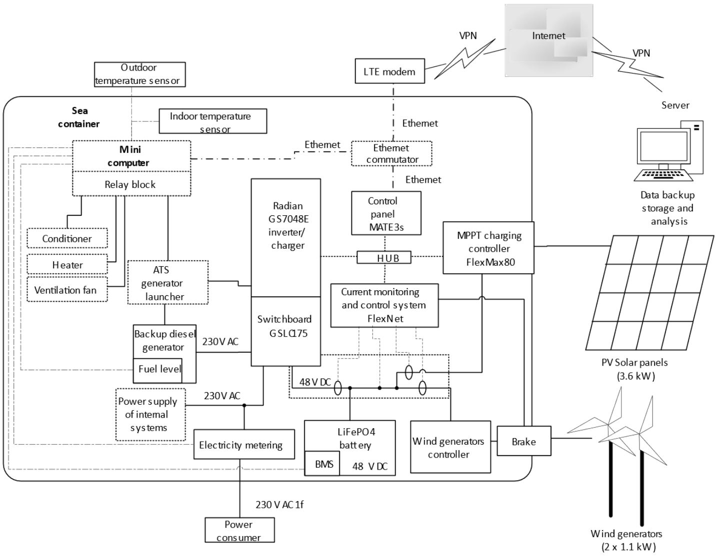


Fig. 3.2. Conceptual diagram of the installed off-grid system.

The principle of power flow control in the off-grid system is based on the voltage level of the battery. 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 the DC bus. If both wind and solar are insufficient or unavailable and the voltage is below 52.8 V, the diesel generator shall take over the control and charge the battery in the way avoiding power supply interruption. The operation of the diesel generator is set at 50 volts.

After the implementation of the off-grid system, it is expected that the quality of the electricity supplied to the household will meet the requirements of Latvian distribution system operator network connection 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. Before installing the new off-grid system, the household owner was surveyed about their electricity consumption and existing electrical appliances, as well as any potential changes after the implementation of the off-grid system in order to create the necessary system configuration. It should be noted that before the experiment, the household was not directly connected to the electricity grid (it was provided by a cable from the neighbour), but “Sadales tīkls AS” requested around EUR 25 thousand to connect this customer. Consequently, the client did not have accurate data on the demand and could not fully use the electrical equipment.

Household load data were collected using a power network analyser, and the average load projection for the entire year was created and used as an input in the Homer Pro software to evaluate the optimal energy source mix and sizing of the off-grid system. Before the creation of the off-grid system, household electricity was mainly used for lighting, powering computers, and other household equipment. The average daily electricity demand for the household was 4 kWh, totalling 1460 MWh per year before the construction of the off-grid system. The 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 4380 MWh, which would be provided by the created off-grid system. After building an off-grid system, the household owner decided to also install a heat pump for heating the building.

Data collection

The accumulation of the off-grid operation data is organized both in a local database in a minicomputer installed in a container (Rapsberry PI) and remotely as a backup copy. The main monitoring data sources are listed below (see Fig. 3.2).

1. OutBack power MATE3 control panel collects data from devices connected to OutBack Hub–FlexMax80, FlexNetDC and Radian GS7048E. It is 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 is connected to a minicomputer via RS485 network.
4. Minicomputer collects information from connected sensors and analogue and digital inputs and outputs.

3.3. Results and discussion

The data analysis of the off-grid system was performed according to the previous sections. It was made 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, and 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.

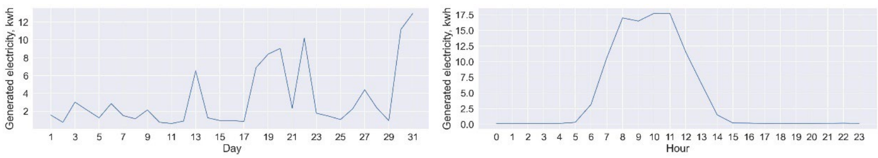
The obtained dataset reflects only one time of the year. To create a more accurate analysis, it is desirable to use historical data to estimate the change taking into account the change of all seasons.

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

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.

3.3.1. Evaluation of off-grid performance

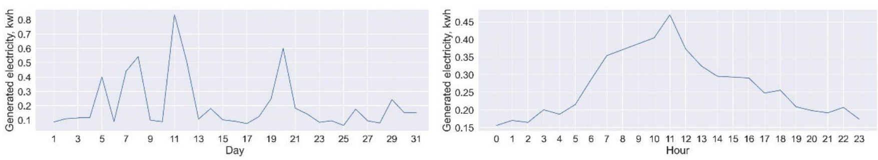
Fig. 3.3 to 3.5 present daily and hourly production data curves of the off-grid system electricity between October 2022 and November 2022. They cover cumulative generation of electricity from solar, wind, and diesel generators.



(a) (b)

Fig. 3.3. Electricity from solar power: (a) daily cross-section; (b) cumulative hourly profile.

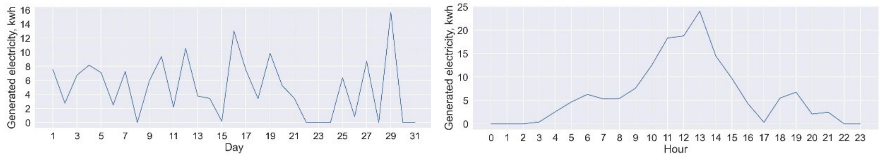
Fig. 3.3 shows that solar power is generated on a relatively large scale and with a distinct tendency to take place from 6 a.m. to 3 p.m. Solar kilowatt hours (kWh) are calculated using data obtained from FlexnetDC.



(a) (b)

Fig. 3.4. Electricity from wind: (a) daily cross-section; (b) cumulative hourly profile.

Fig. 3.4 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.

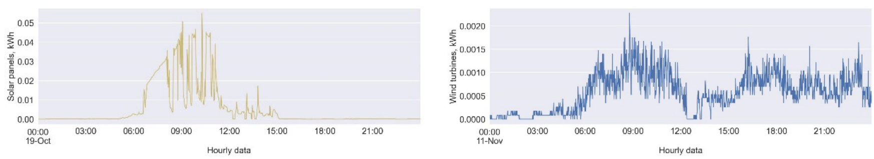


(a) (b)

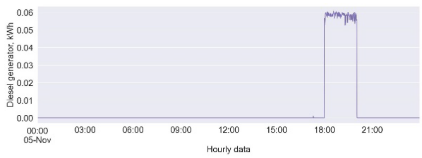
Fig. 3.5. Electricity from diesel generator: (a) daily cross-section; (b) cumulative hourly profile.

Fig. 3.5 shows that diesel generator power is generated almost every day – roughly the same amount (7–12 kWh). In comparison with solar and wind power, 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. 3.6 shows how electricity generation profiles differ by sources.



(a) (b)



(c)

Fig. 3.6. Electricity generation profiles: (a) solar, (b) wind, (c) diesel.

The data was taken from October 19, and November 5 and 11. Thanks to the high granularity of the data, the trend of each generation source can be seen in Fig. 3.6. 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.

Amount of generated electricity by source type

During 31 days of observation (see Fig. 3.7), 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 associated not only with insignificant wind velocity during the investigation period but also due to inadequate operation of wind charger control logic, as well as non-compliance with specifications and technical faults in the Chinese-made wind turbines. This is the challenge to be addressed during the course of experimental activity.

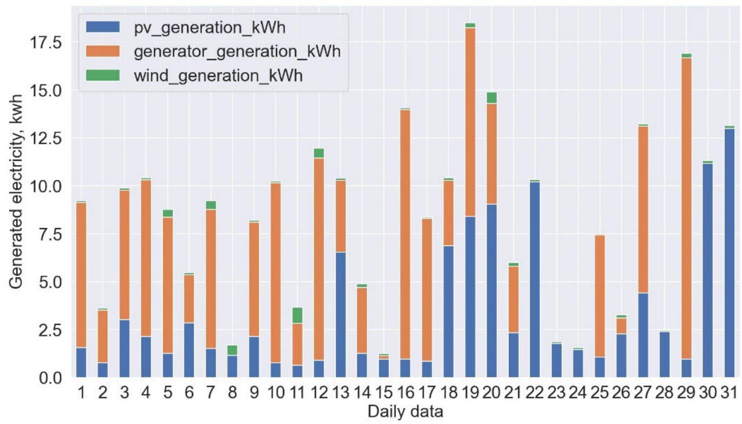


Fig. 3.7. Cumulative electricity generation by source type.

The analysis of the off-grid system's operation throughout the experiment indicated that it works sufficiently. However, during some period of time, missing data were observed.

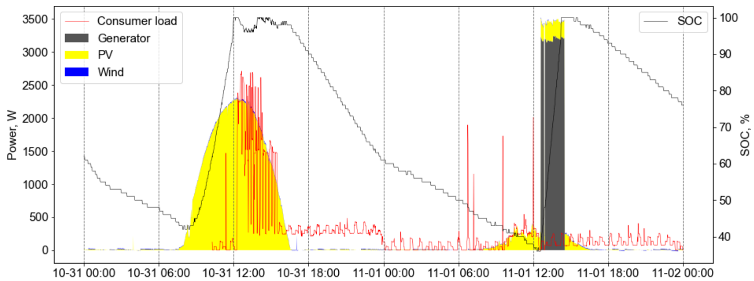


Fig. 3.8. Off-grid system characteristics during a sunny day at the end of October.

For example, Fig. 3.8 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.

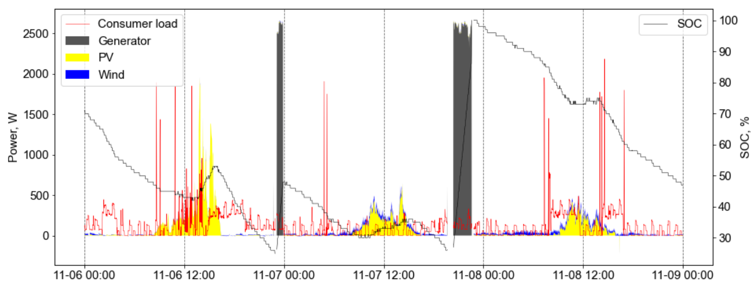
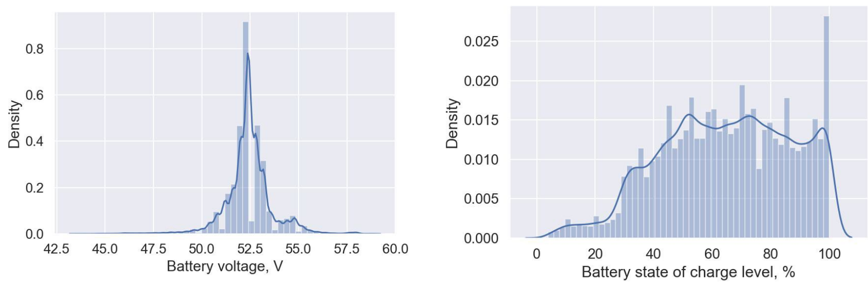


Fig. 3.9. Off-grid system characteristics during a sunny day at the start of November.

In Fig. 3.8 and 3.9, one can see the total contribution from each source. If the load capacity is greater than the total source contribution, the battery's state of charge (SOC) falls, if less – battery charging occurs. When the generator is on, the SOC level climbs rapidly.

Electrotechnical data: voltage, SOC, frequency

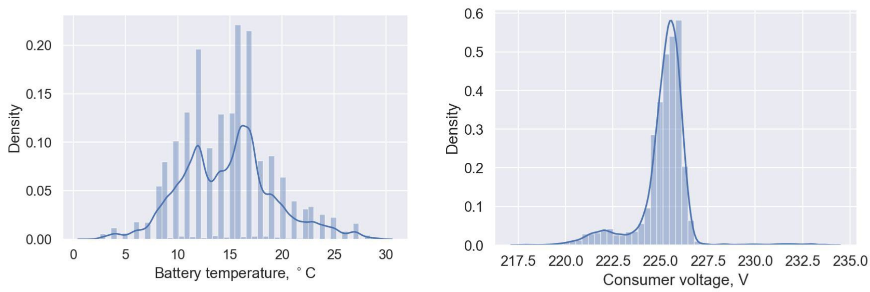
It was also important to observe electrotechnical data in the experiment. Fig. 3.10 and 3.11 show four histograms. A histogram divides the variable into bins, counts the data points in each bin, and shows the bins on the x-axis and the counts on the y-axis. In our case, we used Python library seaborn, which turns the y-axis into a density plot, which is the probability density function for the kernel density estimation. A density plot is a value only for relative comparisons. 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. 3.10. Electrotechnical data: (a) for battery voltage; (b) battery SOC level.

According to the electrotechnical data shown in Fig. 3.11, it can be noticed whether the battery has any overvoltage or it is operated in the most efficient way to reduce the risks of degradation.



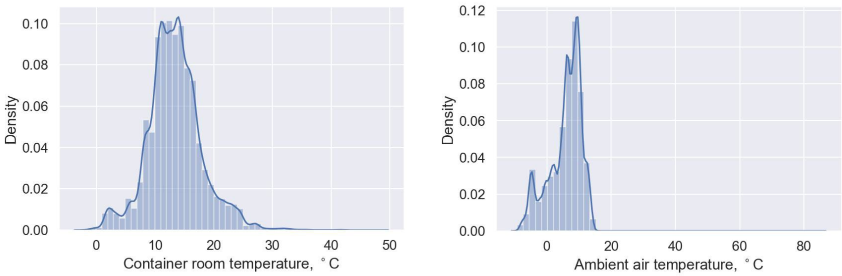
(a) **(b)**

Fig. 3.11. Electrotechnical data: (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 the electricity supply (see Fig. 3.11). 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.

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. The results are shown in Fig. 3.12.

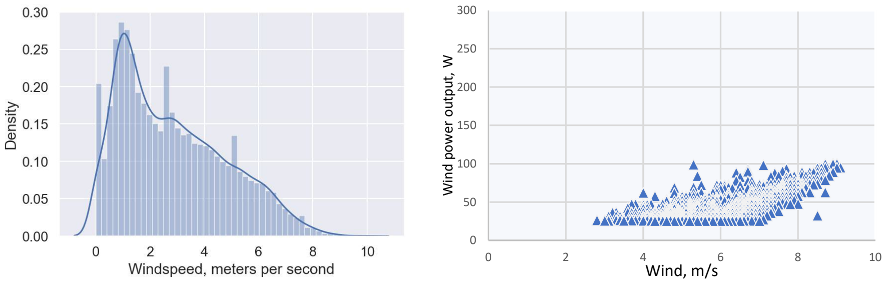


(a) (b)

Fig. 3.12. Air temperature data: (a) for container room; (b) for ambient air.

In the climatic conditions 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 Fig. 3.13), which shows that the wind speed is not particularly high, but it does not explain why wind generator output is so low. The correlation between wind power output and wind speed can be seen in Fig. 3.13 (b).



(a) (b)

Fig. 3.13. Wind speed data: (a) using histogram; (b) using time scatter analysis.

It should be admitted that wind data were obtained for only half of the 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. TRANSITIONING TO DECENTRALIZED ENERGY IN LATVIA

The goals and progress of the European Union (EU) in the field of climate neutrality create opportunities for wider use of distributed generation and the involvement of new market participants in the electricity market.

Therefore, proper system integration and a regulatory framework will be important to simplify and efficiently use all resources and available technologies and ensure higher system reliability and stability. In this chapter, we will analyse new market participants, considering trends in the regulatory environment in the coming years, including decentralized energy resources.

4.1. Amendments to the national legislation

Amendments to the Energy Law

On July 14, 2022, in the second final reading, the Saeima (Latvian Parliament) supported urgently recognized amendments to the Energy Law [11] to adopt the conditions of EU directives. The regulation for energy communities aims to promote the involvement of Latvian society in electricity generation. The amendments to the Energy Law are intended to define new concepts for market participants:

1) "renewable energy community" – an energy community engaged in renewable energy production, owning, developing, or managing renewable energy production facilities territorially associated with the renewable energy community;
2) "electricity energy community" – an energy community operating in the electricity sector;
3) "energy community" – a legal entity with open, democratic, and voluntary participation, aimed at providing environmental, economic, or social benefits to its members or shareholders, or the territories where it operates; which operates energy primarily derived from renewable energy resources, as well as other forms of renewable energy production, trade, electricity sharing, consumption, provision of demand response services, electricity storage, provision of electric vehicle charging services, energy efficiency, or other energy services.

Amendments to the Energy Law, collectively with the supported amendments to the Electricity Market Law and in accordance with forthcoming Cabinet of Ministers' regulations, will establish a legal basis to realize the potential of energy communities. Additionally, investment support programs and extensive public awareness, including the guidelines outlined in the amendments tailored to municipal needs, will be necessary.

Amendments to the Electricity Market Law

On July 14, 2022, during the second and final reading, the Saeima supported amendments to the Electricity Market Law [12], aiming to adopt the conditions of Directives 2019/944 and 2018/2001. The amendments aim to improve the net metering system and supplement it with a net settlement system while setting principles for the operation of electricity communities and active users.

The amendments will define new concepts for market participants:

1) "active user" – an end-user who produces electricity for their own use and can sell any surplus electricity, participate in flexibility services, or energy efficiency schemes, and who is not an energy supply merchant;

2) "electricity sharing" – the transfer of electricity produced by an active user to other end-users, including other active users, or the transfer of electricity produced by an energy community to its members or shareholders;

3) "jointly operating active users from renewable energy resources" – a group of at least two end-users, each separately connected to the electricity distribution system, who, by mutual agreement, jointly produce electricity from renewable energy resources for their own needs, acting collectively in the same building or area with the same address;

4) "active user generating electricity from renewable energy resources" – an active user producing electricity for their own needs from renewable energy resources.

To ensure the full operation of the regulations, the Cabinet of Ministers will need to define:

1) procedures for implementing the NETO settlement system;

2) conditions for using the NETO settlement system, the process for applying the NETO settlement system, and information exchange between involved parties to ensure its administration and the application of de minimis support conditions;

3) procedures for implementing electricity sharing and conditions for electricity sharing.

4.2. Recommendations for future amendments in legislation

Suggestions for future legislative amendments:

1. It should be considered whether there is a need for a more detailed reconciliation between the two communities – "residential energy communities" and "renewable energy communities" – combining them into one. Since the "residential energy community" is technology-neutral while the "renewable energy community" is limited to renewable energy technologies, there should be a focus on the proximity of these communities to the relevant developed renewable energy projects.

2. The law amendments should be clearly communicated to the public, especially regarding the benefits of participation in either the "NETO accounting system" or the "NETO settlement system", distinctly showing the differences between them. For instance, in Fig. 4.1, there is an example demonstrating the potential benefits when not only the generated electricity and consumption are recorded but also the determined value of electricity, considering the specific hour's Nord Pool electricity market price. In this case, the electricity generated in the household is 27 kWh, consumption is 32 kWh, the amount sold to the market is 15 kWh (for 3 EUR excluding VAT, meaning only the electricity component), and the amount purchased from the market is 20 kWh (for 5.71 EUR excluding VAT, again, only the electricity component). The transition from the "NETO accounting system" to the "NETO settlement

system" would likely introduce a fairer distribution of benefits towards the electricity traders but could reduce the benefits of installing solar systems for consumers. This conclusion will be applicable given the price profile depicted in Fig. 4.1 (this kind of situation is likely to become characteristic in Latvia's future, where the installed solar system capacity will be several times larger than it is currently). As the capacity of high-capacity solar farms increases, significant price reductions are expected in peak hours, which will further affect households with solar panels that will use the NETO settlement system principle. In part, this problem can be solved by installing electricity storage equipment; however, for now, the purchase of accumulators is relatively expensive. The following example is considered later in the Thesis (Section 4.3.2).

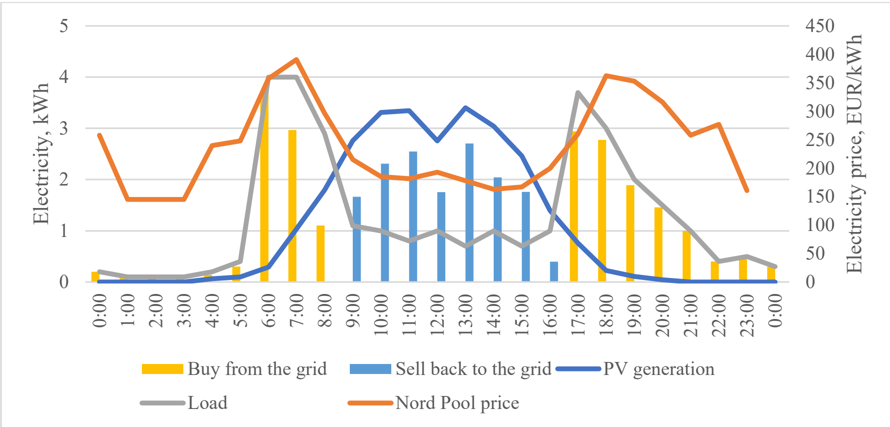


Fig. 4.1. Latvian household solar power usage (July 20, 2022).

3. In the conditions or annotations, it could be clarified how exactly the market value of electricity is allowed to be determined by the trader (i.e., whether it can be the so-called negotiated price, fixed price, or equilibrium price). One of the challenges is how to establish a fair principle of benefit distribution that would be advantageous for the trader, active users, as well as community participants because the transition from the "NETO accounting system" to the "NETO settlement system" is one attempt to address such problems.

4. In the amendments or annotations to the Electricity Market Law, it would be desirable to include a broader assessment of the rights of the system operator to determine the administration fee for the "NETO accounting system", its extent, and the impact on the main task of the "NETO accounting system" – promoting the electricity generation from renewable energy resources.

5. Both sets of law amendments identified several terms that would need to be harmonized in the future, at least across Latvian legislative and policy documents. For example, "renewable energy", electricity "production" or "generation", and others.

6. Introducing the energy community system would require the system operator to assess the development of new principles for tariff calculation, for instance, when electricity distribution occurs within a community and between communities, or additional rules that regulate the community's responsibility for the created imbalance. The public should also be

informed about the benefits of participating in energy communities or electricity trading between such communities.

7. As the number of active users and the capacity of microgeneration systems increase, the income of the distribution system operator from providing electricity distribution services may decrease slightly (on average by 1/3). However, the quantity of electricity transmitted in the network also increases. Hence, an evaluation of tariffs would be necessary to establish fair regulation as the number of active users and the capacity of microgeneration systems increase.

4.3. Decentralized renewable energy payback analysis

4.3.1. Motivation and background

Although there is extensive information regarding the new rules of the NETO settlement system in Latvia, there is a lack of detailed explanation for the general public regarding the potential economic implications for owners of decentralized energy supply solutions [13].

Thus, this section compares the previous NETO accounting system with the new NETO settlement system. Such an analysis would allow for a more accurate assessment of the introduction of new technologies and prediction of the effect of regulatory acts on the economic viability of different situations.

NETO accounting and settlement system in Latvia

Significant changes have been implemented concerning microgeneration in Latvia according to the amendments made to the Electricity Market Law on 16 February 2023.

NETO accounting system (pre-existing system; Fig. 4.2): Previously, the law regulated the NETO electricity accounting system, which outlined the procedure for the distribution system operator to settle payments for electricity produced by users from renewable energy resources.

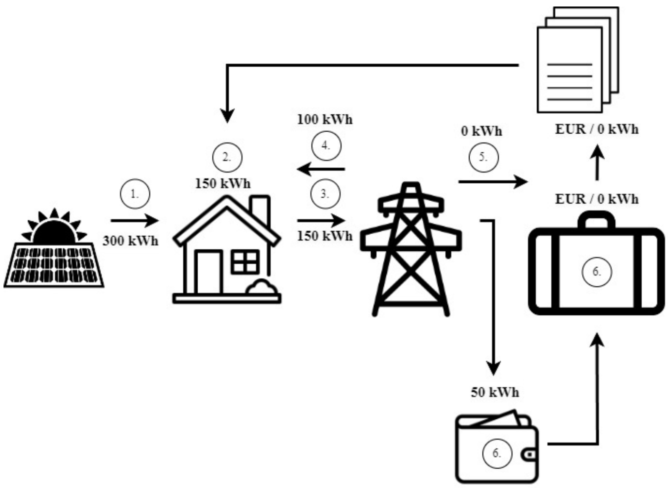


Fig. 4.2. Schematic representation of the NETO accounting system [14].

In Fig. 4.2, the customer transferred 50 kWh more to the electricity network than he received from the network. The customer only has to pay the service fee of the distribution system operator this month but does not have to pay for electricity.

NETO settlement system (new system; Fig. 4.3): The Amendments to the Electricity Market Law introduced a new NETO electricity settlement system. This system not only records the quantity of electricity produced and consumed by the customer but also determines the monetary value of this energy.

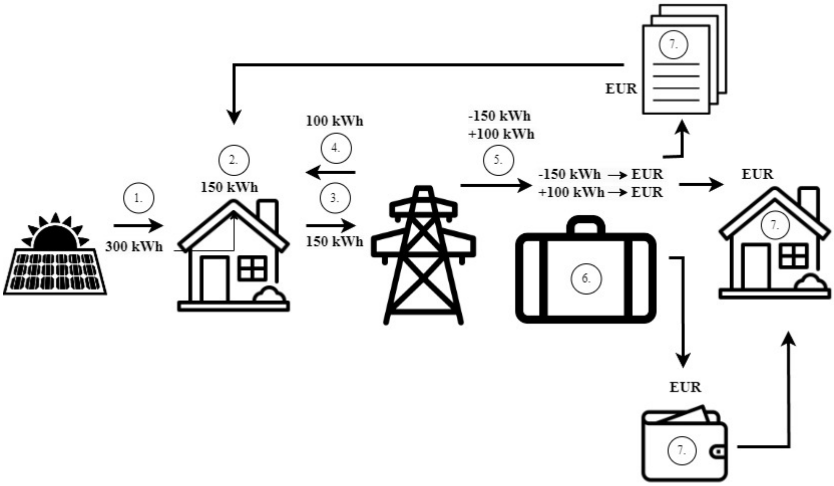


Fig. 4.3. Schematic representation of the NETO settlement system [14].

In Fig. 4.3, the electricity trader determines the value of the electricity transferred to and received from the power grid.

4.3.2. Methodology – case study assumptions

The case study considers a single household as an electricity consumer with access to an electric grid, solar panels, and an electricity storage system in various operating scenarios of the NETO accounting system and the NETO settlement system.

Two NETO system alternatives were compared to investigate how potential household savings change according to different scenarios, namely, with BESS, without BESS, with financial support for their PV system, and without financial support for their PV system.

A significant focus is placed on electricity prices, which have shown considerable volatility in recent years and play a crucial role in determining the economic payback for the installed electricity supply solutions. In the case study, three possible electricity prices (retrospective electricity price from the 2019/20 season, 2022/23 season, or when the electricity price is fixed at 150 EUR/MWh) are analysed. Potential savings, considering the impact of the new distribution system tariff (compared with the previous tariff), which affects all current customers connected to the grid of the Latvian distribution system operator, were thoroughly analysed. Additionally, the implications of the newly introduced special tariff, which is available free of charge to any user, have been also explored.

To study the new NETO settlement system and to compare it with the NETO accounting system, the following annual data at a 1-hour resolution were obtained for one anonymous household from the Latvian distribution system operator "Sadales tīkls AS": date and time, electricity consumption, and electricity generation [15]. The yearly electricity demand of the household was 11.32 MWh, while solar energy injected into the grid reached 4.23 MWh on an annual basis. Unfortunately, information about the specific lifestyle and electricity consumption patterns in the household was not available, including the usage of various appliances. It must also be acknowledged that there is a lack of available data on electricity production, which households consume directly from solar panels (the so-called self-consumption). To ensure a higher economic benefit, households with solar panel systems should achieve the highest possible level of direct electricity consumption. According to [16], the level of direct electricity consumption from solar panels by households in Europe is 20–30 % on average.

Using input data described above, as well as in Table 4.1, all respective scenarios were analysed.

Table 4.1. Input Data and Assumptions on Household Power Supply System [15], [16], [17]

Characteristic	**Indicator or assumption**
Direct electricity consumption from solar panels	30 % of total generation
Solar system capacity and cost	5 kW, 1200 EUR/kW (6000 EUR), which have a possibility to receive the financial support of 2500 EUR
Electricity storage systems (BESS) energy capacity, costs, and operation	10 kWh, 7000 EUR. Maximum discharge level – up to 2 kWh, maximum charging – up to 10 kWh. Roundtrip efficiency is considered 90 %
Current magnitude of the input protection apparatus (IAA) and phases for the electricity connection	Three phases and 25 A
Previous distribution network tariff	Charge for electricity supply 0.04076 EUR/kWh; charge for IAA current magnitude 2.4 EUR/A/year
New distribution network tariff	Charge for electricity supply 0.03985 EUR/kWh; charge for IAA current magnitude 0.92 EUR/A/month
New special distribution network tariff	Charge for electricity supply 0.1594 EUR/kWh; charge for IAA current magnitude 0.37 EUR/A/month

4.3.3. Results and discussion

The First Case Study NETO Accounting System

In Fig. 4.4, the potential savings from solar panels using the NETO accounting system are illustrated. The graph shows the savings based on the current distribution network tariffs and the new ones, as well as considering scenarios with different electricity prices – the 2019–2020 and 2022–2023 season Nord Pool exchange prices, fixed electricity price (150 EUR/MWh), and a scenario with the DSO special tariff. Note that the "special" tariff is intended for households with very small or seasonal electricity consumption. It is assumed that the special tariff is used for three months (June, July, and August), leaving the basic tariff for the remaining months. The special tariff includes a smaller fixed part (capacity maintenance fee, EUR/month); however, it has a higher variable share (charge for electricity supply, EUR/kWh) compared to the basic tariff.

The calculation algorithm has been developed to assess potential savings when compared to a scenario where no solar panels are employed and with a relevant DSO tariff. In this case, BESS is not integrated into the system. This algorithm encompasses both the fixed component (averaged across the total annual consumption) and the variable part of the distribution network tariff, factoring in the per-consumed kilowatt-hour when computing potential savings. Accumulated savings are represented by the bars, while the horizontal lines show the investment in the solar panel system with and without the financial support from the government (assumed to be 2500 EUR).

Fig. 4.4 shows that the lowest potential savings are made in the scenario in which the 2019–2020 Nord Pool electricity exchange prices are adopted (the lowest at the old DSO tariff). It can also be seen that with the 2022–2023 season Nord Pool prices and with the new DSO tariff, the savings could exceed the investments made already starting from the third year, in the case of receiving state support for the installation of solar panels. The significant potential for savings arises from the Nord Pool prices of the 2022–2023 season. In all scenarios, it can be seen that the old tariff system would slow down the savings for the solar panel system, meaning that the new tariff system is more beneficial (as it is more expensive). While it is true that in certain scenarios, the “special” tariff offers greater benefits when compared to the fixed electricity price with both old and new DSO tariffs, it is important to acknowledge that, overall, the electricity price remains the primary determinant in influencing the savings.

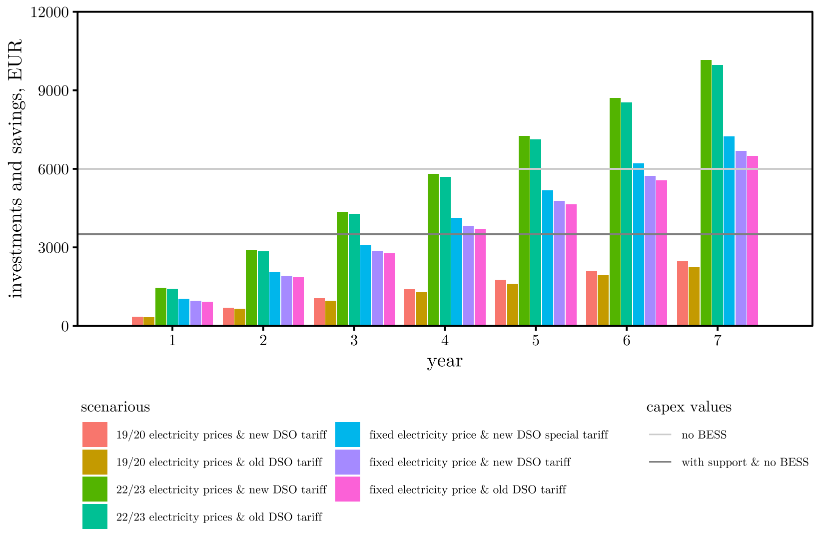


Fig. 4.4. Potential savings in a 7-year period: NETO accounting, without BESS.

Fig. 4.5 shows the potential savings when a BESS system is installed in parallel with solar panels. The algorithm assumes that electricity is consumed from the grid only when it has reached a discharge level of 2 kWh in the installed BESS system. Similar to the scenario shown in Fig. 4.4, it can also be observed here that the old tariffs and low electricity prices slow down the potential savings. At the same time, it is possible to achieve savings at the CAPEX level in the case of state financial support or high electricity prices for seven consecutive years.

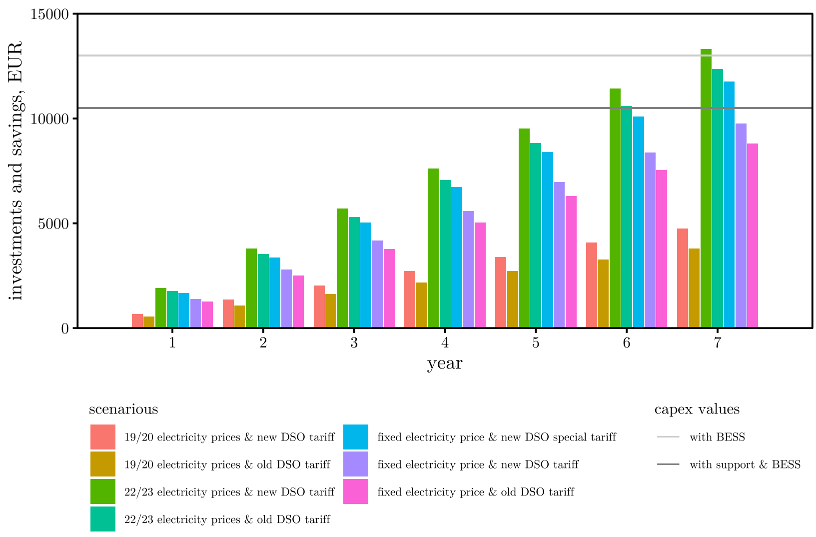


Fig. 4.5. Potential savings in a 7-year period: NETO accounting, with BESS.

Unlike before, when there was no BESS system, having a BESS system and a fixed electricity price in this case does not lead to savings equal to the initial investment.

The first case Study NETO settlement system

A similar algorithm has been created for the assessment of the NETO settlement system. In this case, it is assumed that excess electricity is sold to the electricity trader at a relevant Nord Pool price. The potential savings of the NETO settlement system are shown in Fig. 4.6, where the bars represent accumulated savings, and the horizontal lines show the investment in the solar panel system with and without financial support. In Fig. 4.6, BESS is not integrated into the system. As can be seen, electricity prices have a significant impact on potential savings, i.e., at low market prices and even with subsidies, a solar panel system may not pay off for seven years. Conversely, at high electricity rates and the new DSO tariff, such a system would pay off at around the third year. It can be observed that the savings achieved with the new tariffs are slightly higher than those with the old tariffs.

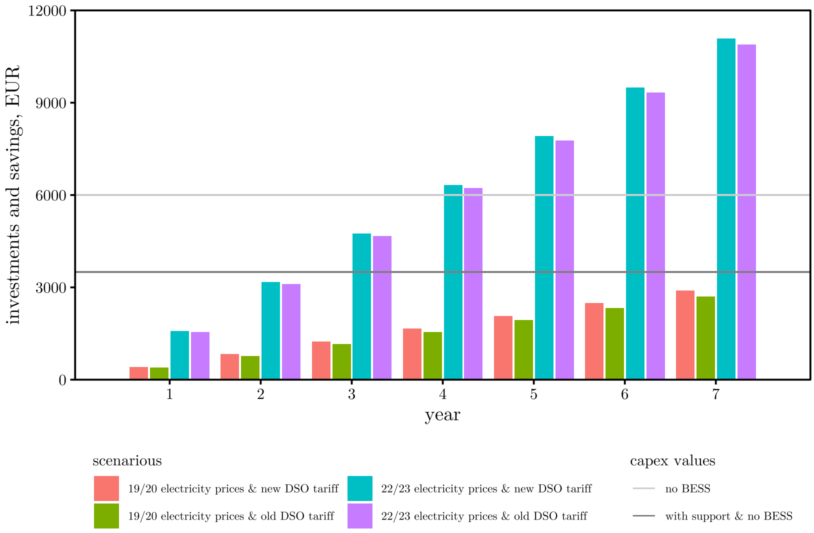


Fig. 4.6. Potential savings in a 7-year period: NETO settlement, without BESS.

Fig. 4.7. shows the potential savings with BESS. Again, the algorithm assumes that electricity is consumed from the grid only when it has reached a discharge level of 2 kWh in the installed BESS. It can be observed that the new tariffs increase the potential savings also in this case. At the same time, it is possible to achieve savings at the CAPEX level only in the case of state financial support and with high electricity prices.

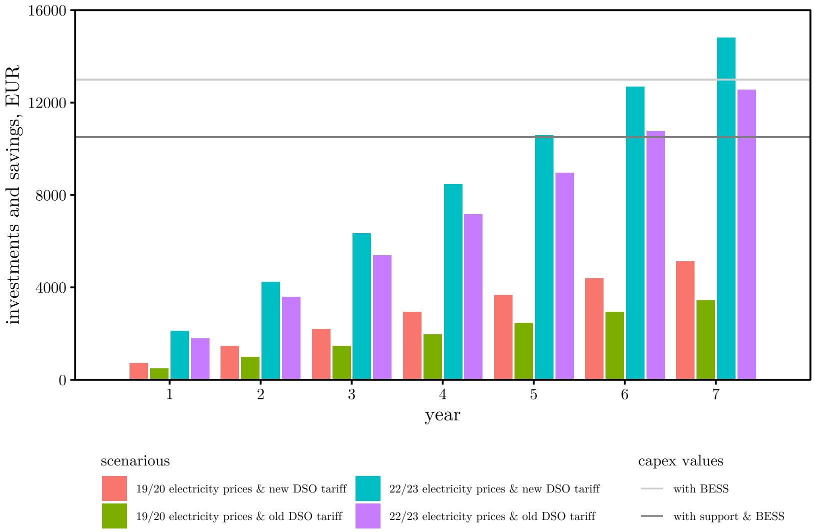


Fig. 4.7. Potential savings in a 7-year period: NETO settlement, with BESS.

At low electricity prices, in this case, savings up to the CAPEX level can hardly be achieved. It could happen only at high electricity rates.

5. CHALLENGES OF NEW SYSTEM SERVICES

5.1. Modelling of battery energy storage system

5.1.1. Motivation and background

The main contribution of this section is the creation of an algorithm that can be applied to evaluate the technical possibility of the provision of frequency containment reserve (FCR) with the battery electric storage system (BESS). It is conducted as a case study to prove the suggested methods' viability in specific circumstances in the Latvian power system.

The idea to use BESS for FCR has been discussed for a while. Other research reviewed on this topic has concluded that BESS can provide the needed response speed to provide FCR. The ability to provide ancillary regulatory services and the prices of ancillary services have a major impact on the economic payback and performance of BESS. Therefore, the BESS operational algorithm should be adapted to the specific electricity system and electricity market needs. Reviewed studies have not addressed the problems Baltic TSOs will encounter in the near future, thus the proposed methodology could be used as guidelines in the decision-making process for the Baltic case [18], [19], [20], [21], [22].

In the following sections, the author proposes a methodology to determine the possibility of using battery systems for FCR service.

5.1.2. Methodology

To understand whether it is possible to maintain frequency stability in the Latvian power system with BESS, a case study was carried out, a calculation model was developed, and the system frequency limiting capability for previously recorded frequency deviations was tested.

Calculation algorithm of the BESS model

The algorithm (see Fig. 5.1) is conditionally divided into two parts – FCR provision and SOC recovery – which in turn is divided into three parts – described SOC management options: deadband utilization, FCR overfulfillment, and scheduled market transactions.

The BESS control provides the FCR service for the requested time, except when the upper or lower charge limit is reached (90 % and 10 %, respectively). When the BESS charge status reaches the specified limits, the FCR service is disabled and the batteries are charged/discharged to the SOC set point, thus restoring the FCR service.

The use of the deadband is activated as soon as the frequency change is within the specified deadband and the SOC level is outside the defined normal value (60 %). Overfulfillment of the specified FCR amount, as well as planned market transactions, take place in parallel with the relevant SOC settings.

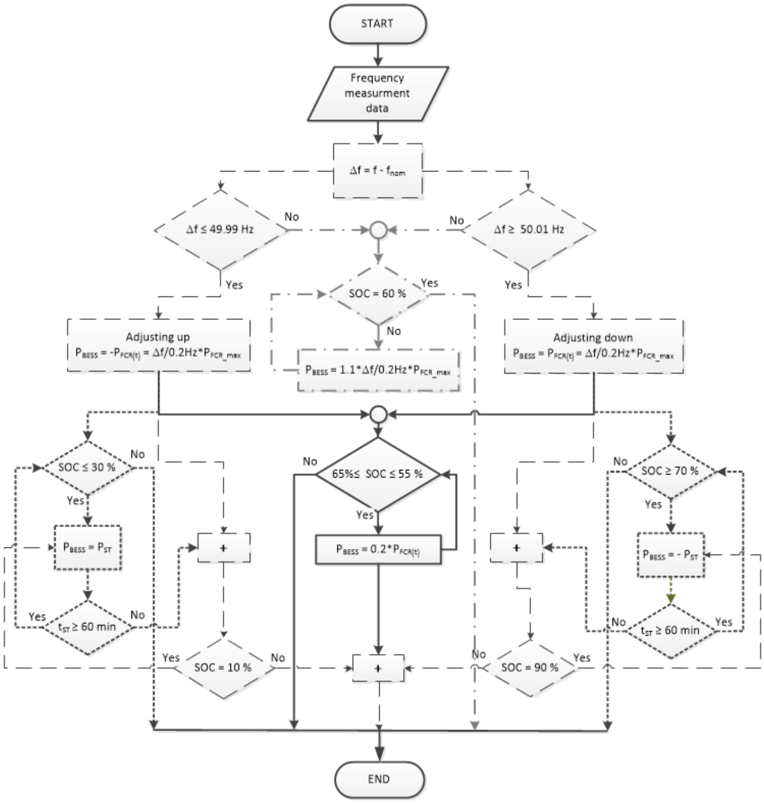


Fig. 5.1. Blocksheme for the BESS operation.

Selection of BESS parameters and operating principle

The choice of BESS nominal power ($P_{\mathrm{BESS\_nom}}$) is determined by the required amount of FCR for the Latvian power system after synchronization with the CESA, which is ± 11 MW. Table 5.1 shows all the technical parameters selected for BESS.

According to the requirements of the European Commission Regulation EU 2017/1485, both upward and downward FCR provisions must be ensured for at least 15 min. This criterion sets the limits for the operation of BESS or the state of charge (SOC). The state of charge for the BESS is an important criterion in planning its operation. BESS manufacturers do not recommend fully discharging or recharging the Li-ion battery systems due to increased degradation of the battery cells. Instead, the maximum and minimum charge conditions must be observed to ensure that the life cycle specified by the BESS is maintained. The developed BESS model assumes that the maximum SOC (SOC_{max}) is 0.9 or 90 % of the nominal capacity ($E_{\mathrm{BESS\_nom}}$) of the battery, while the battery can be discharged (SOC_{min}) up to 10 % of its nominal capacity. Thus, the maximum battery depth of discharge is 80 %, which determines the actual available capacity of the battery ($E_{\mathrm{BESS\_fact}}$).

To ensure the previously mentioned 15-minute criterion in both directions, as well as the permissible SOC levels, a minimum battery capacity is determined mathematically as follows:

$$E_{BESS\_nom} = P_{BESS\_nom} \cdot 0.5/DOD_{max} \tag{5.1}$$

where 0.5 defines half an hour or FCR provision time of 15 min both upwards and downwards, and $DOD_{\max}$ is the coefficient of depth of discharge equal to 0.8.

Calculating Eq. (5.1) and rounding up, the battery nominal capacity of 7 MWh was determined. In addition, the BESS's normal state of charge (SOC_{norm}) should be maintained at close to 50 % to guarantee full BESS availability for both up and down FCR regulation. The calculation assumes that a normal state of charge level is 60 %.

To verify whether the SOC lies within the permitted SOC bandwidth, the state of charge of the battery is calculated as follows:

$$\text{for charging } SOC(t) = SOC(t-1) + \frac{P_{BESS}(t) \cdot \eta_{BESS} \cdot \Delta t}{E_{BESS\_nom}}, \tag{5.2}$$

$$\text{for discharging } SOC(t) = SOC(t-1) + \frac{P_{BESS}(t) \cdot \Delta t}{\eta_{BESS} \cdot E_{BESS\_nom}}, \tag{5.3}$$

where $SOC(t-1)$ is the state of charge at the previous time moment; η_{BESS} is the round-trip efficiency of the battery storage system; and Δt is the time moment of 1 min in the studied case. It is worth reminding that battery power $P_{\mathrm{BESS(t)}}$ is positive when charging and negative when discharging.

The round-trip total efficiency of BESS for charging and discharging processes, also considering the efficiency of the inverter and step-up transformer, is assumed to be 92 % [26].

Due to the BESS's continuous operation with insignificant periods of downtime, its overall self-discharge and self-consumption are not considered in the calculations.

Table 5.1. Selected BESS Parameters

Nominal power	P_{BESS_nom}, MW	11.0
BESS nominal electrical capacity	E_{BESS_nom}, MWh	7.0
Available BESS electricity	E_{BESS_fact}, MWh ($0.8^*E_{BESS\_\mathrm{nom}}$)	5.6
State of charge (min)	SOC_{min}	0.1
State of charge (norm)	SOC_{norm}	0.6
State of charge (max)	SOC_{max}	0.9
BESS round-trip efficiency	η	92 %

5.1.3. Results and discussion

The developed calculation algorithm was used to investigate the performance of the BESS in three cases of frequency fluctuations in the Latvian electricity system in 2018 and 2019 and in the French electricity system in 2019.

Fig. 5.2 shows the amount of FCR provided by the BESS, as well as the electricity consumed or transferred to restore the normal state of charge of the BESS using all three SOC management options (charge with "+" and discharge with "–"). In total, in the Latvian power system, BESS discharged 2100–2240 MWh to the network and consumed 2540–2660 MWh for charging accordingly in the studied year. The electricity required to renew the SOC accounted for only a small part of the total BESS electricity: 0.5 % to 5 % performing FCR overfulfillment and 7 % to 20 % using the deadband.

It should be noted that in the example of frequency deviations in the power system of France, BESS was unable to provide the required amount of FCR with the selected parameters. In the French example, the electricity provided by the BESS in charging and discharging processes exceeded the one of the Latvian examples by almost 70 %. Therefore, in the calculations with frequency fluctuations of the French power system, the capacity required for the scheduled market transactions was increased to 2 MW. The results in Fig. 5.2 show that in this case, BESS transferred around 3160 MWh to the network and consumed around 3800 MWh of electricity for charging.

Fig. 5.3 shows the amount of electricity required for the renewal of the SOC through the scheduled market transactions, which allows to estimate the necessary additional costs for BESS charging or income from BESS discharging. Fig. 5.3 shows that the planned market transactions took place differently on a quarterly basis. In 2018, in the case of frequency changes in the Latvian power system, the predominance was mainly of sold electricity, creating additional income from BESS discharging. On the contrary, in 2019 the amount of electricity purchased for BESS charging was higher (4 MWh), creating additional operating costs. In the case of larger frequency deviations, as was the case in France, a significantly higher volume of market transactions was observed for SOC renewal (with a capacity of 2 MW). In total, the amount of electricity purchased for the renewal of SOC in France through scheduled market transactions was 142 MWh.

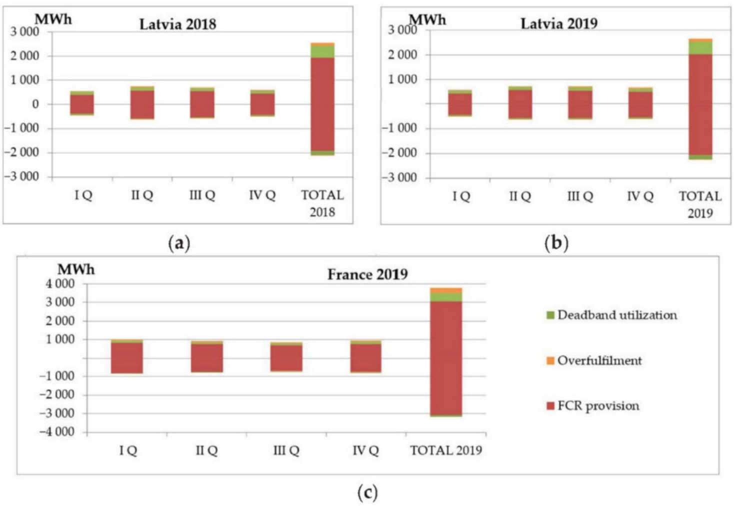


Fig. 5.2. BESS performance for FCR provision and SOC management: (a) Latvia 2018; (b) Latvia 2019; (c) France 2019.

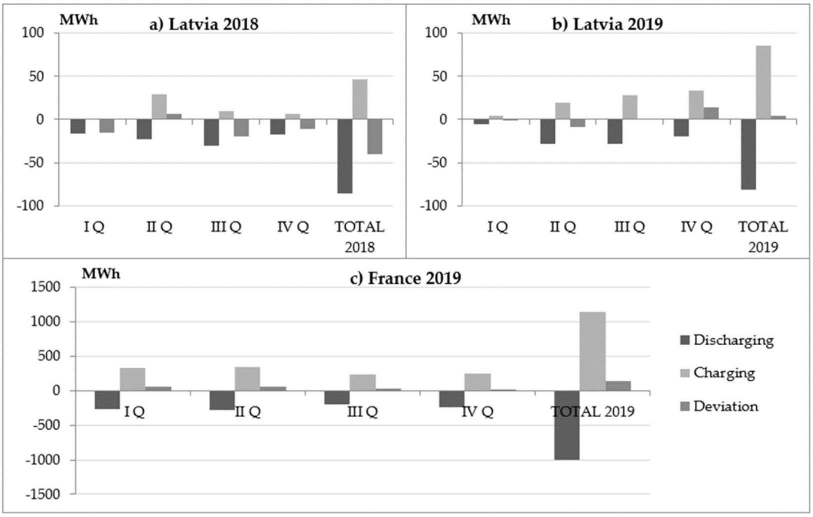


Fig. 5.3. Scheduled market transactions to restore the SOC.

The dynamics for a certain period of time for BESS's active power and state of charge in the case of Latvian power system frequency in 2018 are shown in Fig. 5.4. The total battery power consists of the power provided for the FCR service, as well as all components of the power required for SOC renewal (power of deadband utilisation, FCR overfulfillment, and scheduled market transactions). The SOC of the battery fluctuates on average around the normal setting within the specified limits. When the SOC parameter reaches the set limit of 0.7, the scheduled market transaction is activated with a 1 MW power discharge to the grid for 1 h. Thus, Fig. 5.4 shows how the operating point of the actual BESS power shifts.

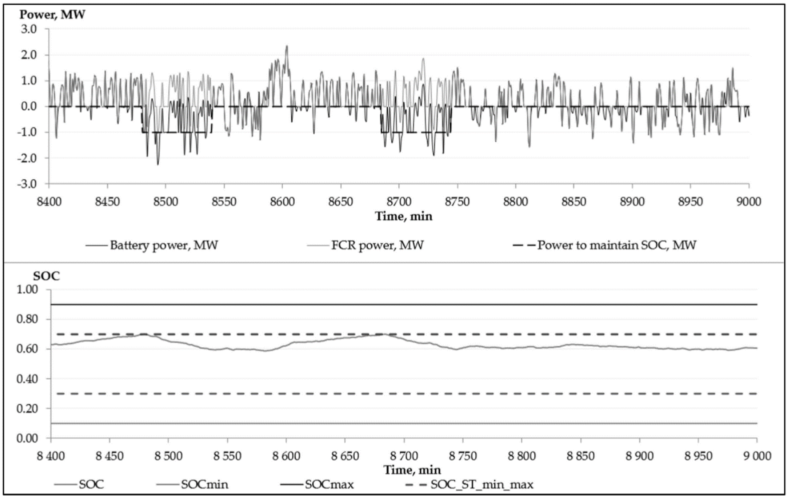


Fig. 5.4. Battery power and SOC dynamics: Latvian power system's frequency changes (Q1, 2018, 06.01.18, 20:00–07.01.18, 06:00).

The dynamics of battery power and SOC in the example of the French power system, are shown in Fig. 5.5. Fluctuations of SOC are more frequent, with larger discharge depths, according to frequency fluctuations. Performed SOC management ensures its maintenance within permissible limits.

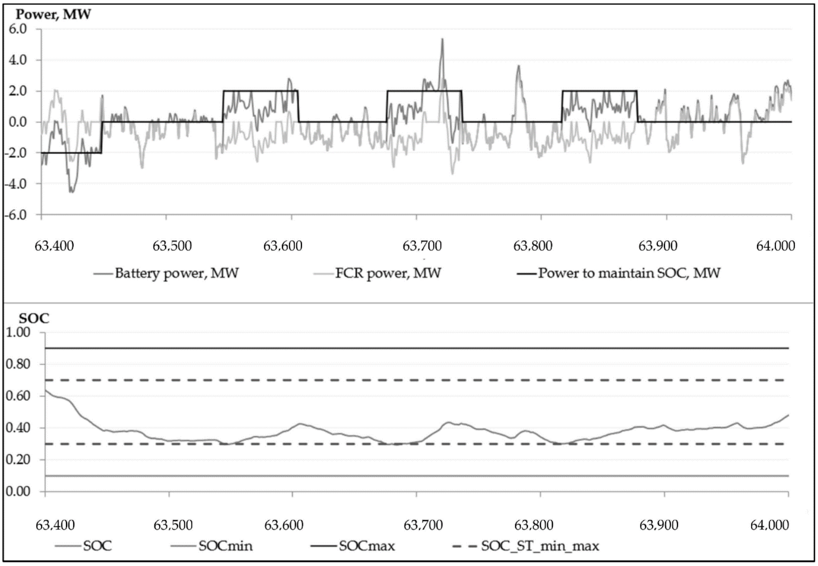


Fig. 5.5. Battery power and SOC dynamics: French power system (Q2, 15.05.19, 00:40–10:40).

In addition, the amount of electricity required to restore the battery's state of charge at the end of its life cycle has been estimated. Due to the yearly cell degradation, it is assumed that at the end of its technical life, the battery capacity has decreased to 80 % of its nominal value. There is no uniform trend in the calculation results. For example, in the case of Latvia, for the frequency data of 2018, it was necessary to additionally discharge the battery for SOC renewal. The surplus electricity sold in the intraday market, in this case, would account for 40 MWh in the first year of operation and increase to 56 MWh (+40 %) in the last. However, analysing the data of 2019, SOC renewal required the purchase of an additional amount of electricity from 4 MWh in the first year to 10 MWh (+150 %) at the end of the battery life. In the French example, the amount of electricity purchased to renew the SOC at the end of the battery's life increased by 35 % compared to the first year of battery operation. The annual electricity consumption for the entire technical life of the battery for the Latvian and French cases is shown in Fig. 5.6.

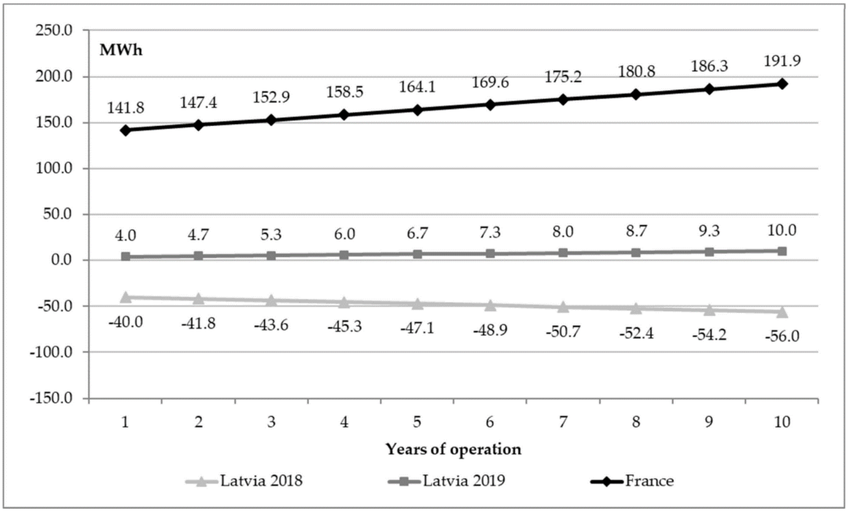


Fig. 5.6. Yearly electricity use for BESS's state of charge renewal over its lifespan.

However, Latvia's two-year observations (for 2018 and 2019) do not allow reliable predictions about the future costs or income of BESS's scheduled transactions. Calculations of BESS operation at the end of its technical life are based on the same frequency fluctuations as in the first year, though frequency dynamics cannot be predicted. It can be assumed that the need to charge BESS will increase due to cell degradation.

All calculations were performed for specific selected parameters to assess possible BESS operation for the provision of the FCR service and the possible BESS income and costs. Changing the parameters of the BESS model may change the overall results. In addition, the choice of BESS parameters is influenced by different frequency characteristics in different synchronous zones. In this case, no optimization task was performed to determine the most economically advantageous and technically useful parameters for the battery system.

5.2. The role of decentralized electrode boiler in ancillary services

5.2.1. Motivation and background

In this section, the installation of EB is evaluated. The aim is to assess different EB capacities and the potential benefits of participating in heat and Baltic balancing markets. More specifically, restoration reserves with manual activation (mFRR) are evaluated in this section, while EB is flexible enough to provide restoration reserves with automatic activation (aFRR) or even frequency containment reserve (FCR). Unlike previous research on district heating system in Riga [24], the use of EB is going to be investigated regarding the provision of ancillary services and heat supply. The proposed methodology considers income from both heat and ancillary services in the Baltic mFRR market.

5.2.2. Methodology

As it has been mentioned above, the plan is to operate an EB in the Baltic balancing market where the mFRR product price and demand vary continuously. The aim is to replace HOB operation with EB. It is assumed that EB will use mFRR downward product to minimize the cost of heat energy, while at the same time generating additional revenues from the Baltic balancing market. Apart from economic benefits, the replacement of HOB with EB could potentially reduce CO_2 emissions.

The calculation principles of EB operation are shown in Fig. 5.7. The cycle is assumed to be one year. At the start of the cycle, the inputs are defined. The inputs to the algorithms include as the following data:

1. Actual heat load data of heat-only boilers in CHP–1 and CHP–2 plants per time unit i (Q_i^{HOB}). For the relevant season, in the range of 0–546 MW, totalling 5751 hours a year.
2. Demand and price data for mFRR product per time unit i (A_i^{mDRR}, P_i^{mFRR}). In 2021, the demand amounted to 223 644 MWh, with an average price of 71 EUR/MWh.
3. The price of natural gas per month m (P_M^{NG}) was in the range of 0.226–1.237 EUR/m^3;
4. Nord Pool day-ahead electricity price per time unit i (P_i^E). In the range of –1.41 EUR/MWh to +1000.07 EUR/MWh, on average, 118 EUR/MWh. Transmission costs and electricity taxes are excluded in calculations.
5. The carbon dioxide price per time unit i ($P_i^{CO_2}$) ranged from 33.54 EUR/t to 79.097 EUR/t.
6. The average efficiency of the HOB (η_{avg}^{HOB}) was assumed to be 0.995.
7. The carbon dioxide emission factor of natural gas (E_{CO_2}) was assumed to be 0.201 t/MWh.
8. Investments in CAPEX were assumed to be EUR 0.08 million per MW, while fixed OPEX at 1100 EUR per MW and variable OPEX was 0.5 EUR per MWh a year.

All data sets were sourced from 2021 to ensure that the analysis would remain unaffected by parameter spikes that emerged from 2022 onwards, such as increased electricity and gas prices, gas savings in CHPs, etc.

As the outputs of the algorithms include the heat production costs from gas boilers and the EB, it is necessary to determine whether there is potential to use an electrode boiler, as well as EB operational costs and potential income together or independently from HOB replacement and mFRR market.

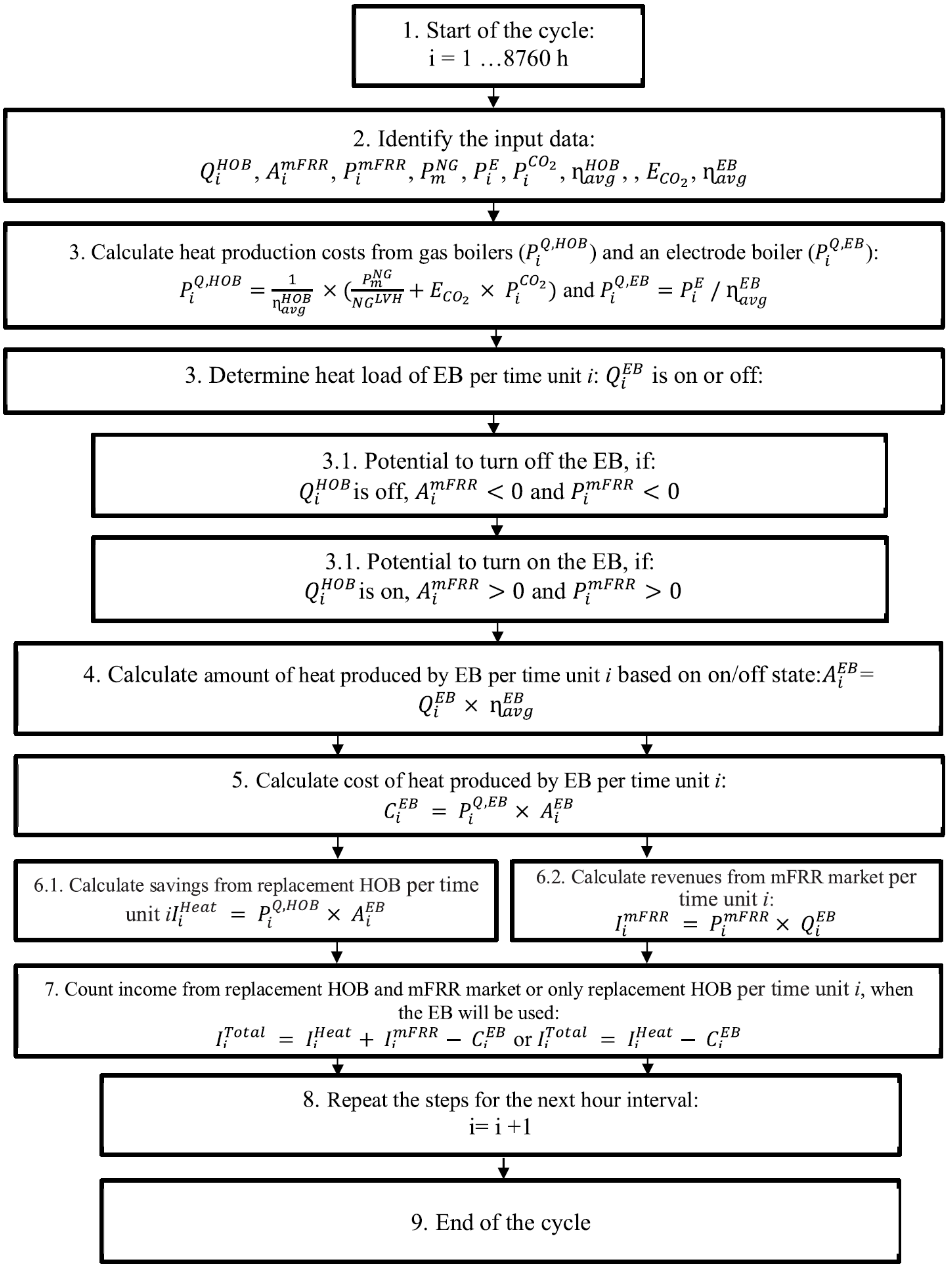


Fig. 5.7. The calculation principles of EB operation.

5.2.3. Results and discussion

Based on an analysis and the operational patterns of CHP–1 and CHP–2, the results have been obtained for various EB capacities, starting from 10 MW to 100 MW.

The use of EB not only reduces the heat production costs of CHPs but also generates revenues from the Baltic balancing market (see Fig. 5.8). Figure 5.8 (a) represents the scenario where the EB operates and receives savings from HOB replacements and revenues in the mFRR market. Fig. 5.8 (b) represents the scenario where the EB can also be used for HOB replacement when it is beneficial, even if there is no demand for the mFRR product during a specific hour.

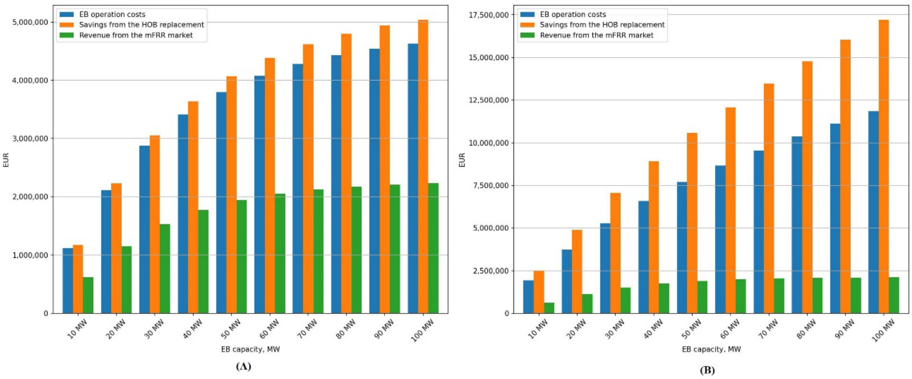


Fig. 5.8. Operation of EB with different capacities.

Fig. 5.9 shows that in both scenarios – A and B – the overall income of using an EB is significantly enhanced. Scenario B demonstrates that the EB should be utilized not only when there is a demand for the mFRR product but also in other situations where it can effectively maximize savings from HOB replacement. Furthermore, Fig. 5.9 illustrates the EB variations in heat production, income, and working hours between Scenarios A and B. This serves as further confirmation that the EB should be employed not solely when there is a demand for the mFRR product but also in other hours where it can significantly optimize savings by replacing HOBs.

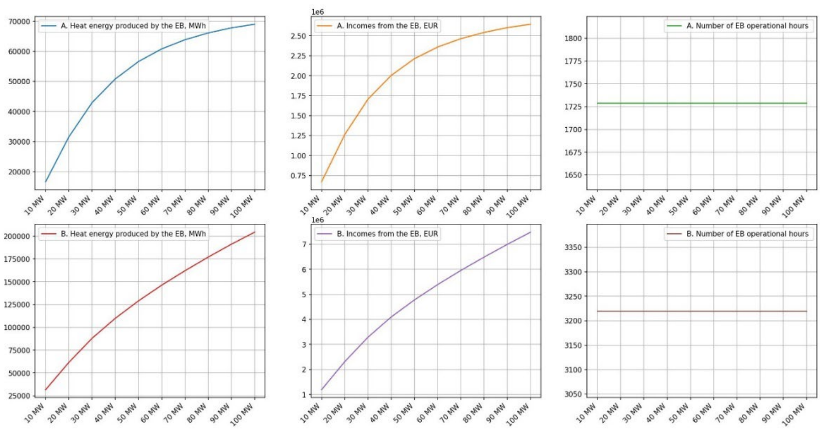


Fig. 5.9. Operation of EB in Scenarios A and B.

It is worth noting that once the EB capacity reaches 50–60 MW, there is no significant increase in the amount of thermal energy produced or revenues from the mFRR market (Fig. 5.9). Even more, the project's payback indicators increase from such capacity. As a result, it is suggested that developing an EB of this size (50–60 MW) would be advantageous.

CONCLUSIONS

1. The hypothesis of the Thesis emphasizing the prioritization of efficient planning and operation of decentralized power supply solutions has been validated. The evidence indicates that adopting appropriate models and methods can lead to a more flexible, sustainable, and balanced energy landscape in Latvia. Decentralized power supply solutions have proven effective in addressing challenges related to intermittent generation, improving system flexibility, reducing energy prices, and enhancing overall infrastructure efficiency. To foster energy transition in Latvia and the Baltic region, advanced models and methods are essential, promoting seamless participation of all market stakeholders, focusing on the integration of renewable energy sources, and optimizing critical components, including microgrids, energy storage, electric boilers, state-run energy programs, and meeting customer demand including electric vehicles, heat pumps, and other innovations.
2. The developed methodology using software (Homer Pro) tool proposed by this research for sizing household off-grid systems provides an easy-to-use method to assess multiple scenarios and criteria for optimal off-grid system equipment sizing, offering simple but at the same time advanced results for planning and operating electricity supply for households.
3. The mathematical model developed within this research can be used as an assessment tool for determining the sizing of off-grid and microgrid equipment . It allows analysing potential generation by source, BESS charging and discharging versus the required load, calculating annual system costs, and other parameters. It gives all the necessary key values to evaluate the possibility of creating a microgrid solution.
4. Practically, both reviewed tools have their advantages and disadvantages. The software tool allows highly automatizing the sizing offering, thus providing a quick multi-scenario approach. Our own developed simulation model gives an advantage to tweak the equipment sizing for very specific cases and can be further implemented on multiple software tools considering users' preferences. It can be used to validate the results from other software tools as well.
5. Both evaluated tools have proven that they are capable of helping with the optimal energy source mix and sizing of the off-grid system determination. However, upon careful examination of the provided data, it became evident that simulation results exhibited discrepancies in specific aspects when compared to the actual operation of the off-grid system. It is important to acknowledge that simulation tools may not consistently validate results in all real-world scenarios. To assess their accuracy, a more extensive period, exploration of various operating modes, and the inclusion of diverse measuring devices, among other factors, may be necessary for more experimental testing.
6. Despite the government's financial support for installing microgenerators in Latvian households, as highlighted in the payback analysis, the investment cost for other relevant technologies, particularly energy storage, is still too high for the end-users in

certain scenarios. Conversely, in other situations, it is evident that solar microgenerators, for instance, can yield positive returns even without external support. The legislative review indicated the need for policymakers to enhance justification and communication with relevant stakeholders before formulating new rules for NETO billing programs and financial support schemes associated with decentralized power supply solutions, for example, showing that the savings from solar panels will mainly depend on the price of electricity in the market, not the NETO systems, or by showing the cases in which the energy storage will generate sufficient savings to justify the investments, how the savings will change at different operating principles of the energy storage.

7. The situation in the Latvian power system following its desynchronization from BRELL is unique, and there are currently no clear forecasts regarding the future frequency dynamics within the power system or the evolution of FCR service prices. Nonetheless, the mathematical model proposed in this study proved that it is worth considering a battery electric storage system (BESS) as an option to provide sufficient levels of frequency containment reserves as well as other ancillary services. With the developed model, it is possible to make calculations for specific selected parameters to assess possible BESS operation for the provision of the FCR service, as well as to assess the possible BESS incomes and costs. It is crucial to note that modifying the parameters of the BESS model has the potential to influence the overall outcomes.
8. Another algorithm designed for technical and economic evaluation has been applied to power-to-heat technology, more precisely, electric boilers. The formulated hypothesis for evaluating electric boilers has been validated, indicating their potential to reduce heat production costs for CHPs and generate additional benefits through participation in the Baltic balancing markets. However, its applicability and economic viability may vary across situations and regions. The economic feasibility of this technology depends on factors such as the chosen electric boiler capacity, initial and operational costs, connectivity expenses, and others, which can be assessed more precisely in future studies.

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