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

Doctoral Thesis

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RIGA TECHNICAL UNIVERSITY
Faculty of Computer Science, Information Technology and Energy
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Doctoral Thesis

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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, conclusion, 69 figures, 23 tables, and 10 appendices; the total number of pages is 121, not including appendices. The Bibliography contains 97 titles.

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

ABSTRACT

The electricity sector is undergoing a continuous transformation, driven by the rapid growth of renewable energy sources and the pursuit of smarter, more energy-efficient electricity supply systems. Europe's ambitious goal of achieving climate neutrality by 2050 necessitates a redefinition of electricity supply rules and a reshaping of market participants' roles. New decentralized power technologies are fundamentally altering the dynamics of the electricity supply sector, both already now and in the future. New types of electricity users are emerging, increasingly conscious not only of electricity consumption, but also of its production. In recent years, the number of EU residents who utilize electricity not only for household needs but also for heat pumps (for heating and hot water supply) or electric vehicle charging has risen significantly. Moreover, these users are increasingly engaging in self-generation, energy storage, demand response, and other energy services. Simultaneously, large electricity producers must adapt to the new reality of rapid demand fluctuations and price changes in energy markets.

Therefore, this thesis focuses on examining modelling and methodology tools for evaluating decentralized power supply system solutions. The findings are intended for use in developing of innovative products and services for customers of decentralized power supply systems, empowering them to assess and enhance energy resilience, promote sustainability, and diversify energy sources while reducing reliance on centralized grids. This assessment of how to operate, plan, and derive economic benefits from new decentralized power supply solutions can be instrumental in establishing robust business cases. Thus, the models and methods presented provide a comprehensive analysis of emerging technologies and their role in the energy transition. Furthermore, the research findings can guide policymakers in developing effective market regulations and determining the need for additional incentives to accelerate energy transition even faster.

ANOTĀCIJA

Elektrības nozare piedzīvo nepārtrauktu pārveidi, ko veicina strauja atjaunojamo enerģijas avotu izaugsme un centieni pēc gudrākām, energoefektīvākām elektroenerģijas apgādes sistēmām. Eiropas ambiciozais mērķis sasniegt klimatneitralitāti līdz 2050. gadam prasa pārskatīt elektroenerģijas apgādes noteikumus un pārveidot tirgus dalībnieku lomu. Jaunās decentralizētās elektroapgādes tehnoloģijas būtiski maina elektroenerģijas apgādes nozares dinamiku gan jau tagad, gan nākotnē. Parādās jauni elektroenerģijas lietotāji, kuri arvien vairāk apzinās ne tikai elektroenerģijas patēriņu, bet arī tās ražošanu. Pēdējos gados ir ievērojami pieaudzis ES iedzīvotāju skaits, kas elektroenerģiju izmanto ne tikai sadzīves vajadzībām, bet arī siltumsūkņiem (apkurei un karstā ūdens apgādei) vai elektrotransportlīdzekļu uzlādēšanai. Turklāt šie lietotāji arvien vairāk nodarbojas ar pašražošanu, enerģijas uzglabāšanu, pieprasījuma slodzes izmaiņām un izmanto citus ar enerģiju saistītus pakalpojumus. Vienlaikus lielajiem elektroenerģijas ražotājiem ir jāpielāgojas jaunajai realitātei, kurā ir straujas pieprasījuma svārstības un cenu izmaiņas enerģijas tirgos.

Tāpēc šī disertācija ir vērsta uz modelēšanas un metodoloģisko rīku izpēti decentralizēto elektroapgādes piegādes sistēmu risinājumu novērtēšanai. Iegūtie rezultāti ir paredzēti izmantošanai, lai izstrādātu inovatīvus produktus un pakalpojumus decentralizēto elektroapgādes sistēmu klientiem, dodot viņiem iespēju novērtēt un uzlabot enerģijas noturību, veicināt ilgtspējību un dažādot enerģijas avotus, vienlaikus samazinot paļaušanos uz centralizētajiem elektrotīkliem. Šis novērtējums par to, kā darboties, kā plānot un kā gūt ekonomiskos labumus no jauniem decentralizētiem elektroapgādes piegādes risinājumiem, var būt būtisks, lai izveidotu stabilus biznesa gadījumus. Tādējādi piedāvātie modeļi un metodes sniedz visaptverošu analīzi par jaunām tehnoloģijām un to lomu enerģijas pārejas procesā. Turklāt pētījuma rezultāti var palīdzēt politikas veidotājiem izstrādāt efektīvus tirgus noteikumus un noteikt nepieciešamību pēc papildu stimulēšanas pasākumiem, lai paātrinātu enerģijas pāreju vēl straujāk.

CONTENT

Appendix I:	Gicevskis K., Linkevics O., Groza E., Kiene S.; “Multiple Scenario and Criteria Approach for Optimal Solution and Sizing of Household Off-grid System”; 2021
Appendix II:	Groza E., Gicevskis K., Linkevics O., Kiene S.; “Mathematical Model for Household Off-Grid Simulation (Off-Grid System Sizing)”; 2022
Appendix III	Linkevics O., Vesperis E., Gicevskis K., Osadcuks V., Pecka A., Galins A.; “Analysis of Experimental Data from Household Off-Grid System in Latvia”; 2023
Appendix IV	Gicevskis K., Linkevics O., Groza E.; “Jauni elektroenerģijas tirgus dalībnieki un tehnoloģijas–regulatīvie izaicinājumi”; 2022
Appendix V	Gicevskis K., Linkevics O., Karlsons K.; “Transitioning to decentralized renewable energy in latvia: a comprehensive payback analysis”; 2023
Appendix VI	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”; 2022.

Appendix VII	Groza E., Smiltans E., Gicevskis K., Karpovica, I.; “Pasaules enerģētikas trilemmas indekss: globālā pieredze lokālu risinājumu meklējumos”; 2022
Appendinx VIII	Groza E., Gicevskis K., Smiltans E., Karpovica I., Valdmanis G.; “Latvia’s Energy Supply and Security”; 2023
Appendinx IX	Groza E., Kiene S., Linkevics O., Gicevskis K.; “Modelling of Battery Energy Storage System Providing FCR in Baltic Power System after Synchronization with the Continental Synchronous Area”; 2022
Appendinx X	Gicevskis K. and Linkevics O.; “The Role of Decentralized Electrode Boiler in Ancillary Services and District Heating: a Feasibility Assessment”; 2023

LIST OF FIGURES

LIST OF TABLES

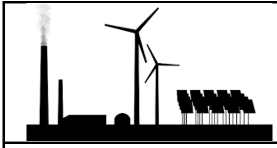
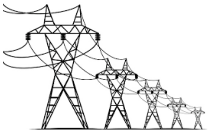
INTRODUCTION

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 to 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. Assess energy security of supply in an environment where decentralized power supply solutions are introduced and the need for flexibility arises.
4. 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).
5. 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 theBauska 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 masters 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 in 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 Linkevics, 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 methodologies for secure energy transition, 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 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)

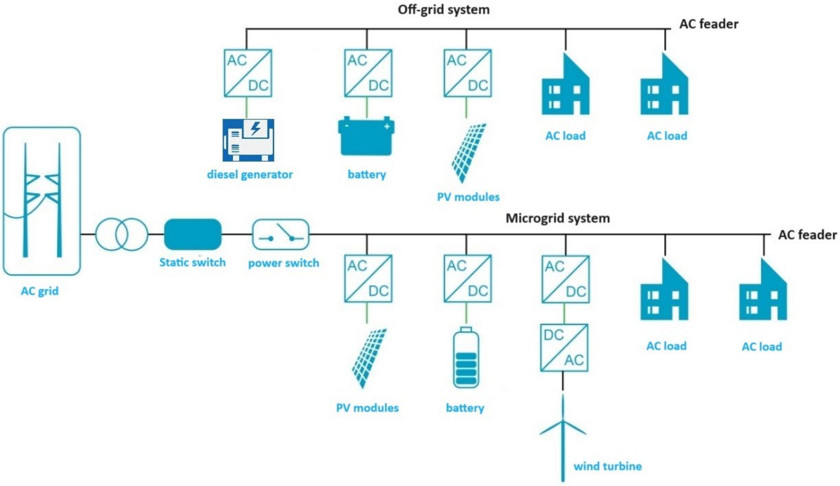


Fig. 1.1. Off-grid and microgrid power supply systems.

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).

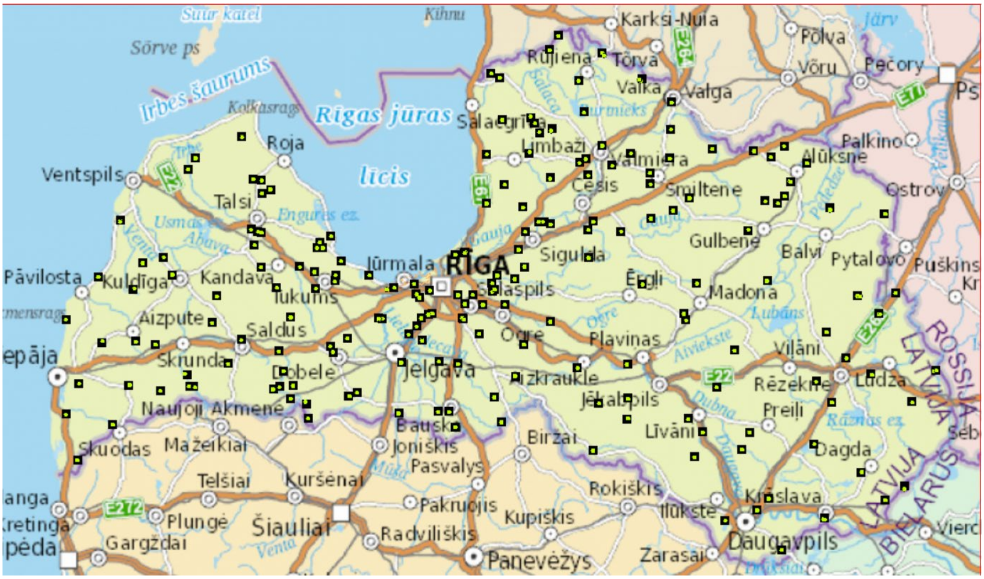


Fig. 1.2. Potential locations for off-grid or microgrid power supply solutions to customers in Latvia [5].

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 rise 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).

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

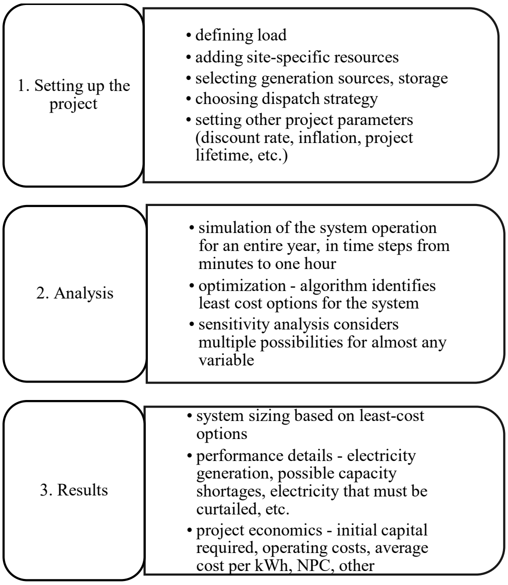


Fig. 1.3. Homer Pro process diagram.

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.

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

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].

The software can satisfy specific constraints like generator operation restrictions, capacity shortage level, fuel costs, etc. and at the same time determining an optimal sizing of system components and providing detailed information on system with a lowest total net present cost.

Compared with other software computing techniques such as RETScreen, PVSOL, Hybrid 2, TRANSYS, SAMS, RAPSYS and MATLAB, HOMER Pro have benefits such as the wider options when setting up the project, realistic and continuously updated library of components, possible combinations over varying restrictions as well as various dispatch strategies [9]. Within Homer Pro software it is also possible to directly download nature resource data from NASA (abbr. for National Aeronautics and Space Administration) databases on specific location user choose. In default situation, such data are obtained:

1. Solar radiation monthly averages over 22-year period (July 1983–June 2005).
2. Air temperature monthly averages over 30-year period (January 1984–December 2013).
3. Wind speed monthly averages over 10-year period (July 1983–June 1993) are obtained.

However, on the other hand, sometimes some scenarios might be needed to be re-calculated individually for the specific situation, because HOMER Pro can only handle single-object optimization and thus the flexibility is limited [9].

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].

After all, users have possibility to write even their own dispatch algorithms for HOMER Pro using MATLAB. Determination of optimal dispatch strategy depends on many factors, including the size of backup generator and battery system, the price of diesel fuel, the operational and maintenance cost of a generator, the amount of renewable power in the system, and the availability of the renewable resources. The right choice of dispatch strategy is an important factor. Selection of nonoptimal dispatch strategy can result in unnecessarily high operating costs from using more diesel fuel or surplus battery capacity. One of the roles of dispatch strategy is to avoid situations where energy that was charged in the battery by the diesel generator is eventually wasted, because the same charging could have been accomplished by the renewable sources before the energy is needed [10].

HOMER Pro ensures that overall power generation meets (or exceeds) the total system electricity demand. Nevertheless, it is possible to have excess electricity at certain time-steps, due to a small demand or high renewable energy generation. This electricity is considered as curtailed or dumped by HOMER Pro software.

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.

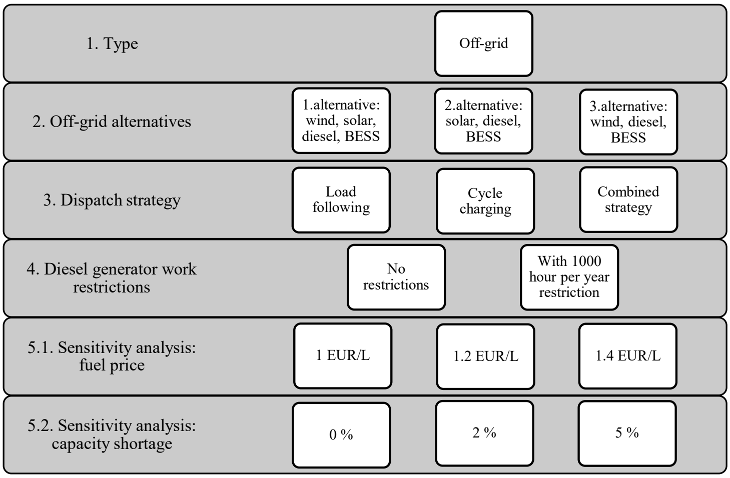


Fig. 1.4. Block scheme for the case study.

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 the 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 a 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 %.

1.2.3. Dispatch strategies

According to the block scheme of the case study, three different dispatch strategies, described previously, are used-cycle charging (CC), load following (LF), combined charging dispatch strategy (CS). All strategies to each of the off-grid alternative to see how it will address the technical and economic aspects are applied. To better understand how dispatch work, Fig. 1.5 shows simulations of 1st of January for all three mentioned strategies. In LF strategy generator mostly follows electric load and is practically not used for BESS charging. In CC strategy generator covers peak demand at full load with surplus used to charge BESS. In CS strategy the combination of both approaches is used. Solar and wind generation is practically unavailable on a given day.

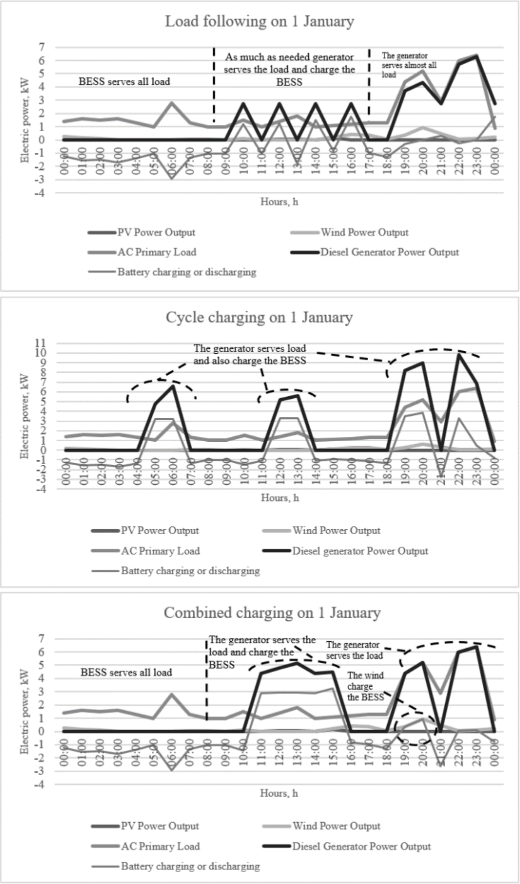


Fig. 1.5. Three dispatch strategies in action on 1st of January.

Fig. 1.6 shows simulations of 1st of June for all three mentioned strategies. Solar and wind generation has higher availability in comparison to simulations of 1st of January. In LF strategy renewable generation is used at most, with surplus used for charging. In CC strategy generator is operated at full capacity to secure higher charging of BESS. In CS strategy-combination of both.

The first alternative (wind, solar, diesel generator and BESS) is used to show electricity flows operated by each of dispatch strategy. Fig. 1.5 and Fig. 1.6 shows that with each dispatch strategy at different hours the load is served from different sources. Consequently, at the end, dispatch strategies have their impact to the renewable energy source (RES) fraction delivered to the load. All off-grid alternatives with and without generator operation restrictions are used to show possible RES fraction.

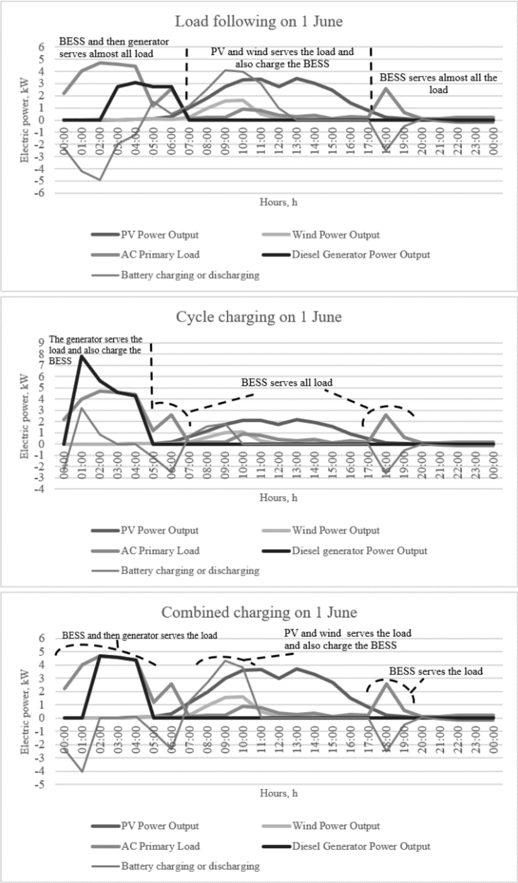


Fig. 1.6. Three dispatch strategies in action on 1st of June.

Fig. 1.7 has a box and whisker chart. This chart type distributes simulated data into three quartiles, to examine how data are dispersed between all results. The bottom of the box represents the first quartile, meaning that 25 % of simulated results fall below this level. While the top of the box represents the third quartile, meaning that 75 % of simulated results fall below this level. Line through the box is median also called as the second quartile, and it marks the mid-point of the data, where one-half (50 %) of the data lies below, and another-half (50 %)

lies above. The element-x in boxes highlights the mean value. The boxes have also lines extending vertically called “whiskers”. The top whisker indicates the maximum value, while the bottom whisker indicates the minimum value in the data set. Any point outside those lines or whiskers is considered an outlier. The outlier is an unusual data present in the data set.

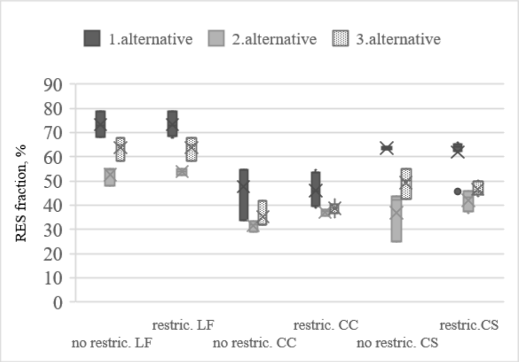


Fig. 1.7. The fraction of RES delivered to the load according to dispatch strategies.

For all off-grid alternatives, Fig. 1.7 shows that using LF strategy the RES fractions reach the greatest values, while. In CC-lowest RES fractions. Fig. 1.7 also shows that the fuel restriction may increase RES fractions, however, the choice of dispatch strategy has a greater impact. In more detail the dispatch strategies have been discussed in following sections where their impact on off-grid equipment components is assessed.

1.3. Results from simulations conducted for three alternative scenarios

The first alternative

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. Results are shown in a box and whisker chart in the Fig. 1.8.

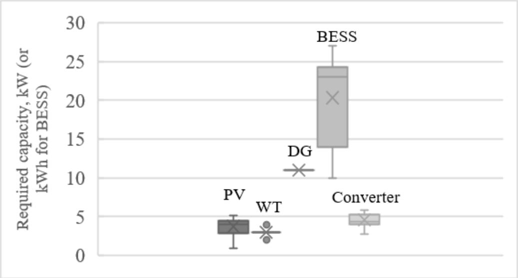


Fig. 1.8. System equipment dimensions for the first alternative.

Calculations show that the required capacity of solar panels can vary within 0.9–5.2 kW range. Wind turbine capacity is within 2–4 kW range (counting outliers). Diesel generator – 11 kW, while BESS storage capacity maximum and minimum values are in 10–27 kWh range, but power capacity corresponds to converter capacity which is within 2.8–5.8 kW range. The capacity of the diesel generator is constant (11 kW) because system must ensure safety and to cover the maximum daily load (which is around 9 kW).

The second alternative

System equipment dimensions for the second alternative (solar, diesel, BESS) is shown in a box and whisker chart in the Fig. 1.9. Required capacity for solar panels is within 6.3–11.8 kW range. There is no wind turbine in this alternative, so its capacity is 0 kW. Diesel generator – 11 kW, while BESS storage capacity is in range 25–32 kWh.

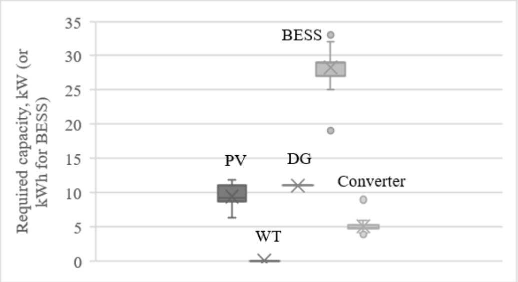


Fig. 1.9. System equipment dimensions for the second alternative.

The BESS power capacity corresponds to max-min values of converter capacity, which is within 4.0–5.8 kW range.

The third alternative

System equipment dimensions for the third alternative (wind, diesel, BESS) are shown in a box and whisker chart in the Fig. 1.10.

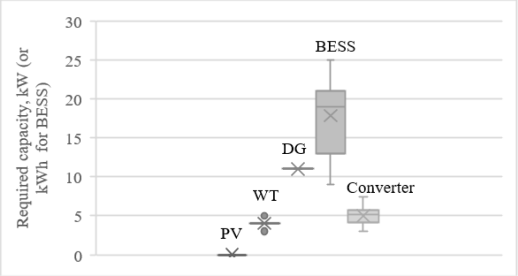


Fig. 1.10. System equipment dimensions for the third alternative.

There are no solar panels in the third alternative, so the capacity is 0 kW. Wind turbine capacity is within 3–5 kW range (if we count outliers). Diesel generator – 11 kW, while BESS storage capacity is within whiskers 9–25 kWh range, but power capacity corresponds to converter capacity, which is within 3.0–7.4 kW range.

Comparison of all off-grid alternatives

Table 1.3 shows the average equipment values for each of 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. First alternative would need less solar panels and wind turbine capacities comparing with second and third alternative.

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. 1.11 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. 1.11 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.

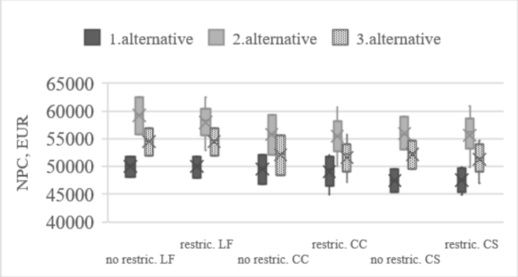


Fig. 1.11. NPC results depending on different dispatch strategies.

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. 1.12 shows how fuel price impacts fuel consumption of 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.

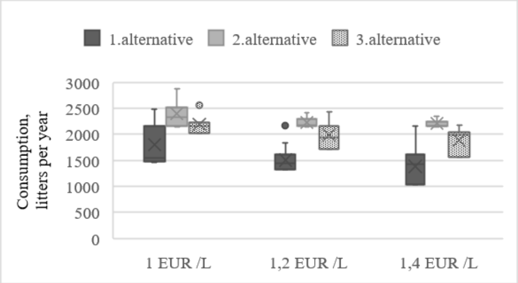


Fig. 1.12. Generator fuel consumption depending on fuel price.

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 the Fig. 1.13, it is possible to assess the capacity shortage impact.

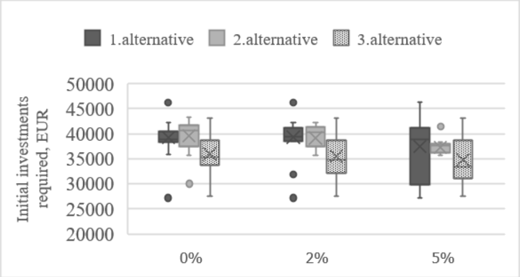


Fig. 1.13. Initial off-grid investment costs depending on capacity shortage.

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. 1.13 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. 1.14.

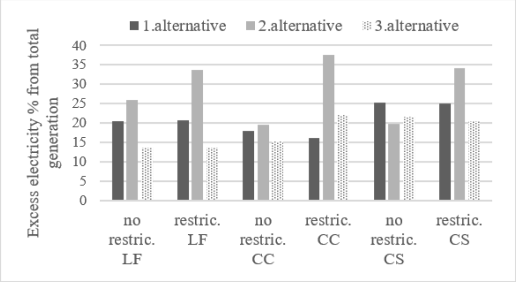


Fig. 1.14. Excess electricity in the all off-grid alternatives.

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

In recent years, microgrid systems either when operated in an off-grid or a grid-connected mode have been recognized as one of the most suitable, cost-effective, and sustainable solutions for commercial, industrial, and residential electrification applications [11], [12]. Decreasing costs of renewable energy technologies, fluctuating fossil fuel prices, environmental concerns and security of electricity supply are the main reasons for looking towards the development of emerging microgrid systems [13].

However, research on such systems still must be examined. For instance, microgrids have challenges regarding determination of proper equipment sizing, the voltage and frequency disturbance problems in unpredictable weather conditions, difficulties with monitoring and managing local power generation and loads, along with constrains related to designing protection devices to cope with bi-directional power flows and so on [11]. Within this paper, our focus is on autonomous household scale microgrid equipment sizing problems.

The microgrid equipment sizing is understood as quantification of the power capacities for renewable generators (solar, wind, etc.), as well as for backup power generator and determination of the power (kW) and energy (kWh) capacities of a battery energy storage system (BESS). The proper sizing of the microgrid may reduce the risk of oversize system equipment, which could lead to higher initial capital costs. On the other hand, it may reduce the risk of undersize equipment, which can lead to the poor power supply reliability [14]. Moreover, environmental and social aspects are no less important. Therefore, it is necessary to consider how to minimize emissions, how to promote socially acceptable system development, which includes issues with land use, visual impact, acoustic noise, etc.

According to literature review, several types of methods and different indicators might be considered in the evaluation process of such microgrid equipment. The sizing methods can be classified as classical methods, software tools, hybrid methods and most recently also artificial intelligence methods as shown in Table 2.1. In the most common cases, four types of indicators are identified which further describe the performance of microgrid: economic indicators (LCOE, LCC, ACS, NPV etc.), reliability indicators (LPSP, LOLP, EENS, etc.), environmental indicators (CE, LCA, EE), and social indicators (HDO, JC, SA, etc.) [15], [16].

In addition to the review mentioned above, some articles have summarised the latest trends of algorithm and indicators, and future overall challenges of microgrid sizing methodologies. For example, ant colony (ACO), firefly algorithm (FA), particle swarm optimization (PSO) and genetic algorithm (GA) and their performance were comprehensively analysed by [17] regarding how to select an appropriate algorithm to solve non-linear problems in the context of storage-based off-grid systems under different alternatives. The results reveal that FA performs better, with the least relative error. Other paper [12] evaluated sizing of an autonomous microgrid considering droop control. Results indicated that a competitive total cost could be obtained if the droop parameters were calculated considering the microgrid sizing results. Electric system cascade extended analysis was developed in [18]. In it, the LPSP, LCC and the LCOE together with tri-objective optimization functions were implemented and validated with system advisor model software. Thus, it suggests that this analysis might help choose the suitable RES capacities for any site worldwide. In [19], a model for a remote community off-grid PV/diesel system using dynamic modelling and artificial neural network (ANN) techniques was developed. Within a comparative analysis, it is concluded that utilising dynamic and predictive modelling techniques would enable the model to be expandable, and simple to use while still maintaining its accuracy. Using an iterative approach based on a recursive algorithm, improvements were made to a techno-economic optimal sizing technique of a hybrid off-grid microgrid system in [16]. However, a new mutation adaptive differential evolution (MADE) based on a multi-objective optimization algorithm is presented in [20] to optimise the configuration of the off-grid stand-alone photovoltaic systems. It is also worth mentioning the publication [14] which showed how important it was to choose the right dispatch strategy for off-grid system regarding equipment sizing, and at the end how it affected the net present costs (NPC) over the project lifetime.

Table 2.1. Microgrid equipment sizing methods and indicators [15], [16]

Type of sizing methods	Type of indicators
Classical: – probabilistic – analytical – numerical – iterative	**Economic:** – levelized cost of energy (LCOE) – life cycle cost (LCC) – annualized cost of system (ACS) – total net present value (NPV)
Software tools: – Homer Pro – RETScreen, – PVSOL – Hybrid 2 – Transys	**Reliability**: – loss of power supply probability (LPSP) – loss of load probability (LOLP) – expected energy not supplied (EENS) – deficiency of power supply probability (DPSP) – loss of load expected (LOLE), – loss of energy expected (LOEE)
Hybrid methods: – combined dynamic programming and region–elimination technique algorithm (DP–RET) – hybrid Simulated Annealing–Tabu Search – hybrid Big Bang–Big Crunch algorithm (HBB–BC) – hybrid GA–mixed integer linear programming (GA–MILP)	**Environmental:** – carbon emission (CE) – embodied energy (EE) – carbon footprint of energy (CFOE) – life cycle assessment (LCA)
Artificial intelligence: – genetic algorithm (GA) – particle swarm optimization (PSO) – simulated annealing (SA) – ant colony optimization (ACO) – artificial bee colony (ABC)	**Social**: – human development index (HDI) – job creation (JC) – portfolio risk (PR) – social acceptance (SA) – social cost of carbon (SCC)

In general, according to the literature review, it can be noticed that there are still difficulties in the field of equipment capacity optimization:

1. Improvements in load forecasting and adoption to methods are necessary.
2. Calculation time step of power output is critical for the optimization of the results; thus, it should be reduced considerably as much as possible (less than 1 hour is preferable).
3. Improved sizing methods equipment could be installed in the research area to obtain real-time data and verify simulation results.
4. New evaluation indicators may be used to provide more effective and overall assessment as the microgrids are emerging solutions for sustainability policy goals.
5. Artificial intelligence sizing methods have advantages in accuracy and computation speed compared to traditional methods, while, on the other hand, those significantly increase optimization complexity.
6. As good practice equipment sizing is validated and improved also with more than one optimization tool.

It can also be concluded that existing articles mainly focus on microgrid operation state; therefore, future research might have more efforts on the planning, construction state, and microgrid servicing.

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 2.2 and Fig. 2.1.

Table 2.2. 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.

For simplicity, the time interval for modelling of off-grid system is assumed to be one hour; thus, the load and at the same time the required generation capacity are defined as P_l in the time interval t. Total power generated (kW) at the time interval t (excluding backup generator) $Pg(t)$ in Eq. (2.1) is defined as the sum of power capacity of solar modules, wind turbine and potentially other generation sources such as fuel cell, small-scale CHP unit, etc.

$$P_{g(t)} = P_{g\mathrm{PV}(t)} + P_{g\mathrm{W}(t)} + \cdots + P_{n(t)}. \tag{2.1}$$

As the off-grid system requires a battery energy storage system, it is necessary to determine its state of charge status at the time interval t:

$$SOC_{(t)} = SOC_{(t-1)} + \frac{E_{b(t)}}{E_{br}}, \tag{2.2}$$

where $SOC_{(t-1)}$ is the state of charge of the BESS in the previous time interval, E_{br} is the rated energy capacity of the BESS, $E_{b(t)}$ is the amount of energy BESS charged or discharged in the time interval. In addition, the model calculates the maximum possible charge and discharge capacities (kW) of the BESS (4), which at the same time gives us the amount of energy per cycle. During the first cycle $SOC_{(t)}=SOC_{\max}$:

$$E_{bmax} \approx \left(SOC_{(t)} - SOC_{min}\right) \times E_{br}, \tag{2.3}$$

$$P_{b\mathrm{max}} \approx E_{b\mathrm{max}}, \text{ for time interval t = 1h} \tag{2.4}$$

If there is a surplus or shortage of electricity (kW) at the time interval t in the off-grid system, equation (2.5) is used:

$$P_{(t)} = P_{g(t)} - P_{l(t)}, \tag{2.5}$$

In next equations (2.6 and 2.7), the model assesses whether to start-up the backup generator and at what power:

$$\text{if } P_{b\mathrm{max(t)}} < \sum P_{(t)}, \tag{2.6}$$

$$P_{r(t)} = P_{br} - P_{b\mathrm{max}(t)} - \sum P_{(t)}. \tag{2.7}$$

If the BESS and other sources can cover the load, the backup generator will not be scheduled for operation. If not, the power output of the backup generator during the time interval t is determined within the range $P_{r\min}$–P_r. The calculation is adjusted so that the backup generator operates closer to the nominal (rated) output and charges the battery at maximum possible power during the time interval t.

The actual power rating (kW) of the BESS and its nature (charging / discharging) in the model is determined by equation (3.8):

$$P_{b(t)} = P_{(t)} + P_{r(t)}. \tag{2.8}$$

The actual charged or discharged energy rating (kWh) of the BESS Eb(i) at the time interval is determined by equations (3.9–3.11):

$$\text{if } P_{b(t)} > 0, \text{then } k_{b(t)} = 0{,}9, \tag{2.9}$$

$$\text{if} P_{b(t)} < 0, \text{then } k_{b(t)} = 1/0{,}9, \tag{2.10}$$

$$E_{b(t)} = P_{b(t)} \times k_{b(t)} \times 1h, \tag{2.11}$$

where k_b is the efficiency of the BESS. The simulation cycle ends with equation (2.12) to initialize calculations for the next time interval t:

$$t = t + 1 \tag{2.12}$$

Fig. 2.1 shows a block scheme within the sequence of operations of the described off-grid 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, configuration of the model is necessary to set up the required dispatching strategy and input data.

The overall model optimization focuses on four aspects: off-grid system highest availability, lowest surplus generation, lowest operation hours of the backup generator, lowest LCOE.

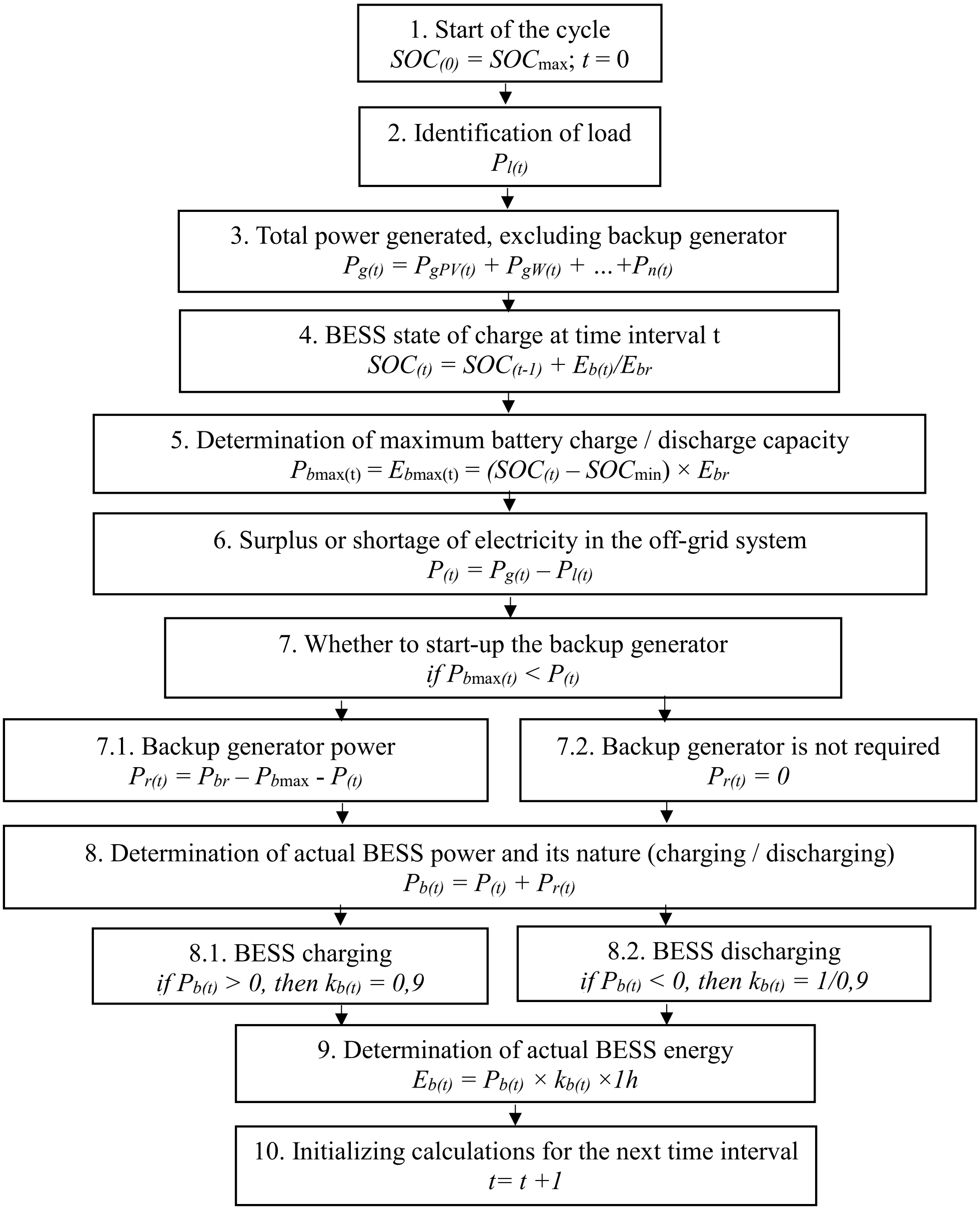


Fig. 2.1. Operational principles of the model of off-grid system.

2.2.2. The annual costs of off-grid system

The objective function in the calculations is minimization of the levelized cost of electricity (LCOE), which in this case is determined based on the method of the annual cost of system (ACS) [21]. *ACS* covers annual capital cost (*ACC*), annual operation and maintenance costs (*AOM*), annual replacement costs (*ARC*), annual fuel costs of backup generator (*AFC*) and annual emission cost (*AEC*). *ACS* (in EUR) is estimated as follows:

$$ACS = ACC + AOM + ARC + AFC + AEC, \tag{2.13}$$

Annual capital cost (in EUR) of each unit which does not need replacement during project lifetime, such as PV system, wind turbine, backup generator and inverter, is calculated as follows:

$$ACC = C_{cap} \cdot CRF(i, y), \tag{2.14}$$

in which

$$CRF = \frac{i \cdot (1+i)^y}{(1+i)^y - 1}, \tag{2.15}$$

where C_{cap} is the capital cost of each component in EUR, but y is the project lifetime in years. *CRF* is capital recovery factor, a ratio to calculate the present value of a series of equal annual cash flows, and *i* is the annual real interest rate.

The annual operation and maintenance cost as a function of capital cost, reliability of components (λ) and their lifetime (y) can be determined using the following equation:

$$AOM = C_{cap} \cdot \frac{1-\lambda}{y}, \tag{2.16}$$

ARC is the annual cost value (in EUR) for replacing units during the project lifetime. In this study, a unit that needs replacement is only battery banks. Other units do not require replacement because their lifetime is the same as project lifetime. Economically, annual replacement cost is calculated as follows:

$$ARC = C_{rep} \cdot SFF(i, y_{rep}), \tag{2.17}$$

where C_{rep} is the replacement cost of battery banks in EUR, but is the lifetime of battery banks in years. In this case, the replacement cost of battery banks is like its capital cost. *SFF* is the sinking fund factor, a ratio to calculate the future value of a series of equal annual cash flows. This factor is calculated as follows:

$$SFF = \frac{i}{(1+i)^y - 1}, \tag{2.18}$$

AFC of backup generator unit is estimated based on optimum dispatch of backup generator system. The fuel consumption (in liters) based on load characteristic of the backup diesel generator is calculated for each time interval *t* using the following equation:

$$F(t) = 0.246 \cdot P_r(t) + 0.08415 \cdot P_r, \tag{2.19}$$

where is the rated power of backup generator in kW, $P_{r(t)}$ is the actual power generated at time interval *t* in kWh. The fuel cost (in EUR) is calculated for a year by multiplying hourly fuel consumption by fuel costs:

$$AFC = C_f \cdot \sum_{t=1}^{8760} F(t), \tag*{(2.20.)}$$

where C_f is the fuel cost per litre (EUR/l). To reach the maximum efficiency of operation the unit should be operated within rated power and specified maximum value. *AEC* is the annual emission cost (in EUR) to capture CO_2 emission generated from backup generator system. The *AEC* can be expressed as follows:

$$AEC = \sum_{t=1}^{8760} E_f \cdot E_{cf} \cdot P_r(t)/1000, \tag{2.21}$$

where E_f is the CO_2 emission factor, kg / kWh, E_{cf} is the CO_2 emission cost in EUR/t. By calculating the *ACS* it is possible to determine levelized cost of electricity (LCOE), which shows how much each kWh of electricity costs in the particular microgrid (EUR/kWh).

$$LCOE = \frac{ACS}{E_{AEC}}, \tag{2.22}$$

where is the annual energy consumption of a microgrid (kWh). Other parameters used in the calculations are shown in Table *2.3*.

Table 2.3. The Economic Data Considered for Calculations

Parameter	Data	Parameter	Data	Parameter	Data
Project lifetime (years)	20	Reliability of PV panel (coef.)	0.98	Cost of Wind turbine (EUR/kW)	3500
Real interest rate (%)	4	Reliability of wind turbine (coef.)	0.8	Cost of battery bank (EUR/kWh)	540
PV panel lifetime (years)	25	Reliability of inverter (coef.)	0.98	Cost of battery bank (EUR/kW)	540
Wind turbine lifetime (years)	20	Reliability of battery (coef.)	0.98	Cost of inverter (EURkW)	1300
Inverter lifetime (years)	20	Reliability of backup generator (coef.)	0.9	Fuel cost (Cf) (EUR/l)	1.2
Battery lifetime (years)	10	Cost of backup generator (EUR/kW)	380	Emission function (kg/kWh)	0.34
Backup generator lifetime (hours)	15 000	Cost of PV panel (EUR/kW)	1250	Emission cost factor (EUR/ton)	30

The parameters shown in Table 2.3 can be changed as needed for other microgrids.

2.3. Case study

For the case study, real household hourly load data are collected, integrated in the model, and used in simulations. Household average daily electricity demand is 30.27 kWh, which reaches 11 049 kWh 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 transports needs can be considered the biggest consumers of electricity in this household. This type of household matches with aims for electrification, which has a critical role to play for achieving the European Union decarbonization policy targets.

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.

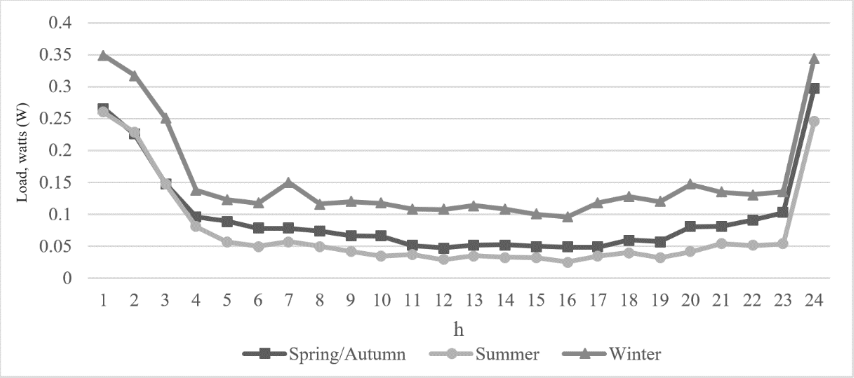


Fig. 2.2. Load curve in relative values for three seasons.

As shown in Table 2.4, 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 [14]. Two additional sizing options were developed to find the most sustainable and economically efficient solution.

Table 2.4. 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 2.5 shows the results for all five equipment sizing alternatives considering three different dispatch strategies.

Table 2.5. Results of Simulations

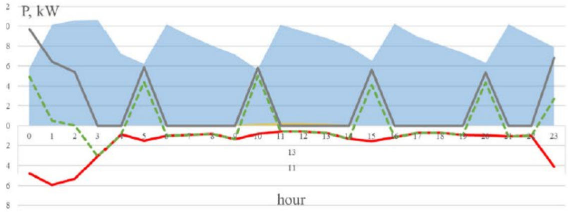
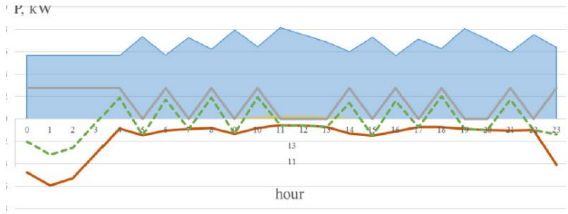
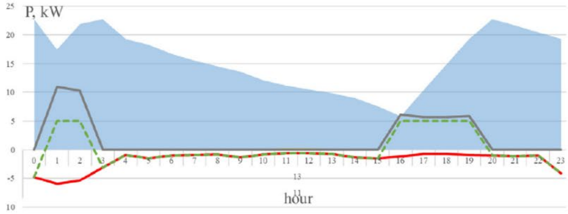
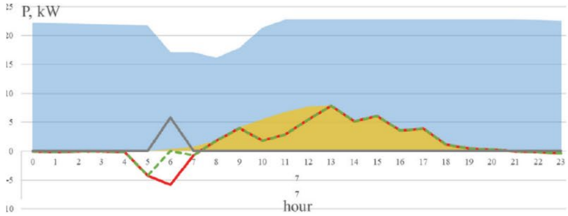
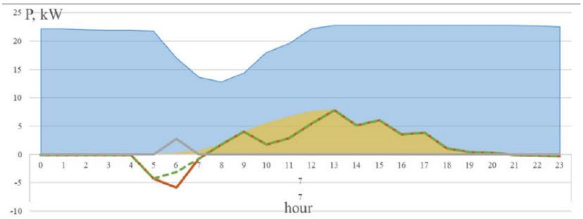
Alternative	**1st**	**2nd**	**3rd**	**4th**	**5th**
Combined charging dispatch strategy (CCDS)					
Backup gen. operating hours	1277	1234	1448	778	953
Excess renewable energy, kWh	1290	3990	71	2083	1029
Excess vs total renew. generation, %	18 %	40 %	2 %	26 %	20 %
LCOE, EUR/kWh	0.71	0.73	0.73	0.79	0.70
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 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. 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 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. 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 day for two equipment sizing alternatives and three dispatch strategies is provided in Table 2.6 and Table 2.7. The graphs show the power source and amount of generation, energy storage capacity, load and its nature, battery power and its nature, backup generators 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 and the 5th alternative, 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 2.6. 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	

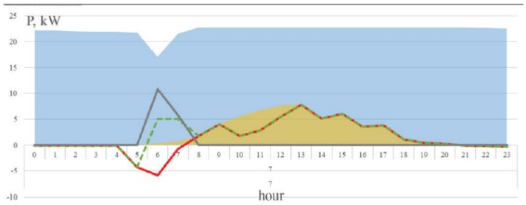
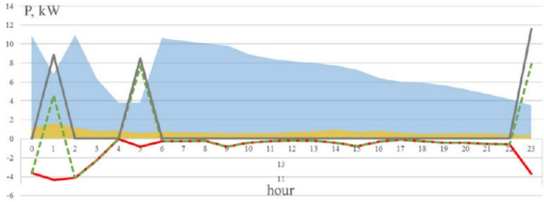
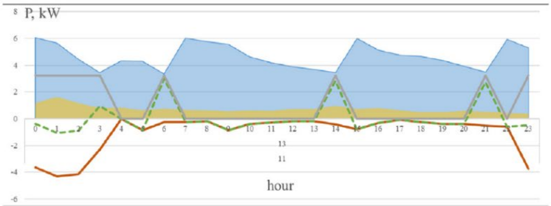
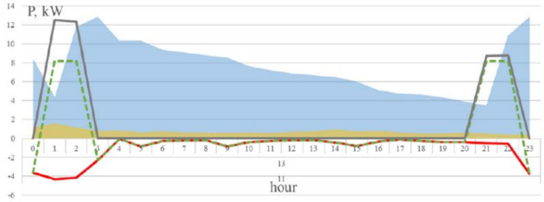
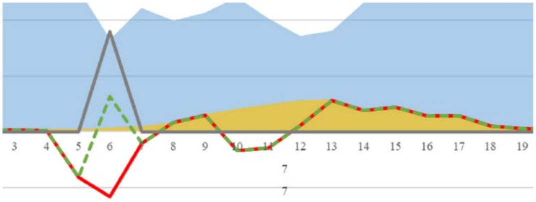
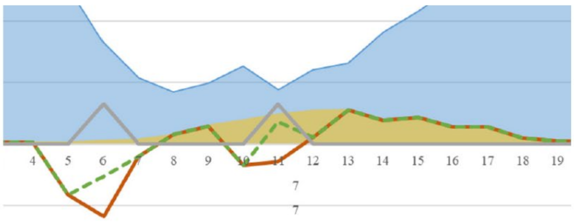
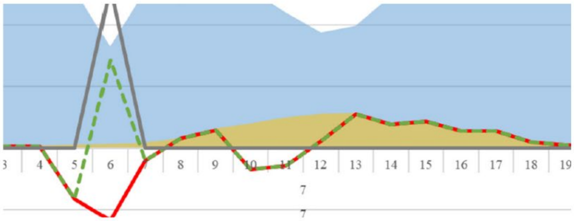
Cycle charging CCS	
LEGEND	🟨 Pg(i) 🟦 SOC(i) ▬ ∑P(i) - - - Pb(i) ▬ Pr(i)

Table 2.7. Off-grid Operation Visualization: 5th alternative and Dispatch Strategies

5th alternative: BESS power 8.2kW, capacity 16kWh, solar power 3 kW, wind power 2kW, diesel gen. 13 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	🟨 Pg(i) 🟦 SOC(i) ━ ∑P(i) ╍ Pb(i) ━ Pl

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).

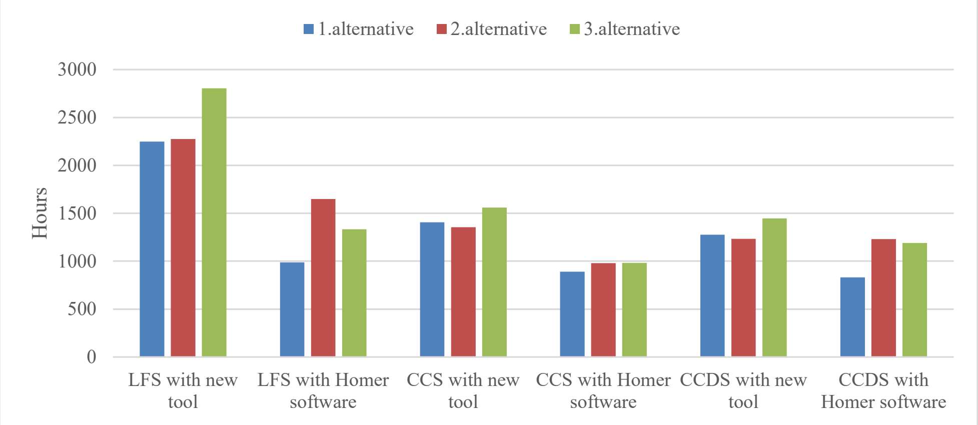


Fig. 2.3. Backup generator operating hours.

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.

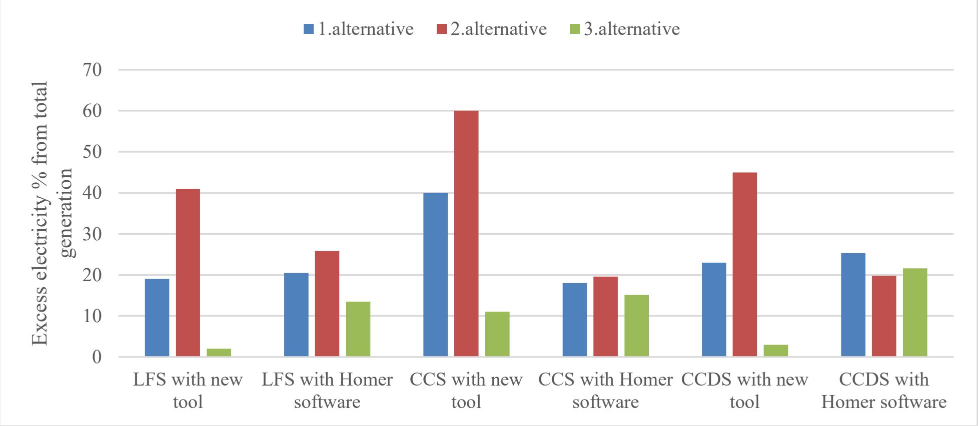


Fig. 2.4. Excess electricity in all off-grid alternatives.

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.

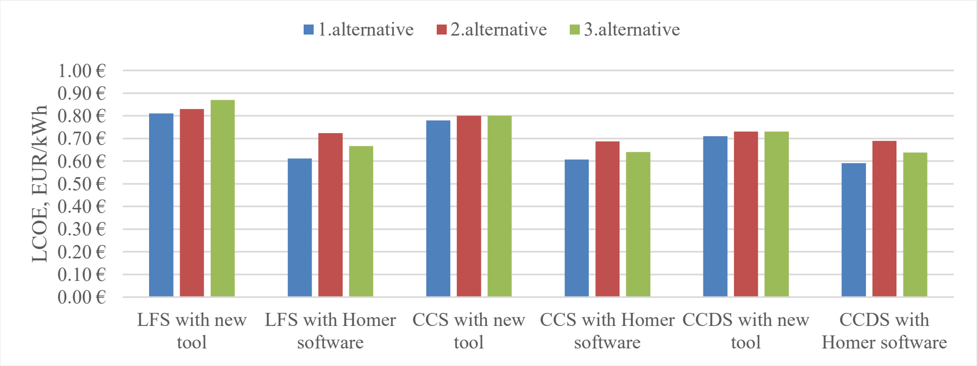


Fig. 2.5. Levelized cost of energy for all off-grid alternatives.

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 scientific literature, self-sustaining microgrid systems that are built for different consumers are analysed. For example, [22] examines the technical feasibility (including system dimensioning) for a single-family house off-grid energy system in Finland's northern climate with short-term battery and seasonal hydrogen storage. While in [23] comparative analysis between an off-grid hybrid power supply for different consumption levels (1825, 3650 and 5475 kWh) and a newly built grid connection for domestic consumers was performed in different regions of Estonia. In another paper [24], the configuration of off-grid systems in Estonia, which includes photovoltaics, wind turbines, a diesel generator, and batteries, is studied.

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

In this 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. Overall, there are several benefits for such an autonomous off-grid system:

1. Useful development of project is possible in places where there are relatively high investments needed for the grid connection to the distribution networks [25].
2. Due to reduced costs of new renewable energy technologies and fluctuating fossil fuel prices, a simplified off-grid system for household electricity supply in remote regions may be an efficient and cost-effective electrification way to the fight against climate change and to reach the European Union (EU) decarbonization targets [14], [26], [27].
3. To protect against electricity supply quality problems and overall reliability due to increased variable generation or decreasing conventional generation in the grid [28].

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

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

Initially, a special mathematical model was created to select energy sources, to size equipment and to further test the operation of this off-grid system in the Latvian climatic conditions. Thus, in this chapter not only focus is on evaluation of this real autonomous off-grid system performance, but also to discuss aspects related to software computing techniques and mathematical models versus a real operational off-grid system.

As it is stated in [29], to ensure optimal design and that such renewable systems are affordable, careful planning preferably with high-resolution data on electricity generation and consumption is necessary. As it is one of research gaps identified in literature, and not delivered in a clear way, the objective of the chapter is to further increase knowledge of such system performance, planning and dimensioning in climatic conditions like it is in Latvia.

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 m × 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.

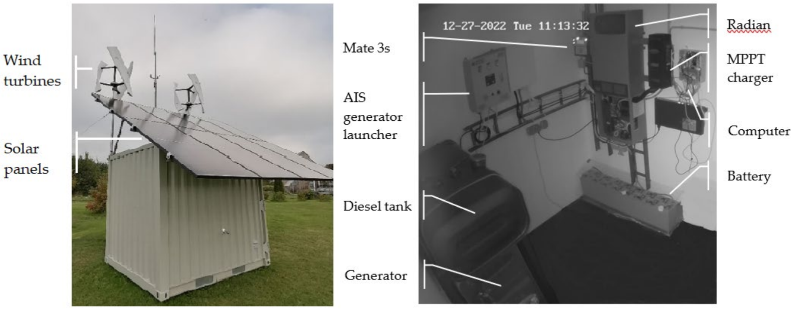


Fig. 3.1. Experimental autonomous off-grid system.

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 LiFePO4 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.

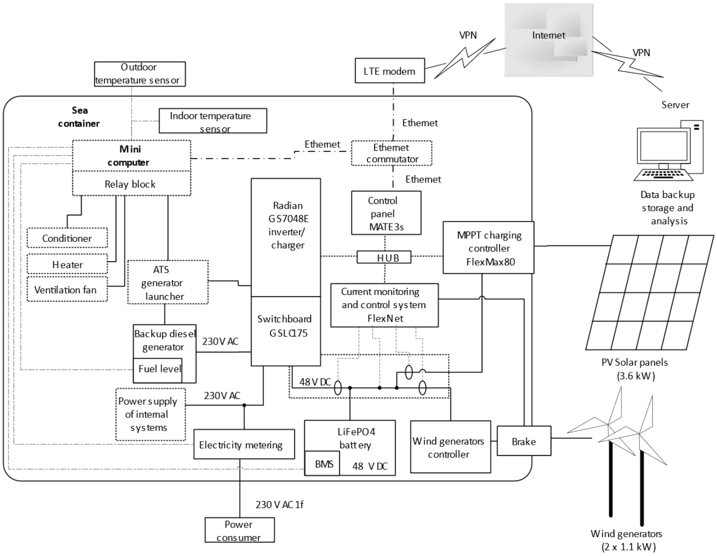


Fig. 3.2. Conceptual diagram of the installed off-grid system.

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. The equipment survey results are summarised in Table 3.1.

Table 3.1. The Current and Planned Electricity Equipment in Household

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

As it can be seen in Table 3.1, 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.

Off-grid system control principle

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

Fig. 3.3 shows the off-grid system control principle, which is summarised based on the above configuration. Figure 3.3 illustrates the operating voltage ranges for the power source and power converter: red indicates the voltage at which battery damage occurs, yellow-charged represents the battery voltage, grey-when the device is working; and dashed grey indicates switch-on or special charging mode.

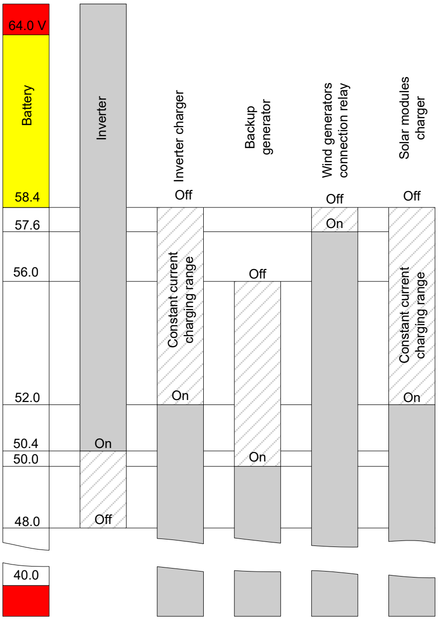


Fig. 3.3. Principle of power flow control based on a battery voltage level.

The principle of power flow control in the off-grid system is based on voltage levels of the battery. Battery is charged from three sources using a two-phase charging method. During the first stage, constant current bulk charge is up to 0.5 C-rate or limited by resource availability, terminated at 58.4 V; and constant voltage absorption charge is terminated at return amps 0.03 C-rate. PV charger and AC charger using diesel generator are managed by a central system controller and obey rules descripted before. Wind turbine controller is a discrete device and, therefore, needs to be connected to DC bus if necessary, using power relay. If the voltage of the battery reduces below 52.0 V and solar energy is available, bulk constant current charging is started. In case solar energy is not available and voltage drops down to 57.6 V, wind turbines start to generate by connecting wind chargers to DC bus. If both wind and solar sources are insufficient or unavailable and voltage is below 52.8 V, a diesel generator shall take over the control and charge battery in that way avoiding power supply interruption. The operation of the diesel generator is set at 50 V.

When multiple sources are running simultaneously, priority is given to the source with the highest resource availability, i.e., for a charge controller that has a higher voltage and a proportionally larger amount of energy available from the renewable source. For example, if it is sunny with moderate wind, then due to higher installed capacity of the solar panels, charging will take place from them, the wind charge controllers will give a minimum current. In darker and windier weather, the situation will be the opposite. If the backup diesel generator is running, it will be able to charge battery at all times.

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.

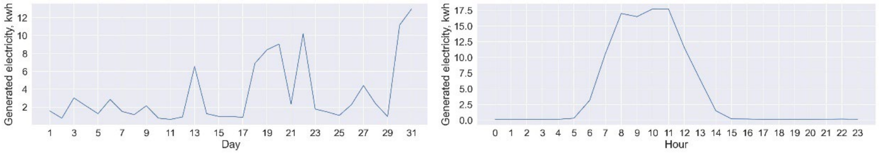
The obtained dataset reflects only one time of the year. To create a more accurate analysis, it is desirable to use historical data to estimate the change taking into account the change of all seasons.

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

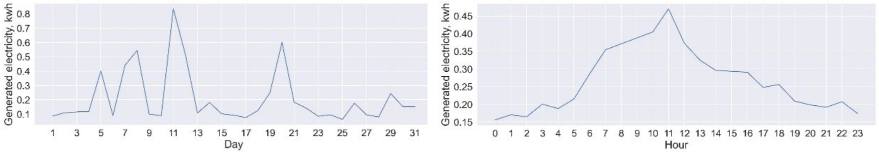
Fig. 3.4 to Fig. 3.6 present daily and hourly production data curves of the off-grid system electricity between October 2022 and November 2022. They cover cumulative generation of electricity from solar, wind, and diesel generator.



(a) (b)

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

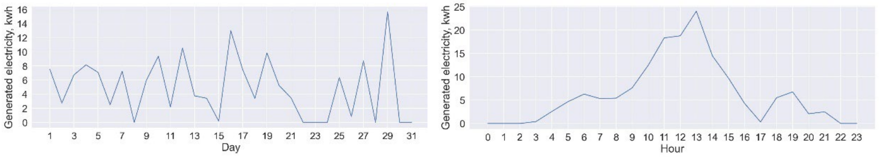
Fig. 3.4 shows that solar power is generated on a relatively large scale and with a distinct tendency to take place from 6 a.m. to 3 p.m. Solar kilowatt hours (kWh) are calculated using data obtained from FlexnetDC.



(a) **(b)**

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

Fig. 3.5 shows that wind power is generated on a relatively small scale and with no distinct tendency during the days. Also, wind kilowatt hours (kWh) are calculated using data obtained from FlexnetDC.

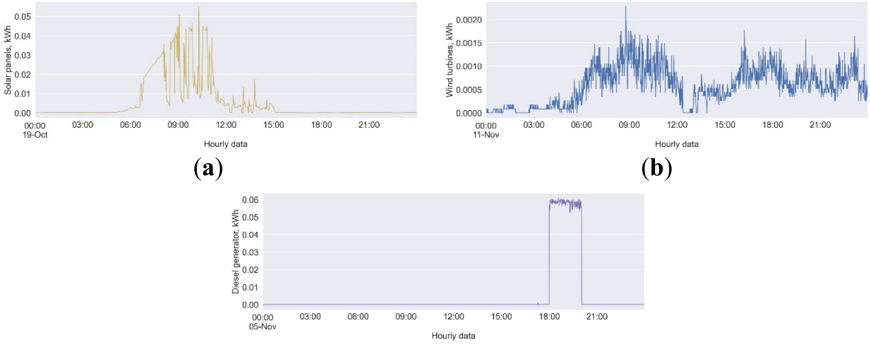


(a) **(b)**

Fig. 3.6. Electricity from diesel generator: (a) daily cross-section; (b) cumulative hourly profile.

Fig. 3.6 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. 3.7 shows how electricity generation profiles differ by sources.



(a) **(b)**

(c)

Fig. 3.7. 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. 3.7. It can be seen that renewable sources in these days show a lot of variability, while the diesel generator has been working for a specific period with a certain capacity.

Amount of generated electricity by source type

During 31 days of observation (see Fig. 3.8), most electricity was generated by the diesel generator (152 kWh), followed by solar (104 kWh) and wind generation (7 kWh). Later on, it was discovered that low output of wind generation was 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.

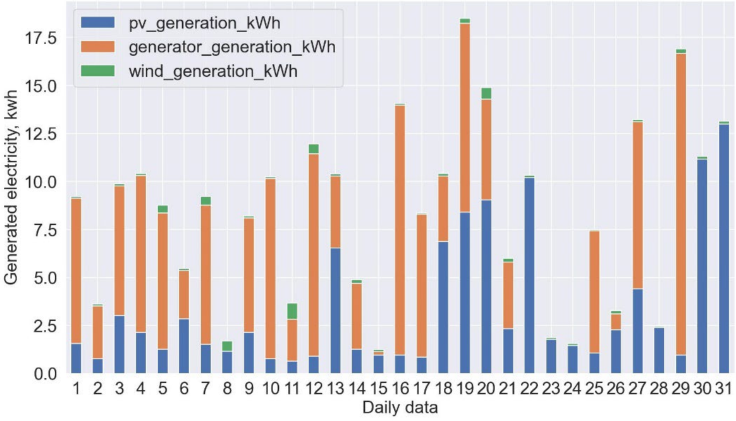


Fig. 3.8. Cumulative electricity generation by source type.

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.

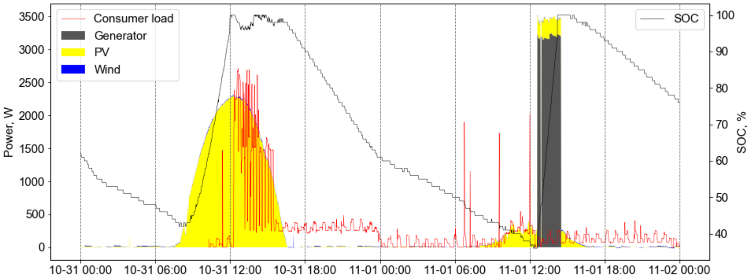


Fig. 3.9. Off-grid system characteristics during a sunny day at the end of October.

For example, Fig. 3.9 shows two sunny days at the end of October and at the beginning of November. During this time, the demand consumption was not logged in the beginning, indicating that the acquisition of data should be checked to ensure data continuity.

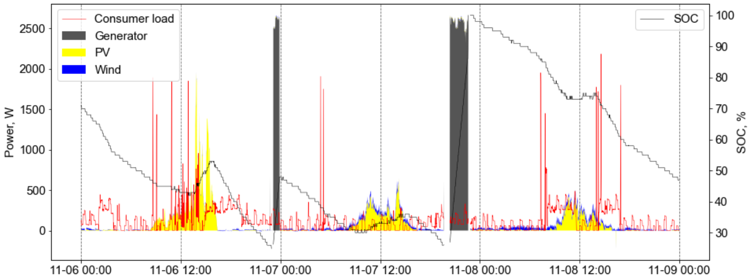
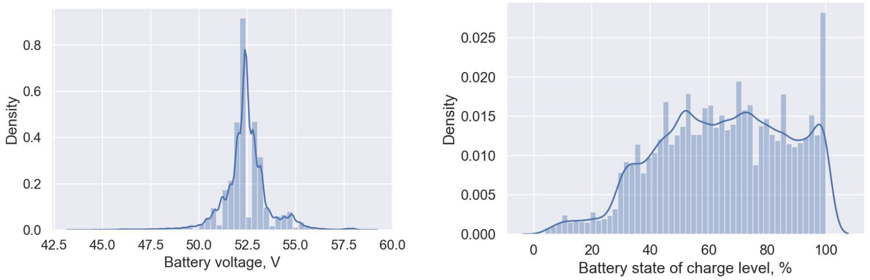


Fig. 3.10. Off-grid system characteristics during a sunny day at the start of November.

In Fig. 3.9 and Fig. 3.10, 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

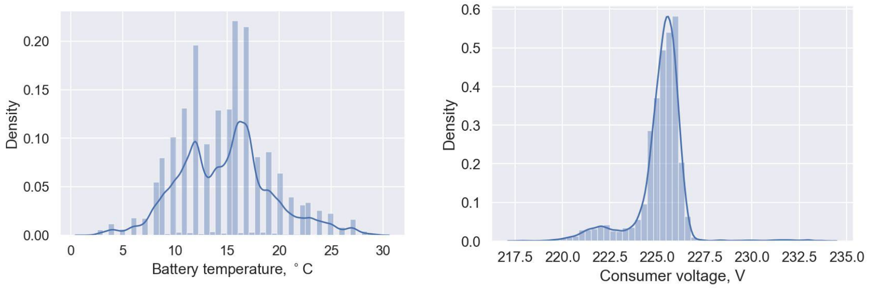
It was also important to observe electrotechnical data in the experiment. Fig. 3.11 and Fig. 3.12 show four histograms. A histogram divides the variable into bins, counts the data points in each bin, and shows the bins on the x-axis and the counts on the y-axis. In our case, we used Python library seaborn, 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 [30].



(a) **(b)**

Fig. 3.11. Electrotechnical data: (a) for battery voltage; (b) battery SOC level.

According to the electrotechnical data shown in Fig. 3.12, 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.



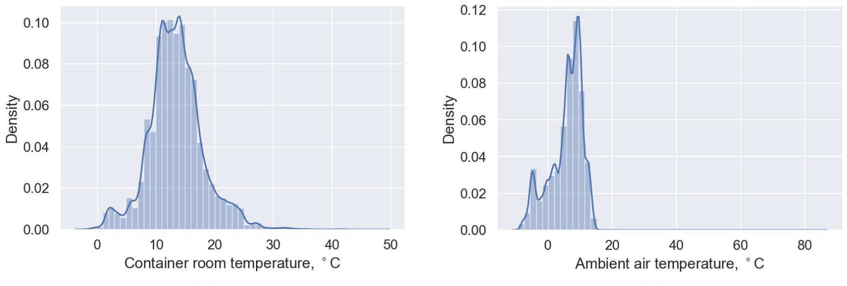
(a) **(b)**

Fig. 3.12. 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. 3.12). Battery voltage data were obtained from inverter RadianGS, SOC and battery temperature data from system monitoring-FlexnetDC device, while consumer voltage from power network analyser-Carlo Gavazzi EM21.

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. 3.13.

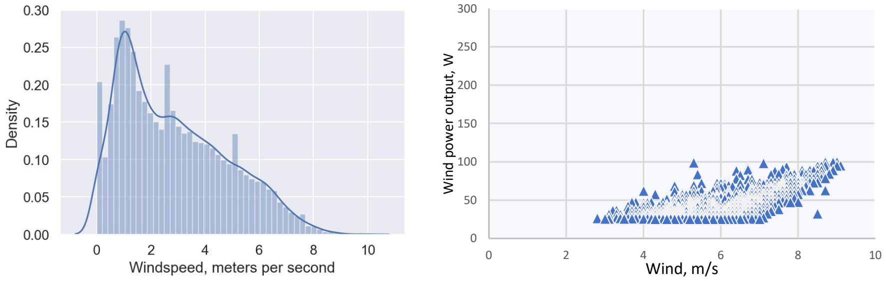


(a) **(b)**

Fig. 3.13. 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. 3.14), 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. 3.14 (b).



(a) **(b)**

Fig. 3.14. Wind speed data: (a) using histogram; (b) using time scatter analysis.

It should be admitted that wind data were obtained for only half of 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.

3.3.2. Modelling tools versus reality

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

1. To obtain life data it would be required to test experimental off-grid system for at least 1-year period.
2. The off-grid system operation should be tested using more than one dispatch strategy (longer analysis than a 1-year period would be needed).
3. To obtain data to be later used in computer tools and mathematical models more measuring devices as planned before would be required, for example, regarding solar radiation.
4. As the off-grid project is still implemented, its true costs can only be clarified after a longer time period than now.

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

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. For example, already today, electricity grid system operators are shaping their operating structure (see Fig. 4.1) by including and taking into account such stakeholders as passive and active users, energy communities, microgrids, aggregators, virtual power plants, platforms for balancing energy and other flexibility products for ancillary services, electricity storage devices, etc. By modelling not only energy, but also data flows between these parties, emphasizing the importance of new technologies (IoT, self-healing, etc.).

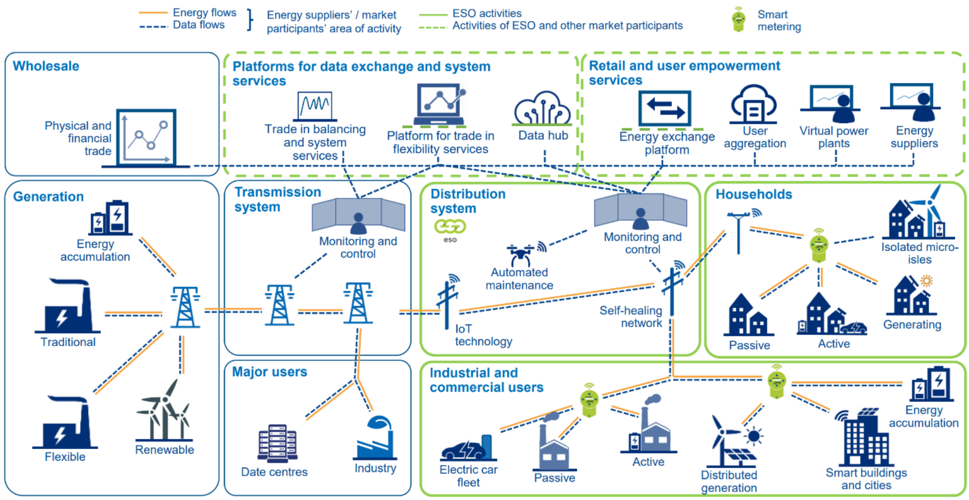


Fig. 4.1. Lithuanian DSO 2030 power system design [31].

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.

Decentralized energy resources (DER) typically refer to low-capacity electricity generation technologies that produce, store, and manage electrical energy. For instance, solar modules, small wind turbines, electric vehicles, microgrids, and others.

Scientific literature discusses that broader utilization of DER could enhance the efficiency of available resources for society, increase energy system resilience (e.g., in cases of large station outages from the market), and empower consumers and communities in achieving decarbonization goals. This aligns with the European Green Deal and plans for a safer, more accessible, and cleaner energy usage. However, the growth of DER could simultaneously disrupt traditional principles of electricity markets, and without proper regulation, its benefits may not be equally felt throughout society [32].

Although there isn't a specific definition of decentralized energy resources, in Latvia, microgenerators can be considered as low-capacity electricity technologies designed for producing single or three-phase AC electricity with a current of up to 16 amperes. In a single-phase electrical network, this corresponds to a power of 3.7 kW, while in a three-phase network, it's 11.1 kW (Type A production modules [33]). Also, power plants up to 14.99 MW (including Type A, B, and C production modules) connected to distribution network operator grids at 0.4, 6, 10, and 20 kV[34].

Some industry research indicates that the use of DER in Europe (thus in Latvia) in the future could potentially surpass the proportion of centralized generation sources. For instance, in this research [35], when DER includes solar modules (<1 MW), wind turbines (<500 kW), micro-turbines, hydrogen fuel cells, diesel generators, and gas boilers (<6 MW), electricity storages, microgrids, electric vehicles, and demand response utilization.

It should be acknowledged that a particularly significant development in microgeneration in Latvia was observed in the first four months of 2022. This was attributed to a considerably higher electricity price on the Nord Pool exchange due to the global economic recovery from the economic downturn caused by the Covid-19 pandemic in 2020. Additionally, the geopolitical situation, particularly with Russia's war in Ukraine, has led to significant uncertainty about future energy supply, prompting the search for alternative sources. The rapid increase in microgenerators has surpassed even the most daring predictions-from January to April, 970 microgenerators were connected to the distribution grid, totalling 7.5 megawatts (MW). By the end of April, the number of microgenerators connected to the grid of the operator, “Sadales tikls AS” reached 3052 connections with a total installed capacity of 21.3 MW.

Considering the current trends in microgeneration development, experts at “Sadales tikls AS” predict that the number of newly connected microgenerators to the distribution grid in 2022 will reach 4000, with the total number of microgenerators connected to the entire system by the year's end exceeding 6000, and the overall capacity reaching 45 MW [36]. There is substantial interest in Latvia not only in the implementation of microgenerators, but also in the development of solar parks. By the end of April 2022, the total reserved capacity for the development of microgenerators and power plants exceeded 670 MW. Although, according to data from the transmission system operator, the maximum load on the Latvian system during the winter of 2020 reached 1184 MW, and the minimum load was observed in summer at 463 MW [37].

The main role of policymakers, regulators, and other market participants is to prepare for changes in existing electricity markets. Variable and renewable energy generation from various decentralized sources will pose a challenge to the electricity grid infrastructure, which was developed and built based on the principles of traditional centralized systems. A decentralized system with a significant share of renewable energy sources is less predictable than a centralized system, and grid operators may face difficulties in responding to fluctuations in demand and the unpredictability of supply and demand.

4.1.1. Amendments to the national legislation

Amendments to the Energy Law

In the coming years, energy communities will play a larger role in transitioning to cleaner energy. Households, individuals, and businesses collectively invest in the development and operation of energy-related assets. Estimates indicate that by 2030, energy communities in the EU could own approximately 17 % of installed wind power and 21 % of solar energy [38]. These communities promote local economic development, provide secure and accessible energy, and encourage collaboration within local communities.

The legal framework for "energy communities" was introduced in European legislation as part of the so-called Clean Energy Package. The term 'energy community' is used in two EU directives:

1. "Citizen energy communities" in the European Parliament and Council Directive (EU) 2019/944 [39] of June 5, 2019 (Directive 2019/944) on common rules for the internal electricity market (amended version).
2. "Renewable energy communities" in the European Parliament and Council Directive (EU) 2018/2001 [40] of December 11, 2018 (Directive 2018/2001) on promoting the use of energy from renewable sources (amended version), also known as "RED II".

Both definitions of communities share similarities, for instance:

1. Communities are legal entities established as a juridical person (as emphasized in Directive 2019/944, it "creates a new kind of entity considering its membership structure, governance requirements, and objectives").
2. They are effectively controlled by their shareholders or members.
3. Their primary goal is to ensure environmental, economic, and social community benefits, rather than financial profit.

However, among the key differences between "citizen energy communities" and "renewable energy communities" are membership issues (the former is much more regulated than the latter):

1. Regarding "renewable energy communities", there is an additional stipulation for private companies that their participation must not be their primary commercial or professional activity.
2. Shareholders or members of "renewable energy communities" should be located near the owned and developed renewable energy projects.

In the case of "citizen energy communities" this entity is exempt from the mentioned requirements. Additionally, members of "renewable energy communities" can collectively engage in various aspects of renewable energy management (production, consumption control, energy sales, renewable gases, etc.). Meanwhile, the scope of "citizen energy communities" is currently limited to the electricity sector, such as electricity production, distribution, supply, consumption control, aggregation, storage, or energy efficiency and electric vehicle charging services, etc. (although this may change with the new EU Gas Directive revision). From a network perspective, these two types of communities are illustrated in Fig. 4.2.

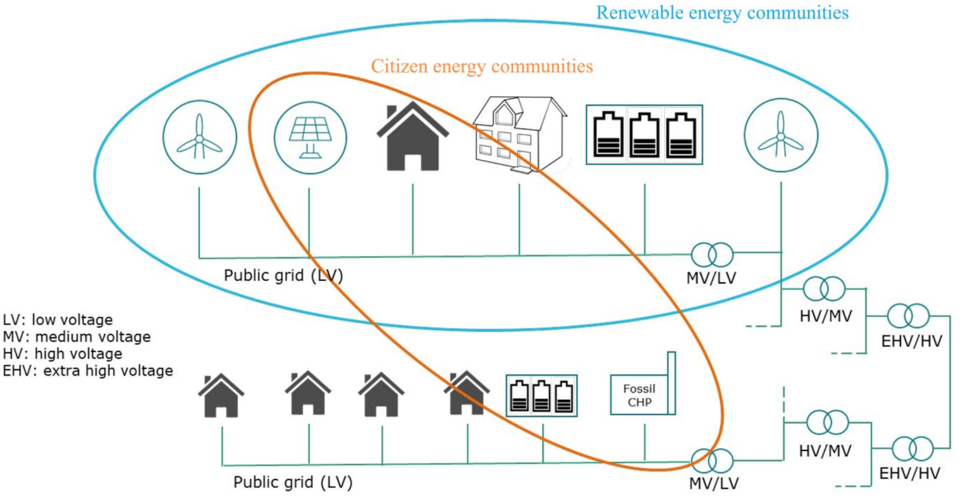


Fig. 4.2. Communities from the perspective of system operators [41].

From the aforementioned, it can be concluded that the "citizen energy community" is technology-neutral, whereas the "renewable energy community" is limited to renewable energy technologies.

On July 14, 2022, in the second-final-reading, the Saeima (Latvian Parliament) supported urgently recognized amendments to the Energy Law [42] 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 stipulate that an energy community meets the conditions of either a "renewable energy community" or a "citizen energy community" meaning that an energy community can comply with one or both of these conditions. It is also stipulated that members of the energy community retain the rights and responsibilities as defined for end-users or active users. The definition of an active user is included in amendments to the Electricity Market Law [43], which were supported concurrently with amendments to the Energy Law.

Additionally, the energy community is more precisely regulated in the amendments to the Electricity Market Law (see the next section). The definition of an electricity energy community is broader, encompassing medium-sized enterprises as well, aiming to unify the conditions for both types of energy communities as much as possible. The definition of small and medium-sized enterprises aligns with the definition specified in Annex I of European Commission Regulation No 651/2014 [44].

It should be noted that the draft law does not specify a particular legal form for an energy community. Previous European experiences suggest that this form can be quite varied: (1) cooperatives, (2) limited liability companies, (3) foundations and funds, (4) housing associations (owners/renters' associations), (5) non-profit organizations (typically in village heating in Denmark), (6) public/private partnerships.

In the case of Latvia, an energy community can be an association or foundation, a cooperative society, as well as a joint-stock company, ensuring compliance with the requirements specified in regulatory acts for an energy community.

For the regulation of energy communities to function fully, the Cabinet of Ministers will have to establish the information to be included in the energy community registry, registration requirements and procedures, information to be provided in annual reports by energy communities, and the procedure for excluding energy communities from the registry or re-registering them. These rules will also outline how the State Construction Control Bureau, as the responsible authority, will decide on the inclusion or exclusion of an energy community from the registry.

Moreover, the Ministry of Economics will have the opportunity to develop support schemes for energy communities utilizing renewable energy resources while observing conditions for commercial support. In this case, it's essential that support is available to energy communities meeting only the conditions of citizen energy communities, but solely in cases where they generate electricity from renewable energy resources.

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

Household electricity consumption constitutes a significant portion of the overall electricity consumption. Peer-to-peer trading, as well as energy sharing among energy communities, could promote the European Green Deal by trading surplus energy locally or storing excess energy for later use or trade.

Peer-to-peer trading, as defined in Directive (EU) 2018/2001, refers to *"the sale of renewable energy between market participants by means of a contract with pre-determined* *conditions governing the automated execution and settlement of the transaction, either directly between market participants or indirectly through a certified third-party market participant, such as an aggregator. The right to conduct peer-to-peer trading shall be without prejudice to the rights and obligations of the parties involved as final customers, producers, suppliers or aggregators".*

Communities and peer-to-peer trading differ from the so-called "virtual power plants" in that, for instance, energy storage systems would be used for providing flexibility, and this flexibility is used within the community rather than in the daily or balancing electricity markets.

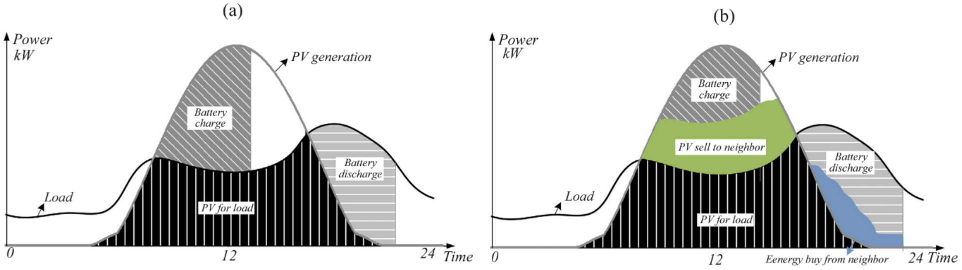


Fig. 4.3. Microgeneration and storage coverage: a) individual consumer, b) community sharing [45].

The amendments aiming to allow electricity sharing in communities provide new opportunities for microgeneration development and optimal distribution of produced electricity, as shown in Fig. 4.3. It illustrates the impact of peer-to-peer trading and electricity sharing within a community on the more effective utilization of micro-generation and electricity storage. On the right-hand side of the image (b), the influence of electricity sharing can be observed-the use of renewable electricity increases compared to the use of the electricity storage, without the sharing capabilities in the image on the left (a). By trading energy and sharing assets, the energy community has a greater chance to efficiently cover the total self-consumption, ensuring self-sufficiency and thus requiring less energy purchase from external sources.

As mentioned previously, on July 14, 2022, during the second and final reading, the Saeima supported amendments to the Electricity Market Law [43], 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.

The improvement and extension of the NETO accounting system will:

1. Encourage legal entities, including manufacturing companies, to participate in self-consumption electricity production.
2. Allow the electricity produced at one user's site to be used at other sites owned by the same user, whose electricity trading is provided by a single trader, and who are connected to the same system operator.
3. Set a 50-kW power limit within the NETO settlement system.
4. Determine the competence of the State Construction Control Bureau to administer commercial state aid under de minimis conditions for electricity end-users within the NETO settlement system.
5. The law defines that the NETO accounting system period will take place within the year starting from March 1 and ending on the following year's February 29 (previously from April 1 to March 31).

Conditions for electricity sharing include:

1. The system operator will ensure sharing according to a closed contract with the electricity community or jointly operating active users from renewable energy resources.
2. Electricity sharing will take place within one trading interval. Unconsumed electricity cannot be stored for sharing in another trading interval; it must be sold to an electricity trader at an agreed price.
3. System participants involved in electricity sharing cannot simultaneously participate in the NETO accounting system, NETO settlement system, or electricity certificate system.
4. Electricity distribution systems used for electricity sharing will be charged according to tariffs set in the “Regulations for Public Service Regulators” law.

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.

4.1.2. 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. 4.4, 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. 4.4 (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);

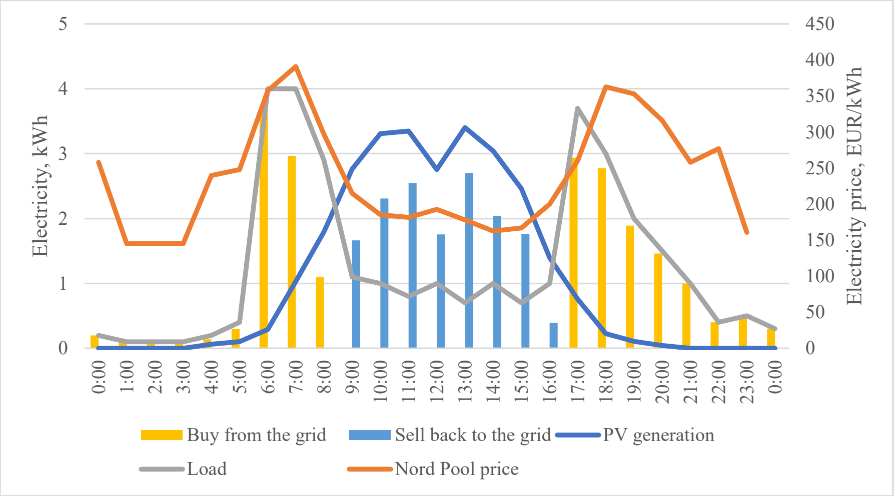


Fig. 4.4. Latvian household solar power usage (July 20, 2022).

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.

4.2. Decentralized renewable energy payback analysis

4.2.1. Motivation and background

Decentralized power supply solutions, such as solar panels, electric vehicle (EV) charging stations, and electricity storage systems (batteries), are becoming increasingly more popular and widely recognized by numerous countries in their endeavours to promote environmentally friendly technologies. The adoption of these technologies is influenced not only by the national legislation, but also by other factors, such as high electricity prices, enhanced electricity reliability, and the desire to be more environmentally friendly.

For example, in Latvia, the swift adoption of solar panels in the past few years was most likely driven by two factors: firstly, the high electricity prices caused by geopolitical circumstances in neighbouring countries (see year 2022 in Fig. 4.5) and, secondly, the support for renewable energy resources provided by the Latvian government. After the start of the Russia-Ukraine war, the average electricity price in Latvia increased to 226.01 EUR/MWh in 2022, in contrast to 46.28 EUR/MWh in 2019, or 34.05 EUR/MWh in 2020, and

88.78 EUR/MWh in 2021, respectively. In early 2023, however, the prices were slightly lower than those recorded in 2022 [46].

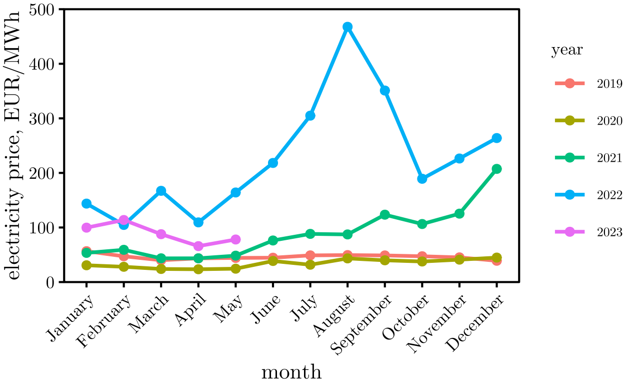


Fig. 4.5. Nord pool average day-ahead electricity price in the Latvian trade area [46].

By installing solar panels or small wind turbines, Latvian residents had the opportunity to receive financial support by means of the following two support programs:

1. The support provided by the administered programme of ALTUM ranges from 700 to 4000 EUR, depending on the nominal power of the inverter.
2. The support provided by the Emission Allowance Auction Instrument (EKII) also ranges from 700 to 4000 EUR, depending on the nominal power of the inverter.

Funding from the EKII support program is only available after the purchase and installation of the equipment. On the contrary, to receive the ALTUM support, one first needs to apply for the programme, await approval, and then commence the work. The EKII programme has a total funding of 40 million EUR, while ALTUM has a funding allocation of 3.66 million EUR [47].

These circumstances have led to a situation where, within a relatively short period, the total number of microgenerators (mostly solar) has surpassed 15 000 units (see Fig. 4.6), with their combined production capacity already exceeding 120 megawatts (MW).

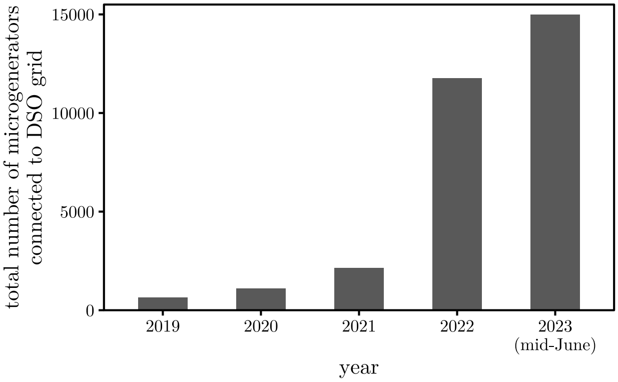


Fig. 4.6. Microgenerator connections to the distribution system operator's grid [48].

The electricity generated by microgenerators is primarily directed towards enabling households to meet their own energy needs, including charging their EVs. EVs are widely recognized as one of the most promising solutions to mitigate environmental impact in the transportation sector and improve energy efficiency. When the electricity for EVs is sourced from a grid predominantly powered by fossil fuels, their life cycle emissions are comparable to vehicles with combustion engines. However, when renewable energy sources are predominant in the energy system, EVs emissions are slightly lower. To truly achieve sustainability in using EVs, it is required to shift the future of electricity towards renewable sources.

Among renewable energy resources, such as wind and solar power, solar energy is considered the most promising in the context of EV charging (see Table 4.1).

Table 4.1. Comparison of Charging EV from Wind or Solar Energy Source [49], [50]

Category	Wind energy	Solar energy
1	Onshore and offshore wind is far from where EVs can be charged	Close to where EVs can be charged. For example, rooftop photovoltaic (PV), so transmission is not needed
2	Different power scales: wind turbines in MW while EV chargers in kW. While on the other hand, with wind turbines it could be possible to charge several thousand EVs	Power scales are similar for rooftop PV and EV charger (both kW)
3	Generation is mostly in winter and nighttime	Generation is mostly in daytime and summer

In most scenarios, one advantage of solar energy as well as EV batteries is that those operate on direct current (DC) power. However, when it comes to grid integration, the standard is alternating current (AC). This leads to the need for unnecessary DC-AC-DC conversions, which can result in energy losses. In contrast, utilizing DC power directly, without conversion, proves to be more efficient [49].

In addition to the support available for installing microgenerators in Latvian households, there is also financial support available for individuals purchasing EVs. A grant of 4500 EUR is provided when purchasing a new electric car, while a grant of 2250 EUR can be received when purchasing used electric cars and new externally chargeable hybrid cars. However, there is a purchase price limit of 60 000 EUR for low-emission and zero-emission vehicles in their basic configuration, as stipulated by regulations. Additionally, there is an extra 1000 EUR support available for beneficiaries, who choose to write off their existing vehicle and hand it over to a processing company [51].

However, unlike microgenerators and electric cars, electricity storage systems (batteries) have not yet been widely adopted in Latvia, and the government has not provided financial support for such equipment. This could be related to the existing NETO accounting system for microgenerators. The NETO accounting system has traditionally allowed for the virtual storage of electric energy produced by microgenerators, enabling its later use, for example, during winter months [52]. Perhaps this is one of the reasons why batteries have not been so popular so far.

However, Latvia has recently made amendments to the Electricity Market Law, resulting in the introduction of a new and improved system, called NETO settlement system. The new NETO settlement system not only records the amount of electricity generated and consumed by customers, but also assigns monetary value to this energy. The advantages of the new system have been communicated and include:

1. Applicability to both households and legal entities (the previous system included only private consumers).
2. Conversion of electricity produced and transferred to the grid into monetary terms, allowing for savings that can be utilized towards future bill payments or applied to electricity costs in other connections of the same customer, as per the conditions of the chosen electricity service provider.
3. The net savings period is not limited by law.
4. The freedom to select the most suitable service provider and the flexibility to switch between providers.
5. Active participation in the electricity market, enabling cost control by tying the value of energy transferred and received to market prices and settlement conditions. Encouragement of consumption habits that maximize the profitability of electricity production and consumption.

These changes aim to empower consumers by providing greater control over their electricity usage and promoting a more economically advantageous approach to energy consumption [53].

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 [54].

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. 4.7): 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. This system applies to the cases when the produced electricity is not immediately consumed but transferred to the grid. If the amount of electrical energy transferred to the grid exceeds the energy received from the grid, the excess energy is carried forward to the next billing period within a NETO year (starts on 1 March and ends on the last day of February). “Energy storage” can only be utilized within the same property (for the specific system connection) where it was generated. At the beginning of a new NETO year, all savings are deleted. It is important to note that the NETO accounting system is currently limited to households and is automatically applied after receiving permission to connect the microgenerator (when the amendments to the law take effect, it will be possible to join the scheme until 31 December 2023).

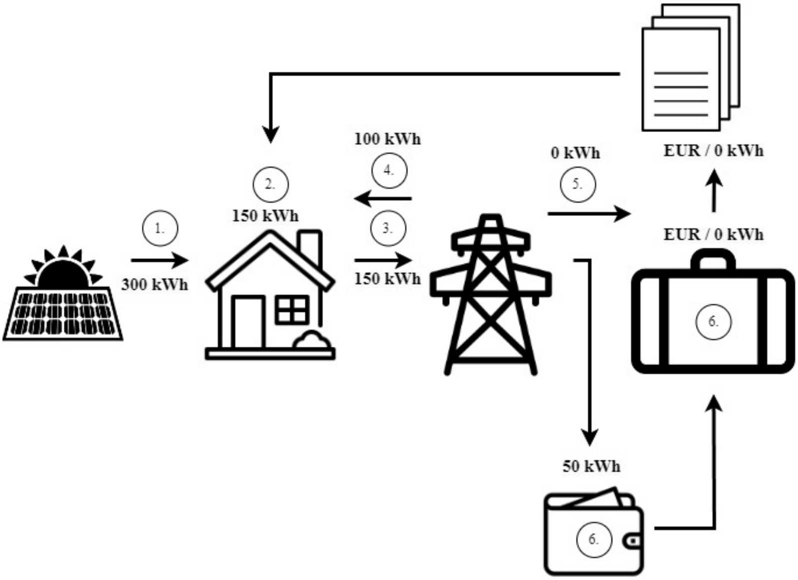


Fig. 4.7. Schematic representation of the NETO accounting system [53].

In the Fig. 4.7 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. 4.8): 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. If the total value of the electricity produced, but not immediately consumed (and transferred to the distribution network) exceeds the value of the electricity received from the same network, the surplus value can be credited in the subsequent settlement period or used for electricity payments in another connection of the same customer. Both households and legal entities will be eligible to participate in the NETO settlement system.

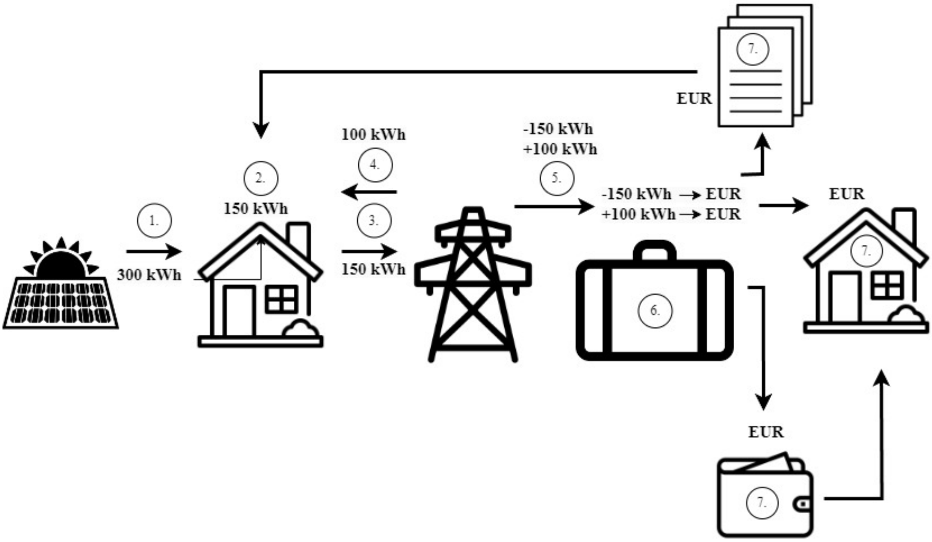


Fig. 4.8. Schematic representation of the NETO settlement system [53].

In the Fig. 4.8 the electricity trader determines the value of the electricity transferred to and received from the power grid.

The law mandates that electricity traders must include the NETO settlement system as part of their trading services. Currently, the Cabinet of Ministers is in the process of developing detailed operational guidelines for the NETO settlement system and determining the date when it will be made available to customers [53].

4.2.2. Methodology – two 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. Fig. 4.9 shows a block scheme of the case study.

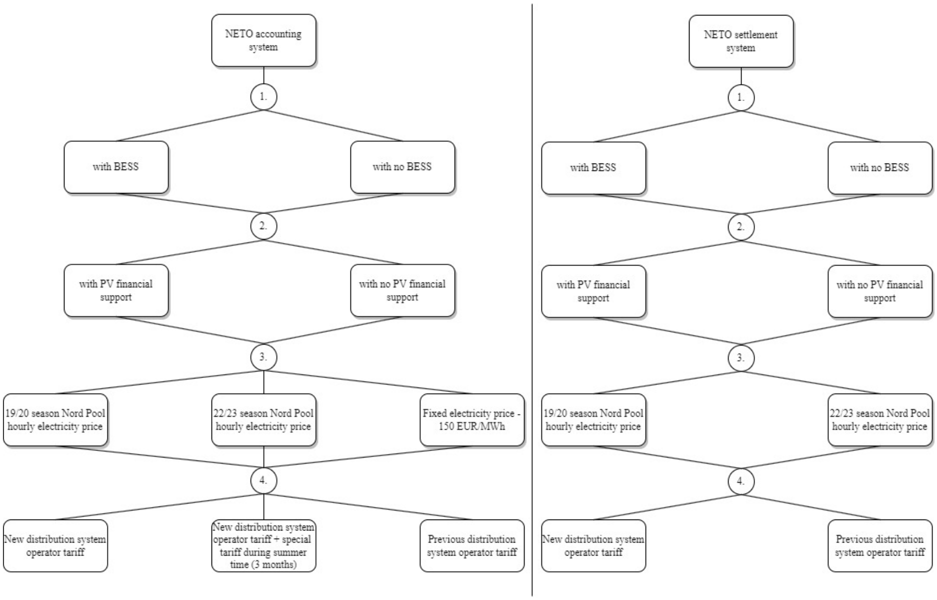


Fig. 4.9. Scheme: NETO accounting and settlement system comparison (first case study).

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 tikls AS”: date and time, electricity consumption, and electricity generation [55]. 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 [52], 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 4.2, all respective scenarios were analysed.

Table 4.2. Input Data and Assumptions of Household Power Supply System [52], [55], [56]

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

While the second case study considers a farm as an electricity consumer that is registered as a legal entity with access to the electric grid and installed solar panels. In this case study, the electricity storage system is added and evaluated for various operating scenarios of the NETO settlement system. Fig. 4.10 shows a block scheme of the second case study scenarios.

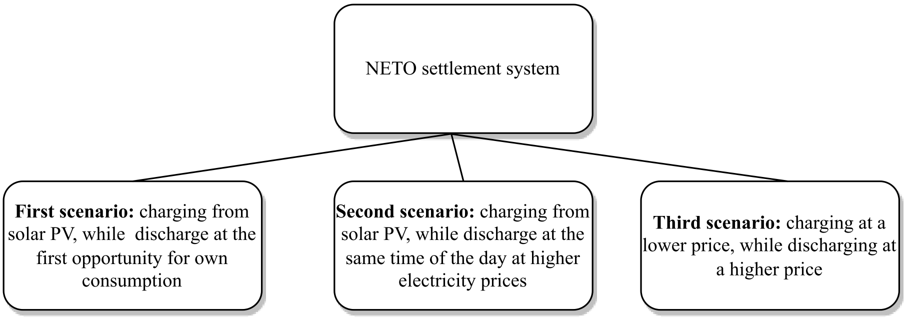


Fig. 4.10. Scheme of the second case study with NETO settlement system scenarios.

In the second case study, three alternatives are compared to examine the best possible scenarios of BESS discharge possibilities and to evaluate savings that could be expected from the smart BESS system management. In all scenarios, annual data at a 1-hour resolution were obtained for one farm of an anonymous customer from “Sadales tikls AS” [55]. The yearly electricity demand of the farm was 8.279 MWh, while the solar energy injected to the grid reached 17.163 MWh on an annual basis (see Fig. 4.11). Unfortunately, like in the first case study, there is no information on the specific electricity consumption patterns at this facility, including information on a contract with an energy trader for the purchase of the produced electricity. As can be seen in Fig. 4.11, on average, the farm produced more than twice as much electricity as it consumed.

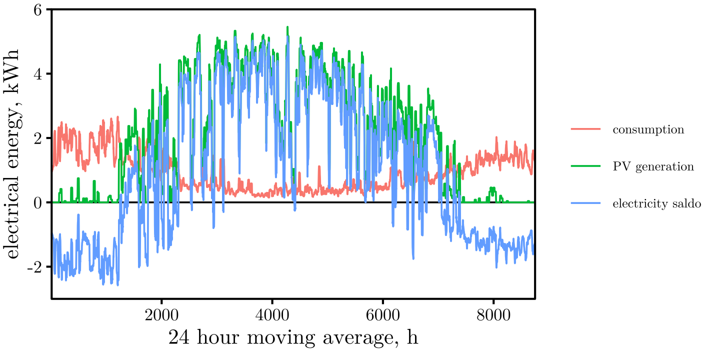


Fig. 4.11. Characteristics of electricity supply at the farm. 24 h moving average was plotted instead of the raw hourly data to improve the visual clarity of the plot [55].

Using data described above (including Fig. 4.10 and Fig. 4.11), as well as in Table 4.3, all three scenarios are analysed.

Table 4.3. Input Data and Assumptions of the Farm Power Supply System [55], [56]

Characteristic	**Indicator or assumption**
Electricity storage systems (BESS) energy capacity, costs, and operation	Energy capacity 15-30-50 kWh, and 10 kW power capacity with capex 225 EUR/kW and 600 EUR/kWh accordingly. BESS charging and discharging efficiency – 95 %
BESS degradation	1.5 %
New distribution network tariff	charge for electricity supply 0.03985 EUR/kWh; charge for IAA current magnitude 0.92 EUR/A/month
Electricity price	Three scenarios analysed with different electricity prices – the 2018 and 2022 season Nord pool exchange prices. Value added tax is not considered.

The significance of selecting the optimal operational mode and energy capacity for BESS is becoming a progressively more important topic for discussion. This analysis aims to approximate the advantages of installing a BESS in a power system that already incorporates solar panels.

4.2.3. Results and discussion

The First Case Study – NETO Accounting System

In Fig. 4.12, 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. 4.12 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.

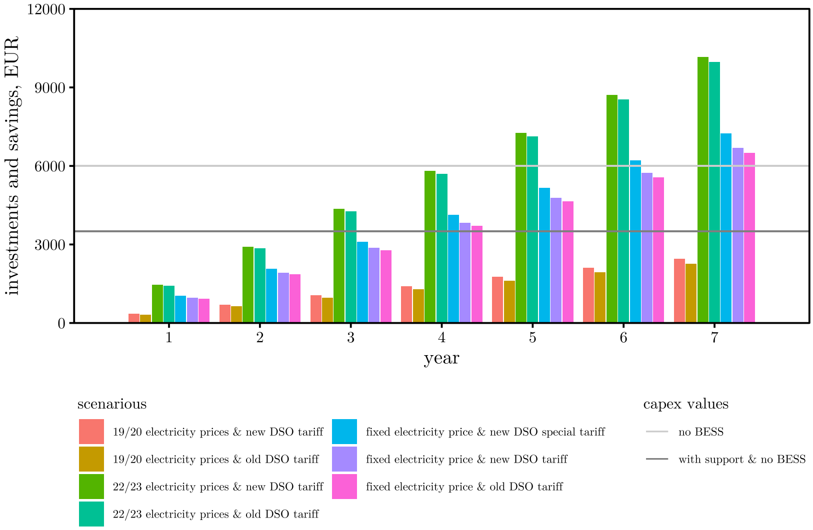


Fig. 4.12. Potential savings in a 7-year period: NETO accounting, without BESS.

Fig. 4.13 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. 4.12, 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.

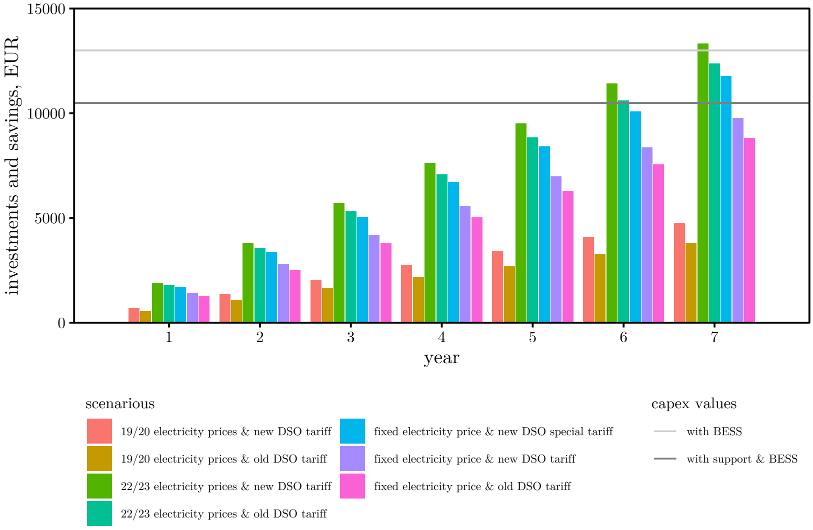


Fig. 4.13. Potential savings in a 7-year period: NETO accounting, with BESS.

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. 4.14, 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. 4.14, 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.

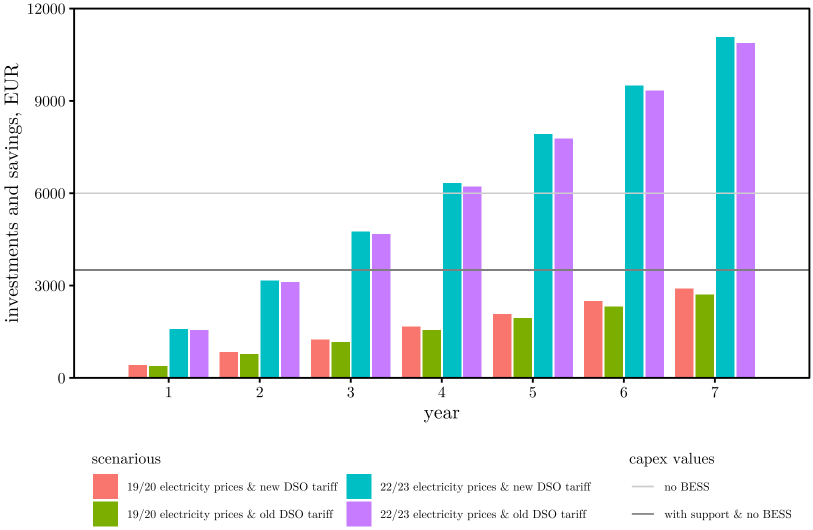


Fig. 4.14. Potential savings in a 7-year period: NETO settlement, without BESS.

Fig. 4.15 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.

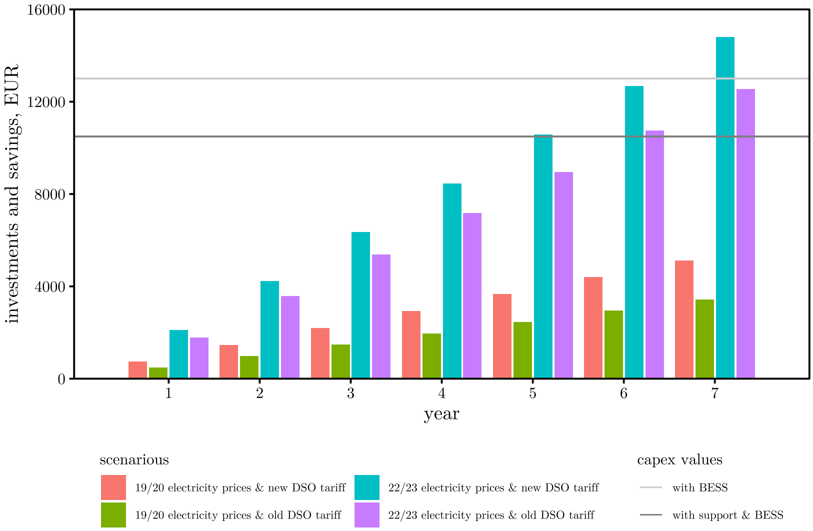


Fig. 4.15. Potential savings in a 7-year period: NETO settlement, with BESS.

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.

The second case study – the BESS management system

In the second case study, three algorithms have been developed to evaluate savings from different BESS discharge and charge management approaches. Energy storage capacities have been assumed and varied – 15, 30, and 50 kWh. This, the second case study, involves a farm operating under the NETO settlement system, equipped with a pre-existing solar panel system.

In the first scenario, the BESS is charged using solar PV, and discharge occurs as soon as there is an opportunity for self-consumption. The second scenario involves charging from solar PV but discharging during peak electricity pricing hours. In the third scenario, the BESS is charged at the lowest electricity rates and discharged when prices are higher.

The analysis is conducted using the new tariffs of the DSO, as well as separately considering the 2018 and 2022 Nord Pool electricity exchange prices in the Latvian electricity trading area. Unlike the first case study, this analysis excludes the consideration of value-added tax. Fig. 4.16 illustrates the potential savings of installing BESS across all three scenarios.

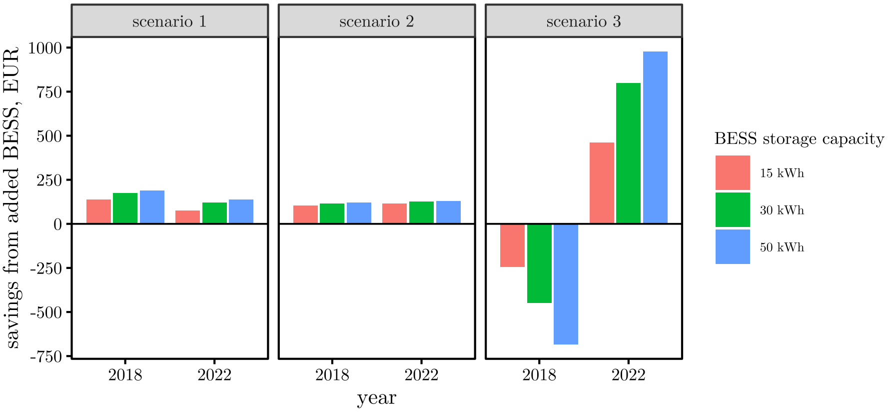


Fig. 4.16. BESS scenarios: potential savings with 2018 and 2022 electricity prices.

In the case of the first scenario, the results show that by creating an additional BESS system, marginally higher savings can be achieved in the case of a larger BESS capacity and lower electricity prices, which were lower in 2018 than in 2022 (the average price in 2018 was 49.89 EUR/MWh, while in 2022 it was 226.32 EUR/MWh).

When considering the second scenario, the results show that neither the BESS energy capacity nor the electricity prices of 2018 or 2022 lead to a significant difference in savings. Overall, the savings are very similar.

On the other hand, in the third scenario there is a significant discrepancy between savings made in 2018 and 2022, as a result of different electricity prices. At the prices of 2018, the savings were estimated to be negative, which could be related to the fact that in 2018 the changes in electricity prices during the day were relatively small, unlike in 2022. This scenario also highlights how the savings are affected by the choice of the energy capacity of the BESS system used; for example, in 2022, the difference in savings between the 15 and 50 kWh BESS is 500 EUR. In general, in 2022, the greater the installed BESS energy capacity was, the greater the savings were.

5. CHALLENGES OF NEW SYSTEM SERVICES

5.1. Latvia’s energy supply and security

Energy Trilemma Index

The World Energy Council’s (WEC’s) Energy Trilemma Index tool ranks 127 countries on their energy system performance through 3 dimensions: energy security, energy equity, environmental sustainability. The goal of the Index is to provide insights into a country’s relative energy system effectiveness in each dimension and together. Highlight challenges and opportunities for improvements in meeting energy goals now and in the future [57].

According to the WEC's evaluation, Latvia exhibits a highly favourable situation regarding the “energy security” dimension, securing the fourth position among 127 countries globally. Within the Baltic States, Latvia records the lowest Index value for the “energy equity” dimension, standing at the 44th position in the ranking. Conversely, in the “environmental sustainability score” dimension, Latvia is positioned at 34th place (see Table 5.1).

Table 5.1. Energy Trilemma Index ranking [58]

“The energy security score”		**“The energy equity score”**		**“The environmental sustainability score”**	
Country	**Score**	**Country**	**Score**	**Country**	**Score**
1.Canada	77.5	1.Qatar	99.9	1.Switzerland	88.2
2.Finland	75.3	1.Kuwait	99.8	2.Sweden	86.3
3.Romania	74.1	1.UAE	99.8	3.Uruguay	85.4
4.Latvia	**74.9**	2.Oman	96.6	4.Norway	84.4
5.Sweden	74.5	2.Bahrain	99.6	5.Panama	83.7
		44.Latvia	**78.1**	**34.Latvia**	**70.9**

But can we leverage the method and knowledge developed by the WEC for creating the index to delve deeper and provide more specific recommendations for actions at the country level? Young professionals in the energy sector, who were part of the “Future Energy Leaders in Latvia” program initiated by the Latvian Committee of the World Energy Council, had examined and proposed opportunities and suggestions for addressing this issue.

Latvian energy security dimension

Healthy energy systems are secure, fair, sustainable, and environmentally friendly. They demonstrate a balance between all three dimensions of the trilemma: security of energy supply, equitable access to services, and environmental sustainability [59].

More specifically, the energy security dimension determines the ability of countries to meet current and future energy demand, withstand and recover quickly from systemic shocks with as few as possible energy supply disturbances. This dimension covers the inner and external energy management efficiency, as well as energy infrastructure reliability and resilience [57].

Latvia is among the top 5 countries in the world according to the current Trilemma score on the Energy security index. Globally, energy security index is focusing on oil and other fossil fuels. Although fossil fuels have been a resource Latvia is importing, well diversified power generation portfolio has granted this high score. Energy security index includes other important criteria that have a positive effect on overall system and its stability.

Three main pillars can measure energy systems security in the context of Trilemma Index:

1. Import – national dependency on resource import in the total energy consumption and supplier diversification.
2. Energy generation capacities and their diversity – country has well balanced and diversified generation portfolio.
3. Energy storage capabilities – countries ability to satisfy its energy demand, in accordance with the available infrastructure [58].

Energy resource availability, economic development, technological development, investment flow, well designed energy market, ability to react on disturbances: these are few aspects that characterizes energy systems security index and are evaluated within WEC methodology.

In this regard, up to ten-year period retrospective analysis of statistical records of those indicators as well as Latvian and foreign scientific and professional research studies was revised and discussed with another 12 experts from a programme "The Future Energy Leaders Latvia" organized by the Latvian WEC committee. The data mostly were obtained from public sources, market reviews, statistical databases. As result, Table 5.2 below was developed that highlights most important opportunities and potential risks of no actions for Latvian energy security dimension [60].

Table 5.2. Indicators of Energy Security Dimension [60], [61]

Indicators	**Ratings in last years**	**Opportunities and risks for Latvia**
Diversity of primary energy supply	not changing	– more solar, wind capacities, new energy carriers (like hydrogen, synthetic fuels, etc.) – greater energy dependence and new high price disruptions
Import dependence	increasing	– stronger focus on energy efficiency, use of biofuels – system would further heavily relay on energy imports
Diversity of suppliers	increasing	– close energy integration with neighboring countries (new markets and platforms) – unsecure and not trustful suppliers who uses dominant state
Diversity of electricity generation	not changing	– access to market for demand response, electricity storage, virtual power plants – not flexible and modern generation underlies weak performance
Energy storage for oil	not changing	– diversity of supply and stocks / storage levels – unsecure and not trustful suppliers may use dominant state
Energy storage for gas	not changing	– infrastructure sharing and integration with neighbours – operational costs may lie mainly to local consumers

System stability as SAIFI (interruptions) and SAIDI (outage duration)	increasing slowly	– digitalisation of infrastructure, new data centres and data policy – not improved ratings, inefficient and costly system operation

Although Latvia is scoring high in Energy Security Trilemma Index by WEC methodology, it is necessary to highlight that even short but focused bursts of specific issues (gas supply interruption, lack of generating capacities in the region) can dramatically impact the energy security as whole and leave significant footprint in further development. Therefore, it is critical to prioritize the energy security determining factors and purposely act on the improvements [60].

Latvia could set a clearer plan for decarbonization of its energy system with explicit actions for humanizing energy transition. For example, starting with development of national hydrogen strategy. In general, Latvian energy security dimension should be more decentralized, distributed, digitalized, and decarbonized, and at the same time maintaining balanced share of dispatchable baseload capacities in generation portfolio. It was acknowledged that there is a need for new sub-indicators to represent the evolving security of an energy system in transition [60].

5.2. Modelling of battery energy storage system

5.2.1. Motivation and background

Historically, power systems of Estonia, Latvia, and Lithuania were operated in parallel with power systems of Russia and Belarus based on the so-called BRELL agreement (abbreviation of Belarus, Russia, Estonia, Latvia, Lithuania) [62], [63]. Frequency control was centralised and provided by Russian United Power System (UPS). Transmission system operators (TSOs) in BRELL were responsible for minimize frequency mitigation by maintaining power generation and demanding equilibrium. According to the existing Network Codes in Baltic States, frequency must be maintained between 49.95 Hz to 50.05 Hz.

In 2018, a political decision was made on the synchronization of the power system of the Baltic States with the continental European electricity system, and the disconnection (desynchronization) from the electricity systems of Russia and Belarus. As desynchronization from the BRELL and synchronisation to the Continental Europe Synchronous Area (CESA) is an approved goal for Baltic States, it will be crucial to maintain the frequency stable for each TSO of the Baltic States [63], [64]. It is expected to be a rather difficult task, so the solution for this problem is complex. While connected to BRELL the frequency control is centralised. After synchronisation with CESA, each of the Baltic States' TSOs must be able to maintain power equilibrium and frequency control-activation of frequency containment reserves (FCR) immediately after a difference in the balance between generation and demand. Both the construction of new interconnections and the reconstruction of existing ones, as well as the strengthening of the existing network, network management, and control systems in each country, require large-scale investments. At the same time, the decarbonization goals are highly responsible for large renewable power penetration in the power system, thus decreasing conventional generation; this could affect the power equilibrium and loss of system inertia [65], [66], [67], [68]. There are several methods for system inertia control. The research conducted by the Institute of Power Engineering in Riga Technical University concludes that synchronous condensers in AC power systems can respond with active power injection during a loss of generation, and in combination with novel load shedding method-show promising results for further investigation, thus opening new methods for system stability control [62].

To carry out this ambitious plan, the Baltic States TSOs have signed the “Memorandum of understanding on development of the Baltic load-frequency control block” [64], [69]. The memorandum explains a high-level concept for balance management, FCR technical requirements, concept of FCR prequalification process, and FCR dimensioning rules. The situation in Baltic power system management will also change with the introduction of new Grid Codes and Guidelines for new pan-European platforms or markets for ancillary electricity services (MARI (go-live planned for 2022), PICASSO, TERRE), according to Regulation (EU) 2017/2195 of November 2017. Therefore, after the synchronization with CESA, there will be an opportunity to offer new ancillary services in the Baltic power market including active power reserves for frequency control.

The main contribution of this section is the creation of an algorithm that can be applied to evaluate the technical possibility of 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 European Commission Regulation EU 2017/1485 on guidelines for the operation of the electricity transmission system, and the European Commission Regulation (EU) 2017/2195, establishing electricity-balancing guidelines provided for four-level frequency regulation processes or platforms. The platforms are dedicated to frequency containment reserves, automatic and manual frequency restoration reserves (aFRR/mFRR), and replacement reserves (RR). All of them (see Table 5.3) are introduced into the system in a certain chronology after the occurrence of active power imbalance, as shown in Fig. 5.1.

Table 5.3. Active Power Reserves in the Continental Europe Synchronous Area

Power reserve	Aim
Frequency containment reserve – FCR	Reserves of active power to maintain stability of systems frequency after power imbalance. The purpose of FCR is to stop the frequency deviation after a disturbance in the power system, achieving a new balance between electricity supply and demand.
Frequency restoration reserve – FRR	Reserves of active power to firstly recover frequency to normal state and secondly to restore the power balance in individual frequency control zones to specific value. aFRR – automatically activated FRR; mFRR – manually activated FRR.
Replacement reserve – RR	Reserves of active power (including generation power) for restoring the required FRR level to be ready for additional imbalances in the system.

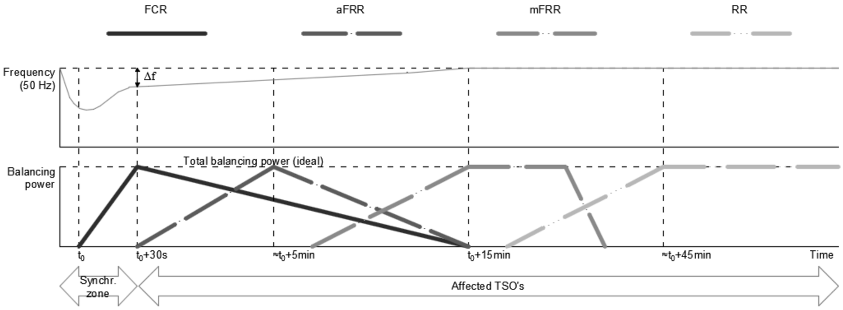


Fig. 5.1. Chronology of frequency control process [70].

The amount of FCR is determined annually according to the amount of generation and consumption in the synchronous zone. The total amount of FCR, aFRR and mFRR must be equal to the largest possible cut-off unit in the Baltics (700 MW in 2025). The distribution of FCR, aFRR and mFRR among the Baltic States calculated in 2020 is given in Table 5.4. As can be seen the estimated amount of FCR for Baltic power system is ± 30 MW. The estimated amount of aFFR in the Baltics in 2025 will be 100 MW (the distribution is based on the current imbalance in the Baltic States). Manually activated FFR is determined as the remaining amount of the total amount of FRR and in 2025 it will be 600 MW in the Baltics.

Table 5.4. Forecasted (2020) Baltic Power Reserve Volumes after Synchronization [73]

	Lithuania	Latvia	Estonia	Baltic States
FCR	±12 MW	±11 MW	±7 MW	±30 MW
percentage	40 %	33 %	27 %	100 %
aFRR	±45 MW	±23 MW	±32 MW	±100 MW
percentage	45 %	23 %	32 %	100 %
mFRR (up)	+243 MW	+148 MW	+218 MW	+600 MW
percentage	39 %	25 %	36 %	100 %
mFRR (down)	−300 MW	−21 MW	−279 MW	−600 MW
percentage	50 %	3.5 %	46.5 %	100 %

Recently, the European Green Deal and decarbonisation goals of energy systems have led to a growing interest in energy storage systems (ESS). ESS are a versatile tool with different technical characteristics that can provide many options of application, such as services to support generation, TSO's or distribution system operator's infrastructure, customer energy management, and ancillary services [72], [73].

For the determined Latvian TSO's reserve volumes, lithium-ion battery ESS (BESS) is expected to be the most suitable option. The main advantages of lithium-ion batteries in electricity system applications compared to other battery technologies are fast response time, high capacity, and long life in partial cycles. In addition, lithium-ion batteries have the potential for different power/capacity combinations. Nevertheless, the energy capacity of all batteries is limited, which limits the maximum power delivery time. Therefore, lithium-ion batteries are best suited for FCR applications characterized by short-term power supply [74], [75]. The possibility to install BESS in almost any place gives this technology a noticeable advantage. Thus, in this research, other ESS technologies are not considered.

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 needed response speed to provide FCR. Regulation capability and ancillary services' price have vast influence on BESS economics and operation. The algorithm should be tailored for specific power systems and electricity market needs. Reviewed studies have not addressed the problems Baltic TSO's will encounter in the nearest future, thus the proposed methodology could be used as guidelines in the decision–making process [76], [77], [78], [79], [80].

In following sections, methodology to determine the possibility to use battery system for FCR service is proposed.

5.2.2. 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.

Mathematical modelling of BESS

The modelling of BESS operation for providing FCR is based on the Latvian TSO planned conditions for the implementation of ancillary services considering synchronization with the CESA until 2025 [70]. The characteristics of the planned FCR product are summarized in Table 5.5.

Table 5.5. FCR Product Characteristics [70]

FCR amount	±11 MW
Time	15 min
Minimum bid	1 MW
Maximum bid	All neccesary FCR amount
Minimum duration between successive activations	0 min
Maximum activation duration	Non limited
Capacity pricing	Pay-as bid

Some principles of the German integrated market for ancillary services have been considered as well. One of these states that all FCR bids must be symmetrical, i.e., up and down regulation must be provided [81].

The FCR provision process or so-called primary frequency control is based on a load-frequency characteristic, as shown in Fig. 5.2. FCR is not intended to restore the frequency to a nominal value (50 Hz), but to restore the balance of generated and consumed power in the system and to keep the frequency at a stable limit. This historically has been done by automatically adjusting the output of generating units. The amount of active power required to restore this balance or prevent the further frequency increase or decrease is proportional to the system's frequency deviation from the nominal value.

According to the proportional load-frequency characteristics, the current battery power $P_{BESS(t)}$ for FCR provision is defined mathematically as following:

$$P_{BESS(t)} = \pm P_{FCR}(t) = \frac{\Delta f}{|\Delta f_{\max}|} \cdot P_{FCR\_max}, \tag{5.1}$$

where $\pm P_{FCR(t)}$ – actual necessary positive or negative power for FCR provision according to frequency deviation, $\Delta f = f - f_{\mathrm{nom}}$ – deviation of actual frequency f from the nominal frequency fnom = 50 Hz, $P_{FCR\_\max}$ – maximal FCR power defined in Table 5.5, and $\triangle fmax$–maximal frequency deviation at which total prequalified FCR power should be activated. In the synchronous grid of Continental Europe, the maximum steady-state frequency deviation is ±200 mHz, at which full FCR power must be activated in 30 s. The frequency band or deadband in which FCR delivery is not required is ±10 mHz [82], [83].

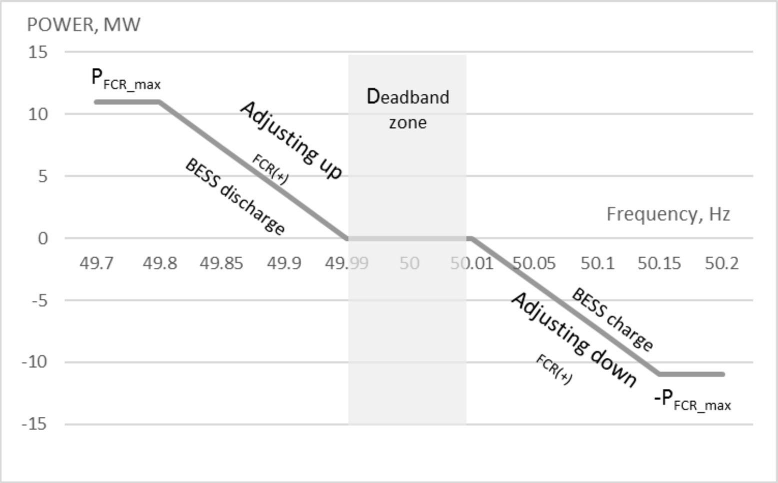


Fig. 5.2. Primary frequency control load-frequency curve.

As the frequency deviation increases, the required active power increases linearly. If the frequency deviation is above 50 Hz, there is active power surplus in the network. This means generated active power must be reduced, or negative FCR provision (FCR (–)) is required, and vice versa – when frequency is below 50 Hz generated active power must be increased or positive FCR power (FCR (+)) is required. In the BESS case the positive FCR is provided by discharging the BESS and negative – by charging BESS. In the calculations, BESS power is assumed to be positive if BESS is charged, and negative if BESS is discharged.

In the event of the frequency deviation, the generating units that provide the FCR automatically activate them within a few seconds; therefore, primary frequency control is the fastest way to control the power system (see Fig. 5.1).

Frequency data

Frequency data provided by the Latvian TSO for 2018 and 2019 were used in the calculations of BESS operation, as well as the calculations with French power system (RTE) data [83] for 2019 were used for comparison. Frequency measurements are summarized at 1-min intervals.

In the Latvian power system, the frequency dynamics have been similar in both analyzed years. For purpose of better perception, Fig. 5.3 and Fig. 5.4 show Latvian and French power system frequency deviations at 4-h and one-month periods accordingly. Fig. 5.5 shows the frequency histogram of Latvian and French power systems. Although the primary frequency regulation is currently provided by the Russian UPS, the frequency characteristics were analysed in the context of the requirements of EU network codes and guidelines. Most of the time, the frequency was within the allowable limits from 49.99 to 50.01 Hz – 61 % of all cases in 2018 and 63 % in 2019. Approximately 37 % of the time in 2018, and 39 % in 2019, the frequency was outside the normal frequency deviation limits of ±0.01 Hz – when no primary frequency control should be performed. In both years, the frequency was above 50 Hz (51 %) most of the time.

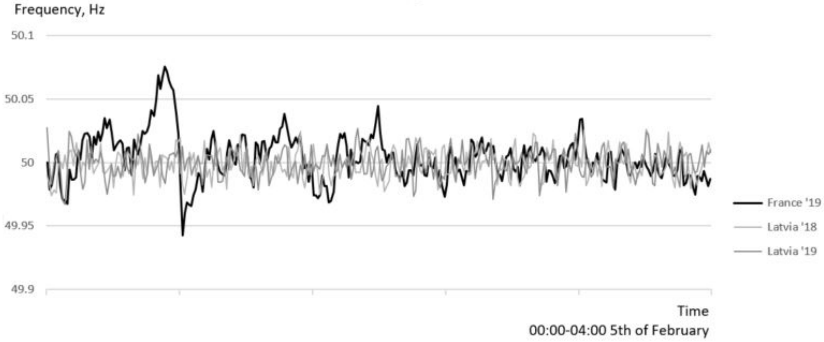


Fig. 5.3. Frequency shifts in Latvian and French power system (00:00–04:00, February 5).

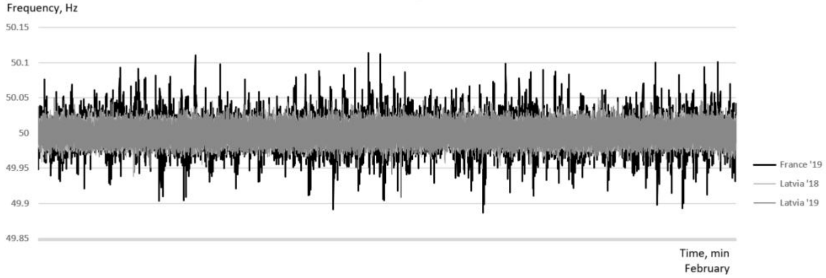


Fig. 5.4. Monthly frequency changes in Latvian and French power system (February).

In contrast, the French power system, which is part of CESA, had significantly larger frequency deviations from the nominal value. The frequency was outside the permissible limits 49 % of the time (Fig. 5.3 – Fig. 5.5). As the frequency data are rapidly changing, the following pictures are used to display the large difference in frequency variability and dynamics in Latvia and France. In Fig. 5.3 the time scale is 4 h on 5 February, and Fig. 5.4 the time scale is whole month of February 2019 (major gridlines represent one week, minor gridlines represent one day).

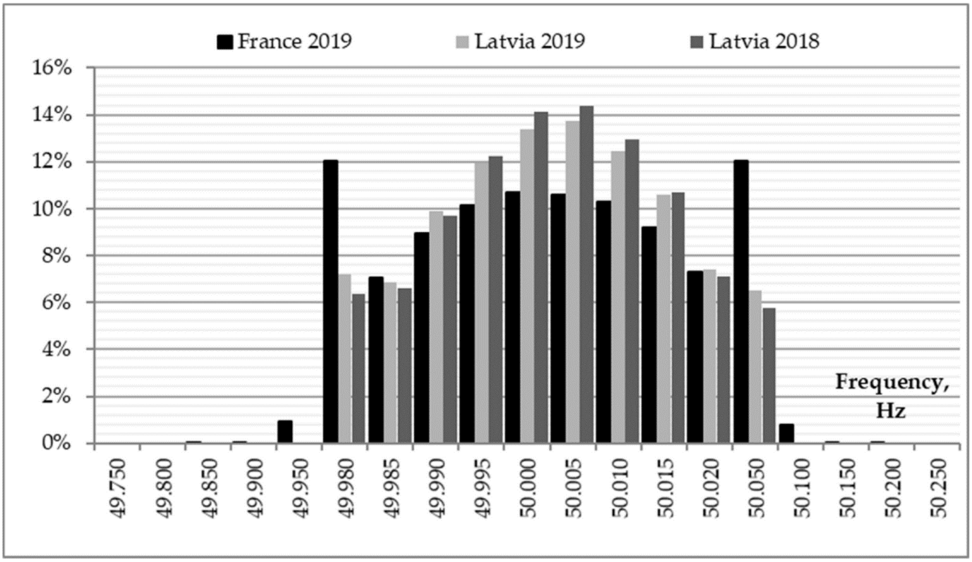


Fig. 5.5. Frequency histogram of Latvian and French power system.

BESS life cycle and degradation

Battery life is one of the most important factors in any BESS application, as it will greatly affect the cost-effectiveness of the project. BESS life cycle is basically evaluated according to two criteria-calendar life and cycle life. At these particular circumstances, the end-of-life criterion is considered to be a 20 % reduction in capacity, which is facilitated by both processes-calendar and cycle aging. As more recycled products are becoming available for stationary cases, the BESS life could be extended up to values lower than 70 % of the initial installed capacity, which could lead to better feasibility results. Battery life depends mainly on temperature, time, state of charge, and number of cycles [75]. To simplify the calculations, it is assumed that the decrease of the lithium-ion BESS capacity is linear over time and amounts to a 2 % reduction from the initial nominal capacity each year. Thus, the technical life of BESS is assumed to be 10 years.

Calculation algorithm of the BESS model

The algorithm (see Fig. 5.6) 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.

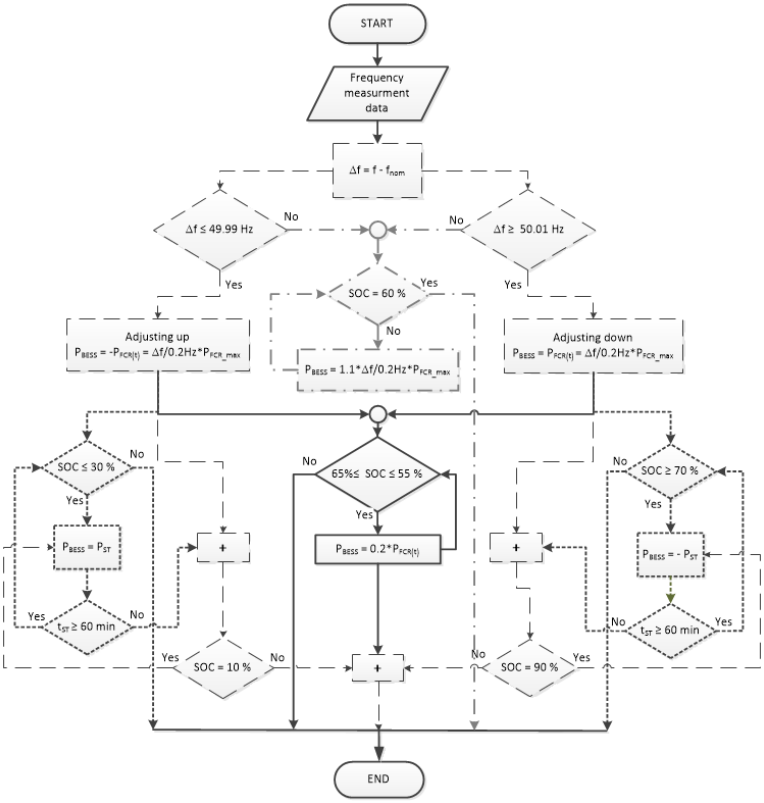


Fig. 5.6. Blocksheme for the BESS operation.

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 (see Table 5.4). Table 5.6 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-min criterion in both directions, as well as the permissible SOC levels, a minimum battery capacity is determined mathematically as follows:

$$E_{BESS\_nom} = P_{BESS\_nom} \cdot 0.5/DOD_{max} \tag{5.2}$$

where 0.5 – defines half of 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 (5.2) 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:

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

$$\text{for discharging } SOC(t) = SOC(t-1) + \frac{P_{BESS}(t) \cdot \Delta t}{\eta_{BESS} \cdot E_{BESS\_nom}}, \tag{5.4}$$

where $SOC(t-1)$ – is the state of charge at the previous time moment; η_{BESS} – is round-trip efficiency of the battery storage system; 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 % [84].

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

Table 5.6

Selected BESS Parameters

Nominal power	$P_{BESS\ \mathrm{nom}}$, 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 %

Maintaining normal state of charge

While providing FCR reserves, the BESS is charged and discharged continuously. At some point – at higher frequency deviations – it may reach full charge or discharge, and at that point it will no longer be able to provide symmetric FCR service. Therefore, a BESS state of charge management strategy is required to ensure that BESS will supply FCR capacity throughout the contracted time slices. Here, some options to maintain normal SOC level have been considered, as practiced in the German FCR market.

The German FCR market legislation allows in certain cases to deviate from the proportional frequency regulation curve. This is especially important for BESS operators, as they can use these options to restore state of charge levels. Typically, the battery operator has three options to balance the charge level and maintain the normal operating range of the BESS during primary control operation [82], [83].

First option is overfulfillment when it is allowed for battery operators to exceed the specified FCR power up to 120 % of the load-frequency curve $P_{(f)}$, as shown in Fig. 5.7. This option can be used to selectively charge or discharge the battery as needed.

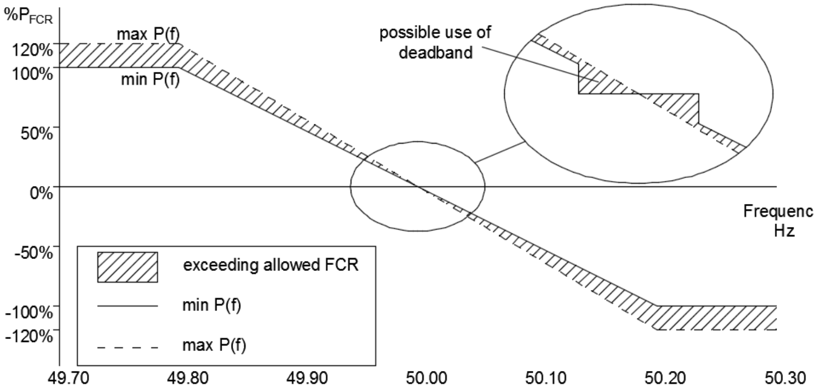


Fig. 5.7. Exceedance range and deadband of the specified FCR [76].

Second option is deadband utilization. BESS operators have the option of resetting the charge level in the frequency deadband, which is ±10 mHz (see Fig. 5.7). They may choose to comply with or deviate from the $P_{(f)}$ curve. However, the opposite control is not allowed – BESS should not be discharged when the FCR is positive, and BESS should not be charged when the FCR is negative. In this case the accuracy of the frequency measurement equipment and the control measurement must be high.

The third option is BESS charging or discharging through scheduled market transactions. This means that the balancing energy can be purchased or sold in the intraday market to restore the desired BESS charge level. It must be ensured that the net FCR supply (battery capacity minus capacity purchased/sold on-the-spot market) continues to comply with FCR regulations. When the BESS is charged or discharged with the planned energy, its operating point is changed to enable the primary control operation at the same time. The BESS operator must present the concept to the responsible TSO and notify the TSO 15 min before the change of operating point.

The intraday market is a part of the wholesale electricity market in which electricity is traded in relatively small volumes with a short delivery time. Products available on the intraday market include hourly and quarterly electricity supply contracts.

In the first and second options, the electricity consumed from the grid to recharge the battery depends on the system frequency, but the energy bought or sold on-the-spot electricity market (third option) does not depend on the system frequency and can be used to significantly adjust the SOC of BESS. On the other hand, the first and second options are free of charge, but on-the-spot market electricity must be purchased at a fixed price, which increases BESS's operating costs, while electricity sold on-the-spot market generates additional income.

All three options are used simultaneously in the calculations of BESS operation to maintain the normal state of charge (see Table 5.7). Therefore, the following characteristics were defined:

1. The deadband utilization is used in the ±10 mHz frequency range.
2. FCR overfulfillment starts when the state of charge decreases to 55 % (SOCOF_min) or increases to 65 % (SOCOF_max). When these limits are reached, the required amount of FCR is exceeded by 20 %, thus speeding up BESS charging or discharging.
3. Scheduled market transactions are activated at 30 % state of charge level (SOCST_min) and 70 % (SOCST_max), respectively. An important aspect to be considered to ensure the SOC management through the scheduled market transactions is the planned transaction capacity (PST), which should be additionally accounted for the BESS investment costs. In the calculation model, additional capacity of 1 MW is assumed for market transactions, which will be sold or purchased on the spot market for 1 h as the SOC level reaches defined limits.

Table 5.7. Parameters for SOC Management

Planned transaction capacity	P_{ST}, MW	1
Minimum state of charge for activation of FCR overfulfillment (OF)	SOC_{OF_min}	0.55
Maximum state of charge for activation of FCR overfulfillment (OF)	SOC_{OF_max}	0.65
Minimum state of charge for activation of scheduled transaction (ST) for charging	SOC_{ST_min}	0.3
Maximum state of charge for activation of scheduled transaction (ST) for discharging	SOC_{ST_max}	0.7

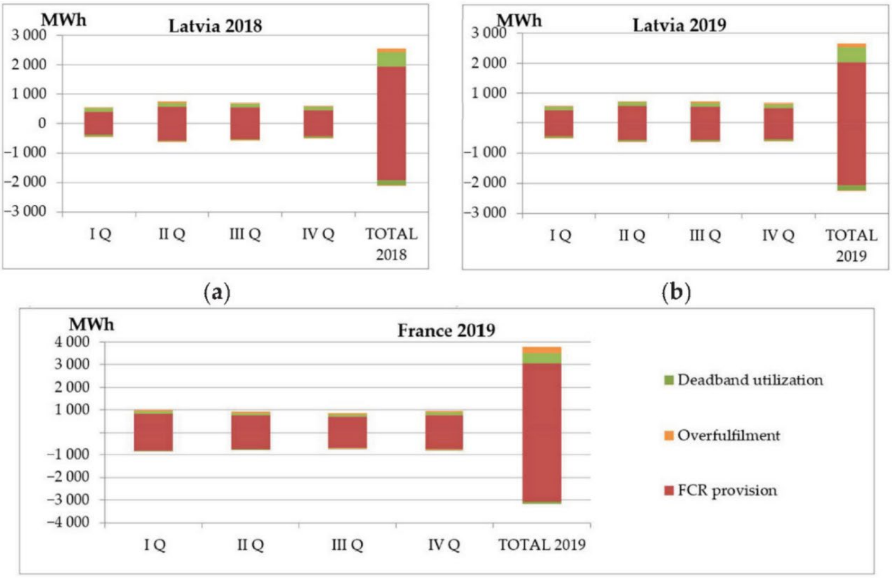
5.2.3. Results and discussion

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. 5.8 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. 5.8 show that in this case, BESS transferred around 3160 MWh to the network and consumed around 3800 MWh of electricity for charging.

Fig. 5.9 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. 5.9 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.



(a) (b)

(c)

Fig. 5.8. BESS performance for FCR provision and SOC management: (a) Latvia 2018, (b) Latvia 2019, (c) France 2019.

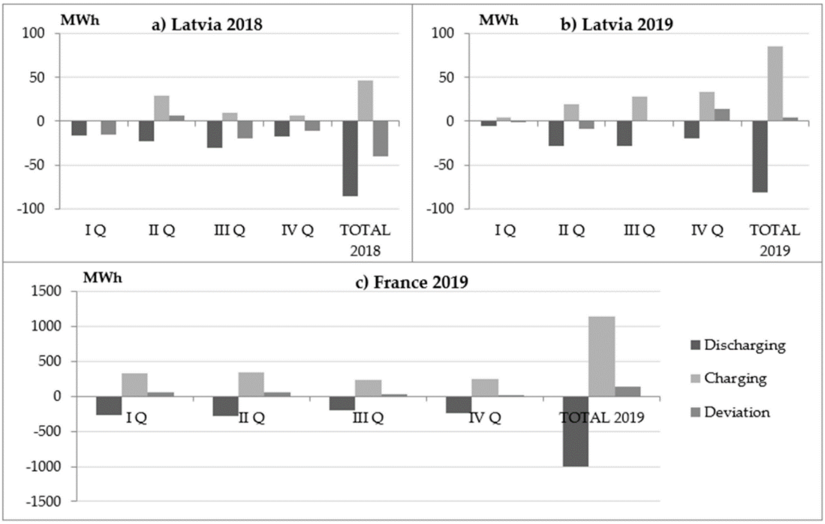


Fig. 5.9. Scheduled market transactions to restore the SOC.

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. 5.10. 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. 5.10 shows how the operating point of the actual BESS power shifts.

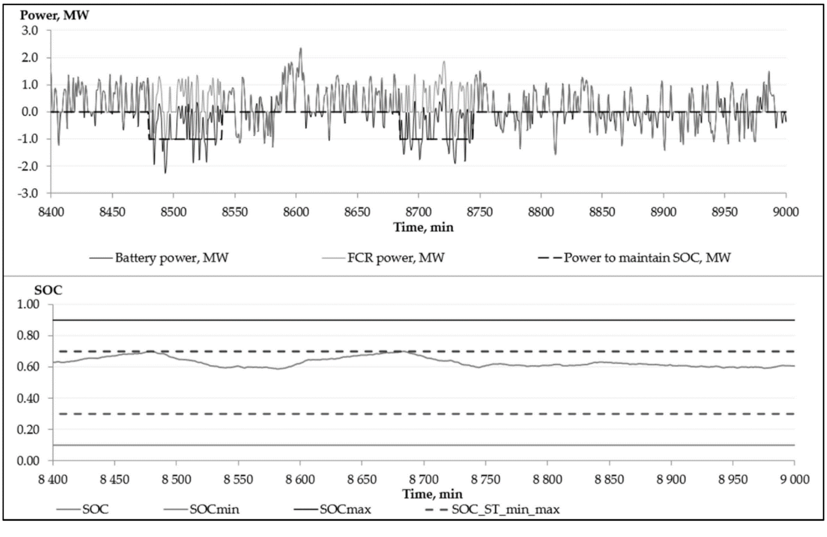


Fig. 5.10. Battery power and SOC dynamics: Latvian power system's frequency changes (Q1, 2018, 06.01.18, 20:00–07.01.18, 06:00).

The dynamics of battery power and SOC in the example of the French power system, are shown in Fig. 5.11. Fluctuations of SOC are more frequent, with larger discharge depths, according to frequency fluctuations. Performed SOC management ensures its maintenance within permissible limits.

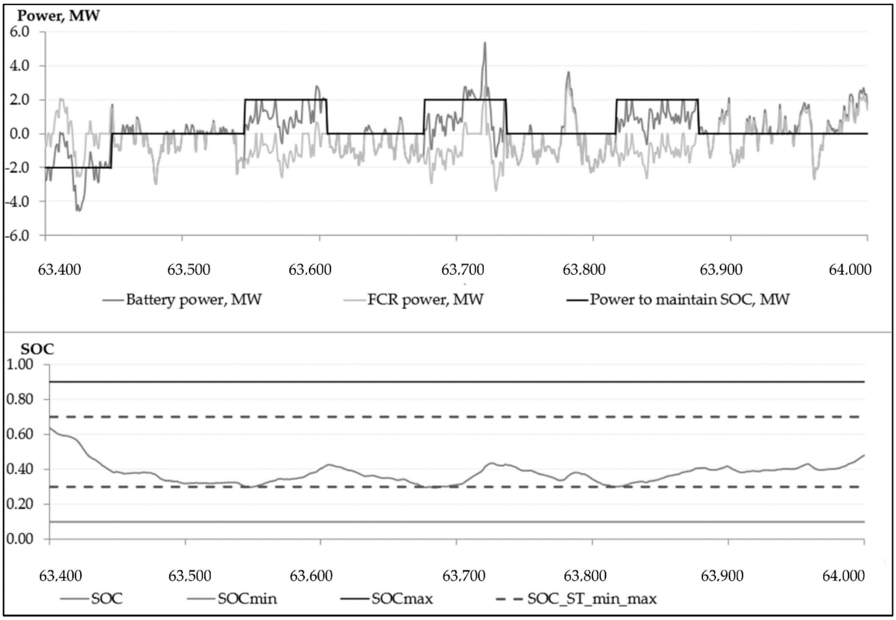


Fig. 5.11. Battery power and SOC dynamics: French power system (Q2, 15.05.19, 00:40–10:40).

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. 5.12.

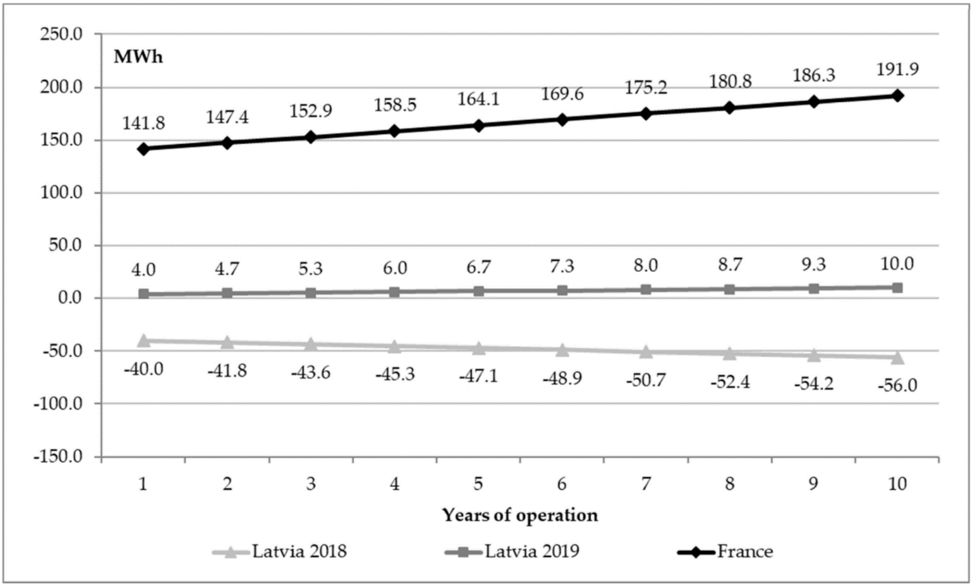


Fig. 5.12. Yearly electricity use for BESS's state of charge renewal over its lifespan.

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.

Economic assumptions

To assess the economic efficiency of the BESS project, the net present value (NPV) of the project is determined as well as the internal rate of return (IRR) and the discounted payback period. To assess the capital investments of the BESS project, the specific capital costs for energy and for power as 359 EUR/kWh and 445 EUR/kW is assumed accordingly. Considering this, the expected capital costs of BESS are estimated at EUR 7.85 million for the example of Latvian power system with 12 MW/7 MWh BESS, and at EUR 8.30 million for the example of French power system with 13 MW/7 MWh BESS. Annual operating expenses amount to 1.5 % of the initial investment, or EUR 0.12 million in the Latvian example and EUR 0.13 million in the French example.

Additional costs for SOC renewal via scheduled transactions in the intraday market are also considered, although the renewal of SOC was not always required to purchase electricity. As can be seen from Fig. 5.12, there was necessity to sell surplus electricity in the intraday market for SOC renewal. However, the amount of additional costs of EUR 6.2 thousand with an annual increase of 3.93 % during battery life cycle were assumed in base calculations. The costs are calculated based on the forecasted electricity price (2022 is the start of BESS operation).

In turn, the revenue from the provision of FCR service amounts to EUR 0.95 million annually at the assumed base price of FCR service of 10 EUR/MW per hour. In calculations, the base price of the FCR service is assumed to be the average of the existing FCR service prices in the German and Finnish FCR markets.

Economic calculations assume that continuous provision of FCR service during the contract period is ensured, as well as the right to provide full FCR service yearly – except for two weeks for BESS maintenance – will be won. The discount rate is assumed to be 5.5 %.

Considering all the above basic economic assumptions, the BESS project does not pay back during its technical life. The calculated NPV in year 10 for the Latvian example is – 1.7 MEUR and IRR 0.64 %. The BESS project would require at least 25 % co-financing to ensure a payback period of 10 years. In the case of the French energy system, for example, there is correspondingly lower return on investment.

As FCR prices are not predictable, the impact of changes in the price of the FCR service on the payback of the BESS project has been further assessed. FCR price changes are assumed to be ±20 % and ±40 % of the base price. According to economic calculations, the BESS project can payback within 10 years without additional co-financing, if the price of the FCR service is at least 14 EUR/MW/h. The respective NPV curves for the frequency deviations of the example of the Latvian power system are shown in Fig. 5.13.

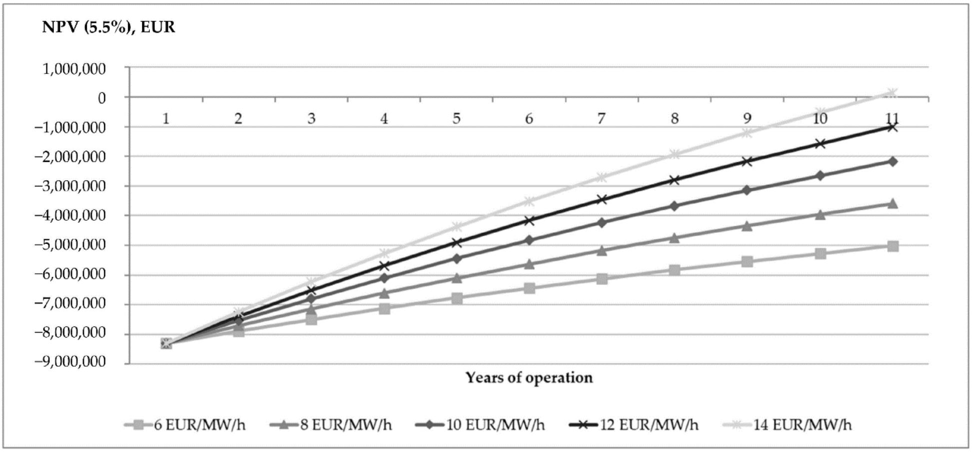


Fig. 5.13. NPV curves for BESS project: Latvian power system, various FCR prices.

5.3. The role of decentralized electrode boiler in ancillary services

5.3.1. Motivation and background

It is widely acknowledged that combined heat and power plants (CHPs) can play a significant role in providing resilient energy systems. This is due to their ability to switch generation between electricity and heat, as well as operate in cyclic modes [85], [86]. Considering the rapid development of renewable energy sources and the emergence of new balancing markets, there is still a need for a comprehensive study on individual power-to-heat technologies that could further enhance the flexibility provided by CHPs. One such technology is the electrode boiler (EB).

EB is a device that uses electricity to generate heat for individual or district heating systems, or other industrial processes. Regarding electrode boilers, two types are typically distinguished: those with an electric heater (known as electric resistance boilers) and those with electrodes. Due to their larger capacity, electrode boilers are most often used for district heating purposes. EBs can provide hot water as well as steam with efficiencies up to 99 % (η_{avg}^{EB}) and capacity of 5-70 megawatt (MW) [87], [88]. Other characteristics of electrode boilers are shown in Table 5.8.

Table 5.8. Electrode Boiler Characteristics [86], [89]

Parameter	Electric boilers	
Ramp rate up/down, s	from less than 30 s	
Operating temperature level input, °C	10-110	
Operating temperature level output, °C	water: 70-140, steam: < 300 at 45 bar	
Investments for different EB capacities, million EUR/MW	Voltage and installed capacity	Net investments
	400 V and 1-3 MW	0.13-0.16
	10 kV and 10 MW	0.06-0.09
	10 kV and 20 MW	0.05-0.07
Total operations and maintenance (O&M)	–	
Fixed O&M, EUR/MW per year	1100	
Variable O&M, EUR per megawatt hour (MWh)	0.5	

As it can be seen in Table 5.8, the investments are decreasing with the increasing of EB capacity. To address potential cost fluctuations, including those attributed to inflation, this publication will incorporate a sensitivity analysis, considering cost adjustments of +15 % and +30 % for EB investments. Besides, valuable characteristics mentioned in Table 5.8, integrating EBs in CHPs is often associated with accommodation of large shares of variable renewable energy. Study [90] argues that despite an increased need for balancing renewables and the technology being available, initiatives to use them, for example, in Sweden district heating systems as flexibility sources are rare because the potential gain is considered low and unpredictive.

Nevertheless studies [91], [92], [93], [94] emphasize importance of flexibility services provided by EBs. Most efforts of reviewed studies were focused on the electricity day-ahead market. Even though the number of works studying the participation in the balancing markets is limited, EBs still demonstrate the potential to increase the flexibility provided by CHPs, due to their high ramp rate from minimum to full load and high efficiency.

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 [86], 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.

5.3.2. Insight into the energy sector of Latvia and other Baltic states

As studied in [71], [95], the Baltic States for the period up to 2030 can face the following: (1) supply of electricity balancing reserves is expected to decrease because the oldest conventional generators are expected to exit the market; (2) due to high geopolitical tensions in relations with ongoing war from Russia since February 2022, natural gas prices hit records – in the Netherlands Title Transfer Facility reached 345 EUR/MWh in March 2022; (3) the growing share of intermittent and distributed generation in the Baltic power system; (4) rising price of carbon dioxide (CO_2) emission allowances; (5) synchronisation of the Baltic power system with the grid of Continental Europe, which will further increase demand for balancing reserves – frequency containment reserves and automated/manual frequency restoration reserves (mFRR and aFRR).

According to a balancing roadmap of the Baltic transmission system operators (TSOs), TSOs have committed to implement and make operational European platform for the exchange of balancing energy from mFRR (the so-called MARI platform) and exchange of balancing energy from aFRR (the so-called PICASSO platform). Baltic TSOs have to join MARI platform no later than 24th July 2024, and the introduction of PICASSO is planned to be concluded by the end of 2024. To ensure necessary reserves for operation of the Baltic States, Baltic TSOs also plan to procure reserves (FCR, aFRR, mFRR) as capacity products. Procurement of all three types of reserves will start at the end of 2024. The main parameters for all three types of reserves are shown in Table 5.9 [96].

Table 5.9. Three Types of Reserves – FCR, aFRR and mFRR

Standard product	**FCR**	**aFRR**	**mFRR**
Activation type	Automatic	Automatic	Manual
Activation time	< 30 s (2 s reaction)	< 5 min	< 12.5 min
Minimum volume	1 MW		
Direction	Symmetrical	Up and down	
Preparation period	0 min	0 min	< 7 min
Linking of bids	No		Yes
Activation command	– (based on local frequency measurement)	Signal (from TSO frequency restoration controller)	Message (WebService)

This study considers EB aligned integration in "Latvenergo AS" natural gas combined heat and power plant one and two (CHP-1 or CHP-2) operation. Both CHPs not only hedge Latvia against possible shortages of electricity supply, but also provide heat energy for the right bank of Riga district heating system. CHP-1 has two gas turbines (P = 158 MW and Q = 145 MW) combined with three gas heat only boilers (HOB, 3 x 116 MW). While CHP-2 consists of two combined-cycle gas turbines CHP-2/1 (P = 412 MW and Q = 275 MW) and CHP-2/2 (P = 419 MW and Q = 270 MW) combined with five gas HOBs (Q = 5 x 116 MW) [86].

The Baltic balancing market volumes and prices

Since 1 January 2018, a single balancing market has been operating in the Baltic States. Operation of the common Baltic balancing market takes place using balancing energy products: Baltic mFRR standard product and Baltic emergency reserve (ER) mFRR product. The total activated energy from mFRR and ER mFRR products in the Baltic balancing market for the four years can be seen in Fig. 5.14. On average, upward balancing electricity was activated in the amount of 193 361 MWh during these years, and 210 355 MWh for downward regulation.

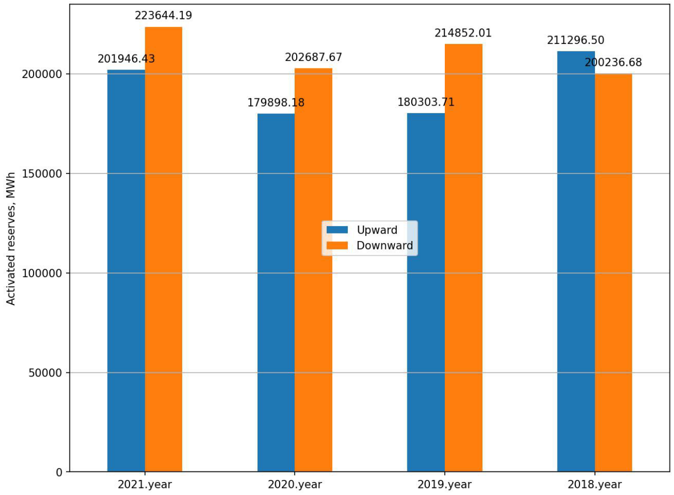


Fig. 5.14. Activated mFRR and ER mFRR volumes in the Baltic balancing market [97].

This study assumes that the EB will only be used for downward mFRR regulation, and the balancing market data and CHPs operation calculations are based on the year 2021. The reason for choosing 2021 is that CHPs units have been operating less than usual since 2022, due to the uncertainty surrounding gas availability following Russia’s invasion of Ukraine.

Fig. 5.15 shows the average annual reserve prices from normal activations for both upward and downward regulation in all three Baltic countries. The price of the ER mFRR specific product is not available on the Baltic Coba platform and not included in these statistics.

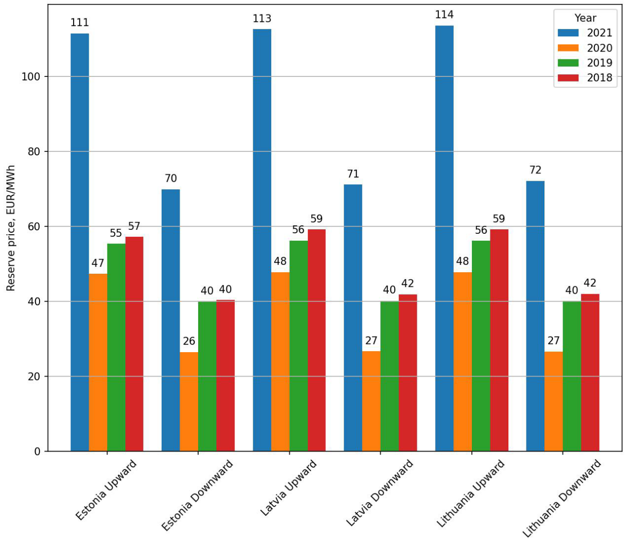


Fig. 5.15. Average annual reserve prices from normal activations [97].

It can be observed in Fig. 5.15, the downward reserve price is relatively lower than the upward reserve price. The EB can theoretically be used in the upward direction, but this study will not consider it. According to the Baltic balancing market rules, downward activation (or negative balancing energy) is balancing energy bid activation to reduce generation or increase consumption.

5.3.3. 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. 5.16. 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/m3.
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.

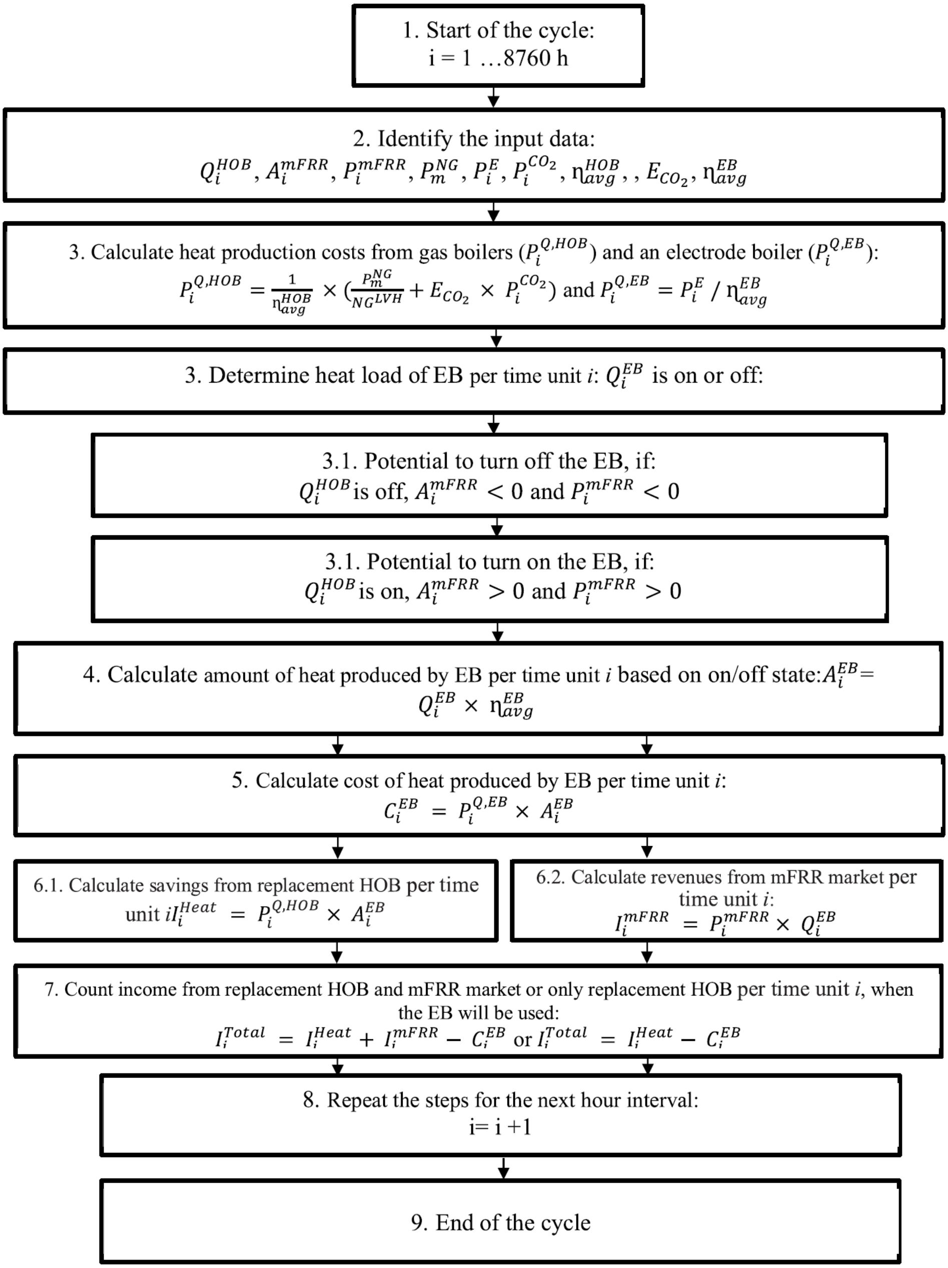
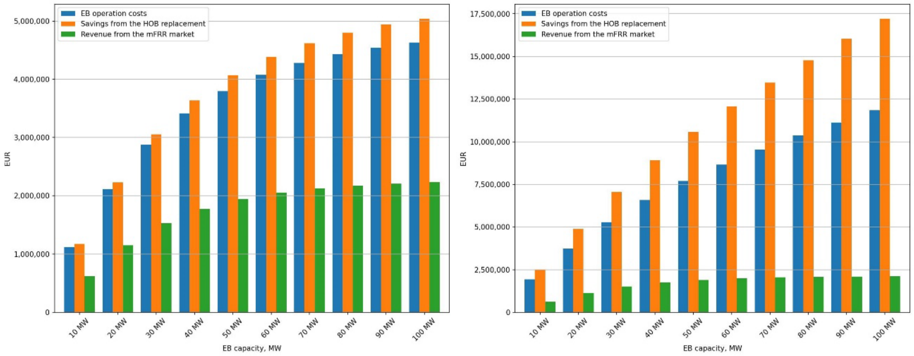


Fig. 5.16. The calculation principles of EB operation.

5.3.4. 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. 5.17). Fig. 5.17 (a) represents the scenario where the EB operates and receives savings from HOB replacements and revenues in the mFRR market. Fig. 5.17 (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.



(A)

(B)

Fig. 5.17. Operation of EB with different capacities.

Fig. 5.18 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. 5.18 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.

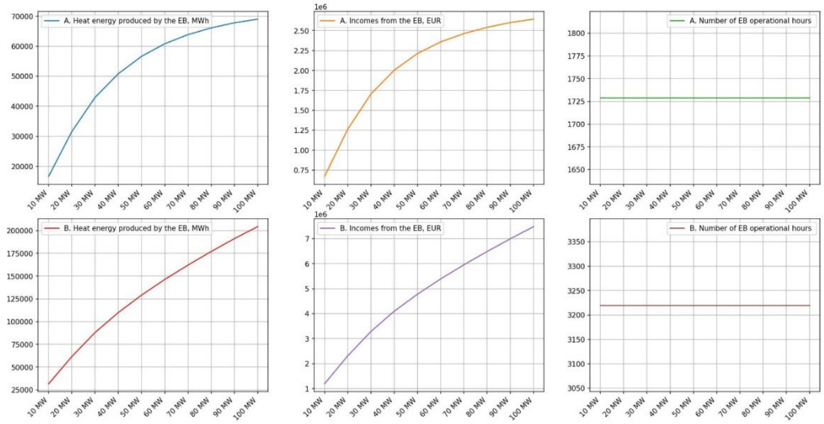


Fig. 5.18. Operation of EB in Scenarios A and B.

Fig. 5.19 illustrates the broader characteristics for various EB capacity levels. It showcases the project economic indicators, which are expressed as net present value (NPV), internal rate of return (IRR) and the number of years it would take for the project to payback.

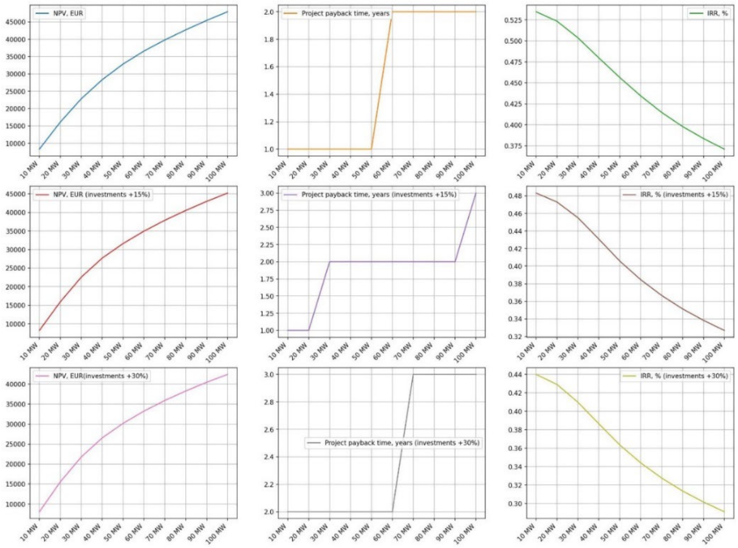


Fig. 5.19. Characteristics of EBs at different capacity.

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. 5.18 and Fig. 5.19). 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.

Fig. 5.20 shows the hours of operation for both the HOBs and EB (with 50 MW capacity) throughout the year.

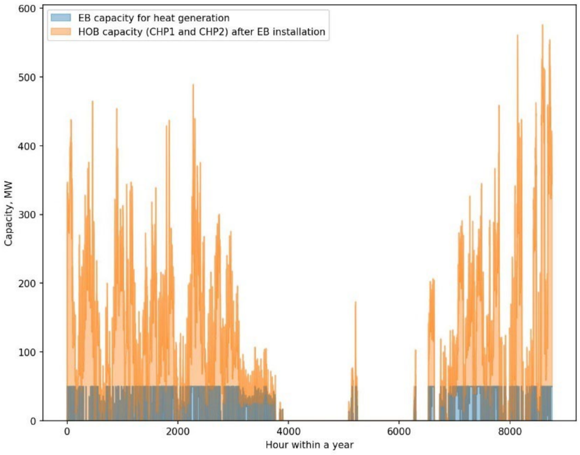


Fig. 5.20. HOB and EB capacity on an annual basis.

The HOB capacity is denoted in orange, while the EB capacity is shown in blue. Fig. 5.20 demonstrates that the performance of the EB is reliant on the nature of the HOBs. Additionally, it indicates that the utilization of the EB could be even further enhanced if there were possibility to increase EB capacity or it could be profitable to operate under another heat or electricity market conditions.

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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APPENDICES

Appendix I:

Multiple Scenario and Criteria Approach for Optimal Solution and Sizing of Household Off-grid System

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***Abstract*—The aim of this publication is to determine the optimal mix and sizing of household off-grid system, using the scenario approach. Homer Pro software was used to simulate the off-grid systems, using multiple criteria, such as minimisation of net present costs, increasing the fraction of renewable energy sources (RES), and reducing excess electricity. Three different off-grid technological alternatives, three dispatch strategies, restrictions on some component operation as well as sensitivity of fuel price and capacity shortage were considered to build up scenarios. The case study was calculated for real household customer with load profile, which includes load of heat pump and charging of electric vehicle. The results were thoroughly analysed to determine the advantages and disadvantages of used method and propose the improvements to this method to be implemented in the future research.**

Keywords*—*off-grid, scenario approach, dispatch strategy, Homer Pro, net present costs, capacity shortage

I. INTRODUCTION

Electrification may be efficient and cost-effective way to the fight against climate change and to reach the EU decarbonisation targets [1]. 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 rise series of questions and issues. Often they are either oversized or undersized to fulfil the energy demand [2,3]. The case study is made to analyse off-grid solutions required for a modern electrified household. Different starting points in terms of energy demand, available resources, economic situation, viability may require deep research on aspects how to choose the most suitable off-grid equipment and its operation strategy. Results of this paper compares the scenarios and reveals the most feasible and cost-effective off-grid system for an electrified household.

II. HOMER PRO SOFTWARE

HOMER (abbr. for Hybrid Optimization of Multiple Energy Resources) Pro software is an economic optimization tool for simulation and optimization of off-grid and grid-connected hybrid energy systems. 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).

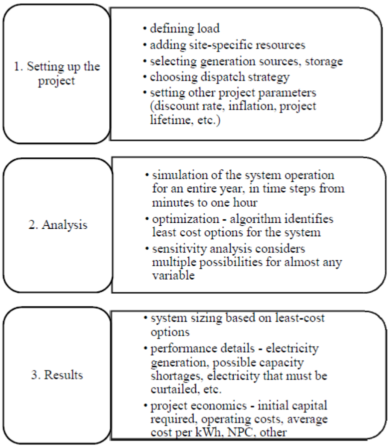

Fig. 1. Homer Pro process diagram.

Objective function of HOMER Pro is used for minimisation of the total Net Present Cost (NPC - which also known as 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 (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 use following equation.

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$$C_{NPC}=\frac{C_{ann,\ tot}}{CRF_{(i,\ R_{proj})}} \quad (1)$$

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

$$CRF(i,\ N)=\frac{i(1+i)^N}{i(1+i)^N-1} \quad (2)$$

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

$$i=\frac{i'-f}{1+f} \quad (3)$$

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 [4].

The software can satisfy specific constraints like generator operation restrictions, capacity shortage level, fuel costs, etc. and at the same time determining an optimal sizing of system components and providing detailed information on system with a lowest total net present cost. Compared with other software computing techniques such as RETScreen, PVSOL, Hybrid 2, TRANSYS, SAMS, RAPSYS and MATLAB, HOMER Pro have benefits such as the wider options when setting up the project, realistic and continuously updated library of components, possible combinations over varying restrictions as well as various dispatch strategies [5]. Within Homer Pro software it is also possible to directly download nature resource data from NASA (abbr. for National Aeronautics and Space Administration) databases on specific location user choose. In default situation, such data are obtained:

- solar radiation monthly averages over 22-year period (July 1983 - June 2005);
- air temperature monthly averages over 30-year period (January 1984 - December 2013);
- wind speed monthly averages over 10-year period (July 1983 - June 1993) are obtained.

However, on the other hand, sometimes some scenarios might be needed to be re-calculated individually for the specific situation, because HOMER Pro can only handle single-object optimization and thus the flexibility is limited [5].

While setting up the project, software user must choose dispatch strategy to determine how generation can provide the load. Dispatch strategy can be defined as a set of rules that pertains to energy flows among off-grid components. The software provides various dispatch strategies, like cycle charging, load following, 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 battery with back-up diesel generator unless it reaches the minimum power of 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 back-up generator is required, it operates at full capacity, and surplus power charges the battery bank. It stops charging battery at the setpoint of 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 load following and cycle charging strategy. That way it can improve performance over the cycle charging and load following dispatch strategies by making more efficient use of back-up generator [4].

After all, users have possibility to write even their own dispatch algorithms for HOMER Pro using MATLAB. Determination of optimal dispatch strategy depends on many factors, including the size of back-up generator and battery system, the price of diesel fuel, the operational and maintenance cost of a generator, the amount of renewable power in the system, and the availability of the renewable resources. The right choice of dispatch strategy is an important factor. Selection of nonoptimal dispatch strategy can result in unnecessarily high operating costs from using more diesel fuel or surplus battery capacity. One of the roles of dispatch strategy is to avoid situations where energy that was charged in the battery by the diesel generator is eventually wasted, because the same charging could have been accomplished by the renewable sources before the energy is needed [7].

HOMER Pro ensures that overall power generation meets (or exceeds) the total system electricity demand. Nevertheless, it is possible to have excess electricity at certain time-steps, due to a small demand or high renewable energy generation. This electricity is considered as curtailed or dumped by HOMER Pro software.

III. CASE STUDY

The study considers household electricity consumer with no access to electric grid and high connection costs. As the alternative the consumer could be supplied from off-grid system. Fig. 2 shows a block scheme of the case study.

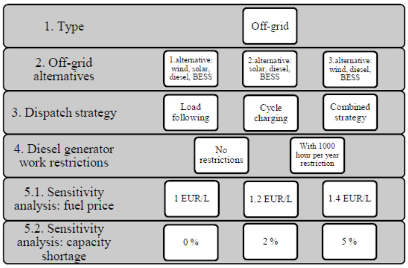

Fig. 2. Block scheme for the case study.

Authors compare various off-grid alternatives to determine the most optimal solution for the selected household. Great attention is paid to ensure the following criteria: highest use of RES, the smallest excess electricity, and the lowest cost of system. Depending on the energy sources, three off-grid alternatives are assumed. The first alternative includes wind turbine, solar panels, back-up diesel generator and battery energy storage system (BESS; lithium-ion type). The second alternative have solar panels, back-up diesel generator and BESS. The third alternative comprise wind turbine, back-up diesel generator and BESS. By considering the location of household, the relevant default nature resource data are obtained. Authors analysed all off-grid equipment components and costs of all alternatives through three different dispatch strategies with and without certain restrictions of back-up diesel generator operation. The restriction of the generator operation time is set to 1000 h per year (to extend 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 the Fig. 2 and in the next sections, authors analysed all off-grid alternatives with respective scenarios (together 162 simulations).

A. *Site location and household load*

The location of the off-grid is in Latvia, near the capital city Riga. Default data of solar radiation, temperature, and wind resources for selected location is obtained from Homer Pro software databases. For the proposed location, the maximum solar radiation is 5.5 (kWh/m^2/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 50 m 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 household is obtained at the reference height of 50 m, while the defined hub height for household's wind turbine is 10 m. For extrapolating the wind speed at the hub height, authors used the wind speed logarithmic profile in Homer Pro. For this case study, real household hourly load data are collected, integrated in the software, and used in simulations. 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 transports 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 for achieving European Union decarbonisation policy targets.

B. *Off-grid power supply system parameters*

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

TABLE I. 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 hight - 10 m
Back-up 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%.

C. *Dispatch strategies*

According to the block scheme of the case study, three different dispatch strategies described previously in Section II are used - cycle charging (CC), load following (LF), combined charging dispatch strategy (CS). Authors applied all strategies to each of the off-grid alternative to see how it will address the technical and economic aspects. To better understand how dispatch work, Fig. 3 shows simulations of 1st of January for all three mentioned strategies. In LF strategy generator mostly follows electric load and is practically not used for BESS charging. In CC strategy generator covers peak demand at full load with surplus used to charge BESS. In CS strategy the combination of both approaches is used. Solar and wind generation is practically unavailable on a given day.

Fig. 4 shows simulations of 1st of June for all three mentioned strategies. Solar and wind generation has higher availability in comparison to simulations of 1st of January. In LF strategy renewable generation is used at most, with surplus used for charging. In CC strategy generator is operated at full capacity to secure higher charging of BESS. In CS strategy – combination of both.

The first alternative (wind, solar, diesel generator and BESS) is used to show electricity flows operated by each of dispatch strategy. Fig. 3 and Fig. 4 shows that with each dispatch strategy at different hours the load is served from different sources. Consequently, at the end, dispatch strategies have their impact to the renewable energy source (RES) fraction delivered to the load. All off-grid alternatives with and without generator operation restrictions are used to show possible RES fraction.

Fig. 5 has a box and whisker chart. This chart type distributes simulated data into three quartiles, to examine how data are dispersed between all results. The bottom of the box represents the first quartile, meaning that 25% of simulated results fall below this level. While the top of the box represents the third quartile, meaning that 75% of simulated results fall below this level. Line through the box is median also called as the second quartile, and it marks the mid-point of the data, where one-half (50%) of the data lies below, and another-half (50%) lies above. The element – x in boxes highlights the mean value. The boxes have also lines extending vertically called "whiskers". The top whisker indicates the maximum value, while the bottom whisker indicates the minimum value in the data set. Any point outside those lines or whiskers is considered an outlier. The outlier is an unusual data present in the data set.

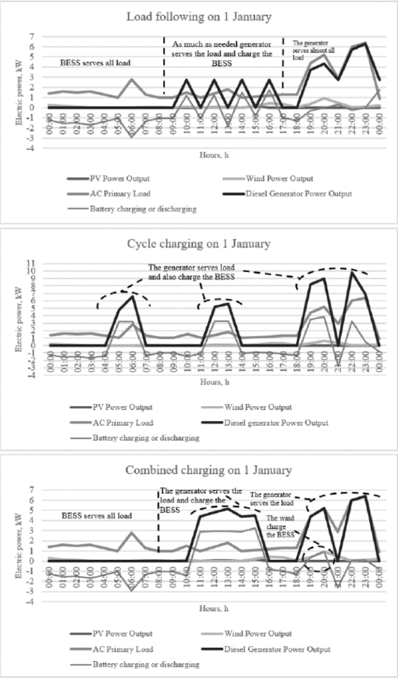

Fig. 3. Three dispatch strategies in action on 1st of January.

For all off-grid alternatives, Fig. 5 shows that using LF strategy the RES fractions reach the greatest values, while. In CC - lowest RES fractions. Fig. 5 also shows that the fuel restriction may increase RES fractions, however, the choice of dispatch strategy has a greater impact.

In more detail the dispatch strategies have been discussed in following sections where their impact on off-grid equipment components is assessed.

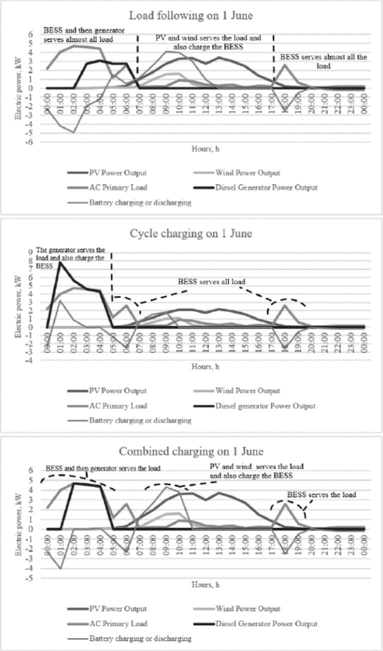

Fig. 4. Three dispatch strategies in action on 1st of June.

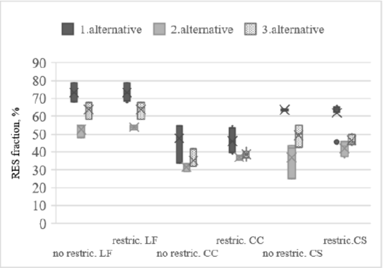

Fig. 5. The fraction of RES delivered to the load according to dispatch strategies.

D. *Simulation results for the first alternative*

System equipment dimensions (in kW and kWh) or the possible sizing parameters of off-grid equipment components are determined considering all dispatch strategies, scenario with and without diesel generator restriction, and considering all different fuel prices and capacity shortages levels. Results are shown in a box and whisker chart in the Fig. 6.

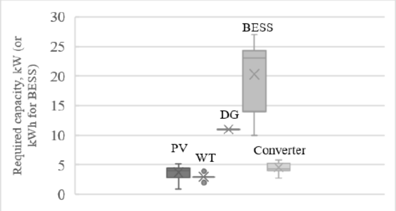

Fig. 6. System equipment dimensions for the first alternative.

Calculations show that the required capacity of solar panels can vary within 0.9–5.2 kW range. Wind turbine capacity is within 2–4 kW range (counting outliers). Diesel generator - 11 kW, while BESS storage capacity maximum and minimum values are in 10–27 kWh range, but power capacity corresponds to converter capacity which is within 2.8–5.8 kW range. The capacity of the diesel generator is constant (11 kW) because system must ensure safety and to cover the maximum daily load (which is around 9 kW).

E. *Simulation results for the second alternative*

System equipment dimensions for the second alternative (solar, diesel, BESS) is shown in a box and whisker chart in .the Fig. Required capacity for solar panels is within 6.3–11.8 kW range. There is no wind turbine in this alternative, so its capacity is 0 kW. Diesel generator - 11 kW, while BESS storage capacity is in range 25 – 32 kWh.

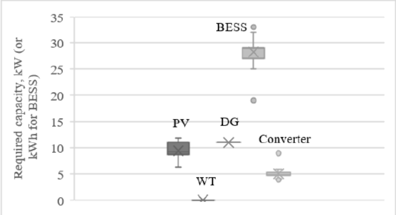

Fig. 7. System equipment dimensions for the second alternative.

The BESS power capacity corresponds to max-min values of converter capacity, which is within 4.0–5.8 kW range.

F. *Simulation results for the third alternative*

System equipment dimensions for the third alternative (wind, diesel, BESS) are shown in a box and whisker chart in the Fig. 8.

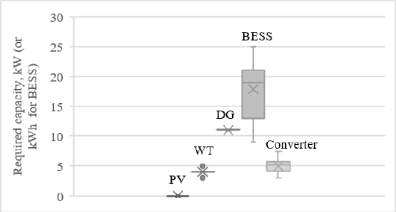

Fig. 8. System equipment dimensions for the third alternative.

There are no solar panels in the third alternative, so the capacity is 0 kW. Wind turbine capacity is within 3–5 kW range (if we count outliers). Diesel generator - 11 kW, while BESS storage capacity is within whiskers - 9–25 kWh range, but power capacity corresponds to converter capacity, which is within 3.0–7.4 kW range.

IV. COMPARISON OF ALL OFF-GRID ALTERNATIVES

The Table II shows the average equipment values for each of 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. First alternative would need less solar panels and wind turbine capacities comparing with second and third alternative.

TABLE II. AVERAGE EQUIPMENT SIZE FOR ALL ALTERNATIVES

System equipment	No.1	No.2	No.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 (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 as well as diesel fuel costs. Fig. 9 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 44 863–52 066 EUR range. First alternative with 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. 9 also shows that 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 impact on the NPC values. There is an effect, and it can be seen with whiskers - the NPC values in some cases are extended both ways. If correctly applied generator restrictions can reduce NPC.

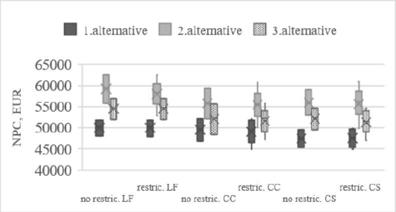

Fig. 9. NPC results depending on different dispatch strategies.

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

Performing sensitivity analysis, the Fig. 10 shows a fuel price impacts on fuel consumption of back-up diesel generator. With price increase from 1 to 1.4 EUR/L the mean value of fuel consumption for first alternative is reduced from 1806 to 1386 litres per year.

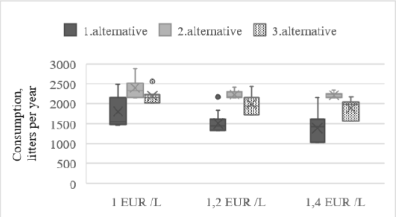

Fig. 10. Generator fuel consumption depending on fuel price.

One-year consumption for all off-grid alternatives is compared. Firstly, the sensitivity analysis shows that as soon as the price of fuel increases, consumptions of fuel tend 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. For some cases, it can be more than thousands of litres per year. While by comparing the initial off-grid investment costs according to capacity shortage levels in the Fig. 11, it is possible to assess capacity shortage impact.

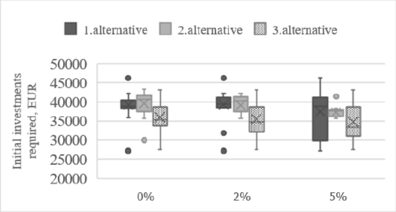

Fig. 11. Initial off-grid investment costs depending on capacity shortage.

Higher capacity shortage (5%) most likely will mean that less initial investments might be required to develop off-grid system. At the same time, Fig. 11 shows that there is practically no difference between no capacity shortage (0%) and relatively small capacity shortage level (2%).

In addition to all analysis 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 a renewable sources) and the batteries are unable to take all electricity. Excess electricity as the percentage (%) from 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. 12.

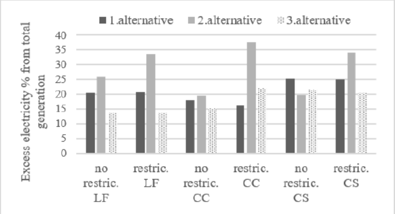

Fig. 12. Excess electricity in the all off-grid alternatives.

In average, the smallest "excess electricity" resulted for the third alternative – 17.68% (which is around 2 670 kWh per year). The next with – 20.9% (or 3 235 kWh) is the first alternative, while the greatest "excess electricity" resulted for the second alternative – 28.41% (or 5 108 kWh). Here authors conclude 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.

V. CONCLUSION AND DISCUSSION

The case study results showed that lower installed capacity of renewable energy sources might be required if off-grid consists of solar panels and wind turbine (first alternative). Most likely it is due to fact that solar and wind energy are complementary. In wintertime more electricity is produced from wind, but in summertime from the sun. The NPC results for the first alternative has proven to be the most cost-effective almost in all scenarios. Besides that, the first alternative proved the greatest possibilities to increase RES fraction across the dispatch strategies used in simulations.

The results show how important it is to choose the right dispatch strategy. Firstly, it may largely impact required system equipment dimensions, especially for the BESS storage capacity whose changes were observed the most. For the first alternative 10–27 kWh range, for the second alternative 25–32 kWh range, but for the third alternative 9–25 kWh range. Secondly, chosen strategy impacts fuel consumption of back-up generator, RES fraction and at the end also the NPC over the project 10-year lifetime. From economic perspective, combined charging dispatch strategy has proven to be the most cost-effective dispatch strategy for almost all cases. While from RES integration perspective, the best is load following strategy.

Simulations showed that diesel generator fuel restrictions may cause both, savings, and additional costs for the total system. Due to limited fuel consumption, fuel costs cannot be higher than certain level, thus may create savings. But due to the need for additional equipment capacity, overall system costs may also increase. As soon as fuel prices started to rise only by 0.2 EUR cents per litre, considerable drop in fuel consumption was observed (for the first alternative in average 120-300 litres per year).

Regarding capacity shortage aspect, results showed that as higher capacity shortage is allowed fewer initial investments might be required. Nevertheless, a more detailed analysis should be made to analyse whether capacity shortage may be allowed for such an electrified house. Especially considering Latvia's climatic conditions.

Overall results could be even more accurate if a site-specific resource data is obtained and used instead of HOMER Pro build-in databases. But on the other hand, for example, a proper measurement of wind speed is expensive and time consuming. Wind speed may vary greatly even over short distances.

Calculations performed by the authors in this paper evaluated benefits and drawbacks of HOMER Pro model for simulation of an off-grid systems and will be used as the reference. In the future research, the authors have a goal to develop their own multi-objective simulation tool to evaluate the performance of different off-grid cases under different scenario approaches, which would further increase flexibility of such simulations.

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Multiple scenario and criteria approach for optimal solution and sizing of household off-grid system

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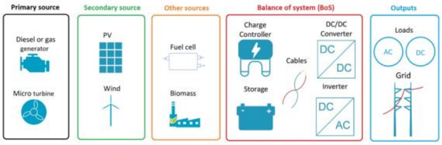
23.04.2021

Topicality

A microgrid benefits its customers and society in many ways:

- improves the environment and promotes clean energy;
- can lower energy costs for consumers and businesses;
- enhances resilience/recovery;
- improves electric reliability;
- supports cybersecurity;
- brings economic value to society;
- strengthens the central grid;
- improves community well-being.

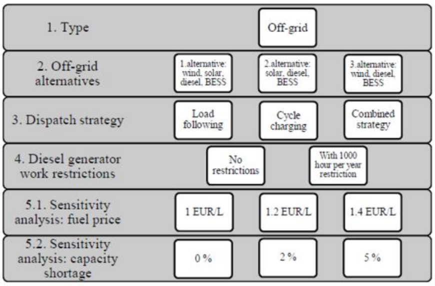


Major structural components of microgrid

Microgrids are electricity distribution systems containing loads and distributed energy resources that can be operated in a controlled, coordinated way either while connected to the main power network or while it is islanded. In this study, only off-grid systems were analyzed.

The purpose and methodology of the research

- To simulate the off-grid systems for modern household needs, which includes load of heat pump and charging of electric vehicle. Real household hourly load data are collected, integrated in the software, and used in simulations (annual consumption of 11 MWh).
- The location of the off-grid is in Latvia, near the capital city Riga. Default data of solar radiation, temperature, and wind resources for selected location was obtained.
- Three different off-grid technological alternatives, three dispatch strategies, restrictions on some component operation as well as sensitivity of fuel price and capacity shortage were considered to build up scenarios.
- Homer Pro software was used to simulate the off-grid systems using multiple criteria, such as minimisation of net present costs, increasing the fraction of renewable energy sources (RES), and reducing excess electricity.



1. Type
Off-grid

2. Off-grid alternatives
1.alternative: wind, solar, diesel, BESS
2.alternative: solar, diesel, BESS
3.alternative: wind, diesel, BESS

3. Dispatch strategy
Load following
Cycle charging
Combined strategy

4. Diesel generator work restrictions
No restrictions
With 1000 hour per year restriction

5.1. Sensitivity analysis: fuel price
1 EUR/L
1.2 EUR/L
1.4 EUR/L

5.2. Sensitivity analysis: capacity shortage
0 %
2 %
5 %

Fig. 2. Block scheme for the case study

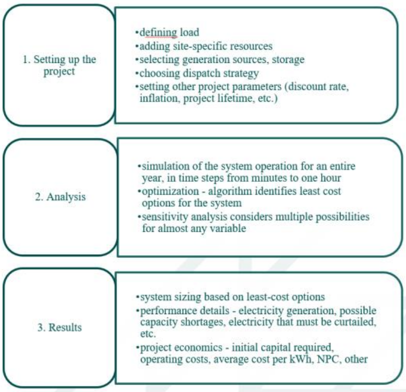
Homer PRO software

- Objective function of HOMER Pro is used for minimisation of the total Net Present Cost. To calculate NPCS the software use following equation:

$$C_{NPC} = \frac{C_{ann,\ tot}}{CRF_{(i,\ R_{proj})}}$$

$C_{ann,tot}$ - the total annualized cost (EUR/year);
i - the annual real interest rate;
R_{proj} - the project lifetime (years);
CRF(.) - the capital recovery factor.

- The software can satisfy specific constraints, like generator operation restrictions, capacity shortage level, fuel costs, etc. and at the same time determining an optimal sizing of system components and providing detailed information on system with a lowest total net present cost.
- Together 162 of the best simulations were analysed.



1. Setting up the project
- defining load
- adding site-specific resources
- selecting generation sources, storage
- choosing dispatch strategy
- setting other project parameters (discount rate, inflation, project lifetime, etc.)

2. Analysis
- simulation of the system operation for an entire year, in time steps from minutes to one hour
- optimization - algorithm identifies least cost options for the system
- sensitivity analysis considers multiple possibilities for almost any variable

3. Results
- system sizing based on least-cost options
- performance details - electricity generation, possible capacity shortages, electricity that must be curtailed, etc.
- project economics - initial capital required, operating costs, average cost per kWh, NPC, other

Fig. 1. Homer Pro process diagram

Simulation results (1) - dispatch strategies

Three different dispatch strategies:

1) load following (LF) - when a generator is needed, it produces only enough power to meet the demand. It tries not to charge battery with back-up diesel generator unless it reaches the minimum power of 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 back-up generator is required, it operates at full capacity, and surplus power charges the battery bank. It stops charging battery at the setpoint of 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 load following and cycle charging strategy. That way it can improve performance over the cycle charging and load following dispatch strategies by making more efficient use of back-up generator.

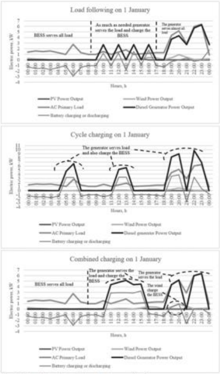


Fig. 3. Three dispatch strategies in action on 1st of January

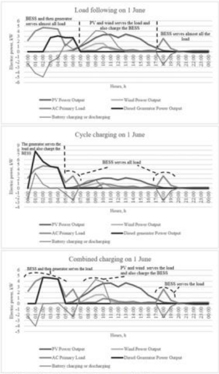


Fig. 4. Three dispatch strategies in action on 1st of June

Simulation results (2) - system equipment

Fig. 6. System equipment dimensions for the first alternative

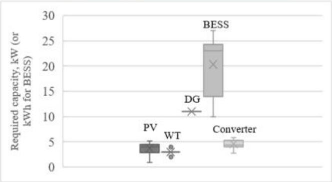


Fig. 7. System equipment dimensions for the second alternative

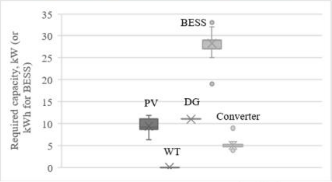
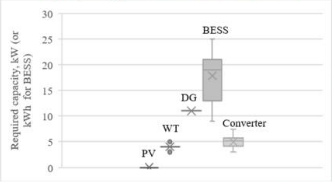


Fig. 8. System equipment dimensions for the third alternative



Simulation results (3) - NPC and RES fraction

Fig. 9. NPC results depending on different dispatch strategies

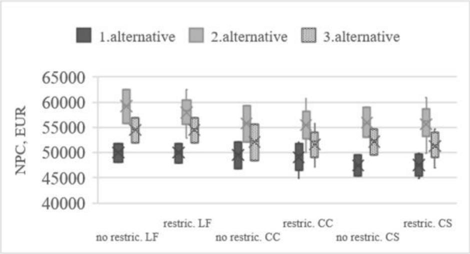
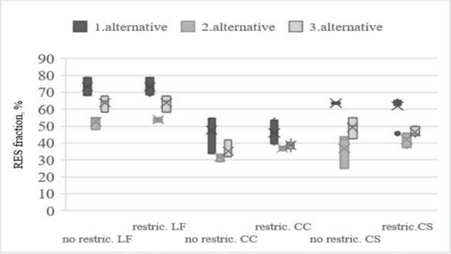


Fig. 5. The fraction of RES delivered to the load according to dispatch strategies



Simulation results (4) - sensitivities and excess electricity

Fig. 10. Generator fuel consumption depending on fuel price

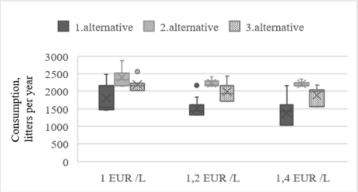


Fig. 11. Initial off-grid investment costs depending on capacity shortage

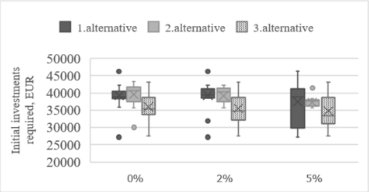
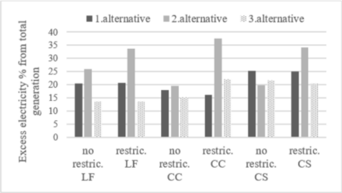


Fig. 12. Excess electricity in the all off-grid alternatives



Conclusions

- The NPC results for the first alternative has proven to be the most cost-effective almost in all scenarios.
- The first alternative proved the greatest possibilities to increase RES fraction across the dispatch strategies used in simulations.
- The results show how important it is to choose the right dispatch strategy. Firstly, it may largely impact required system equipment dimensions, especially for the BESS storage capacity. Secondly, chosen strategy impacts fuel consumption of back-up generator, RES fraction and at the end also the NPC over the project 10-year lifetime.
- From economic perspective, combined charging dispatch strategy has proven to be the most cost-effective dispatch strategy for almost all cases. While from RES integration perspective, the best is load following.
- Simulations showed that diesel generator fuel restrictions may cause both, savings, and additional costs for the total system. Due to limited fuel consumption, fuel costs cannot be higher than certain level, thus may create savings. But due to the need for additional equipment capacity, overall system costs may also increase.
- As soon as fuel prices started to rise only by 0.2 EUR cents per litre, considerable drop in fuel consumption was observed (for the first alternative in average 120-300 litres per year).
- Regarding capacity shortage aspect, results showed that as higher capacity shortage is allowed fewer initial investments might be required. Nevertheless, a more detailed analysis should be made to analyse whether capacity shortage may be allowed for such an electrified house.

The future research

- HOMER Pro software can only handle single-object optimization and thus the flexibility is limited;
- In the future research, the authors have a goal to develop their own multi-objective simulation tool to evaluate the performance of different off-grid cases under different scenario approaches, which would further increase flexibility of such simulations.

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Thank you!

Appendix II:

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MATHEMATICAL MODEL FOR HOUSEHOLD OFF-GRID SIMULATION (OFF-GRID SYSTEM SIZING)

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The paper presents the results of the research, which was initiated in our previous publication. The main goal of the research is to develop and validate our own multi-objective simulation tool for determination of optimal mix and sizing of off-grid and grid-connected microgrid systems. The first version of the developed model was tailored specifically for simulation of household off-grid system, which consisted of solar photovoltaics (PV), micro wind turbine, electric batteries, and backup power generator. Proposed algorithms are based on simulation of mentioned resources and hourly electric loads of off-grid system with the objective to reduce unsupplied energy volumes and total system costs. Several alternatives were considered with different configurations of the off-grid system and dispatching strategies of available resources. The developed model was validated with calculations of real off-grid system and results were compared to those, which were made in the previous publication, using Homer Pro software.

Keywords: *Annual costs of system, dispatch strategy, microgrid equipment sizing, off-grid system, RES fraction.*

1. INTRODUCTION

In recent years, microgrid systems either when operated in an off-grid or a grid-connected mode have been recognized as one of the most suitable, cost-effective, and sustainable solutions for commercial, industrial, and residential electrification applications [1], [2]. Decreasing costs of renewable energy technologies, fluctuating fossil fuel prices, environmental concerns and security of electricity supply are the main reasons for looking towards the development of emerging microgrid systems [3].

However, research on such systems still must be examined. For instance, microgrids have challenges regarding determination of proper equipment sizing, the voltage and frequency disturbance problems in unpredictable weather conditions, difficulties with monitoring and managing local power generation and loads, along with constrains related to designing protection devices to cope with bi-directional power flows and so on [1]. Within this paper, our focus is on autonomous household scale microgrid equipment sizing problems.

The microgrid equipment sizing is understood as quantification of the power capacities for renewable generators (solar, wind, etc.), as well as for backup power generator and determination of the power (kW) and energy (kWh) capacities of a battery energy storage system (BESS). The proper sizing of the microgrid may reduce the risk of oversize system equipment, which could lead to higher initial capital costs. On the other hand, it may reduce the risk of undersize equipment, which can lead to the poor power supply reliability [4]. Moreover, environmental and social aspects are no less important. Therefore, it is necessary to consider how to minimize emissions, how to promote socially acceptable system development, which includes issues with land use, visual impact, acoustic noise, etc.

According to literature review, several types of methods and different indicators might be considered in the evaluation process of such microgrid equipment. The sizing methods can be classified as classical methods, software tools, hybrid methods and most recently also artificial intelligence methods as shown in Table 1. In the most common cases, four types of indicators are identified which further describe the performance of microgrid: economic indicators (LCOE, LCC, ACS, NPV etc.), reliability indicators (LPSP, LOLP, EENS, etc.), environmental indicators (CE, LCA, EE), and social indicators (HDO, JC, SA, etc.) [5], [6].

In addition to the review mentioned above, some articles have summarised the latest trends of algorithm and indicators, and future overall challenges of microgrid sizing methodologies. For example, ant colony (ACO), firefly algorithm (FA), particle swarm optimization (PSO) and genetic algorithm (GA) and their performance were comprehensively analysed by [7] regarding how to select an appropriate algorithm to solve non-linear problems in the context of storage-based off-grid systems under different alternatives. The results reveal that FA performs better, with the least relative error. Other paper [2] evaluated sizing of an autonomous microgrid considering droop control. Results indicated that a competitive total cost could be obtained if the droop parameters were calculated considering the microgrid sizing results. Electric system cascade extended analysis was developed in [8]. In it, the LPSP, LCC and the LCOE together with tri-objective optimization functions were implemented and validated with system advisor model software. Authors of this paper argue that this analysis might help choose the suitable RES capacities for any site worldwide. In [9], a model for a remote community off-grid PV/diesel system using dynamic modelling and artificial neural network (ANN) techniques was developed. Within a comparative analysis, authors concluded that utilising dynamic and predictive modelling techniques would enable the model to be expandable, and simple to use while still maintaining its accuracy. Using an iterative approach based on a recursive algorithm, improvements were made to a techno-economic optimal sizing technique of a hybrid off-grid microgrid system in [6]. However, a new mutation adaptive differential evolution (MADE) based on a multi-objective optimization algorithm is presented in [10] to optimise the configuration of the off-grid stand-alone photovoltaic systems. It is also worth mentioning the authors of previous publication [4] which showed how important it was to choose the right dispatch strategy for off-grid system regarding equipment sizing, and at the end how it affected the net present costs (NPC) over the project lifetime.

Table 1. Microgrid Equipment Sizing Methods and Indicators [5], [6]

Type of sizing methods	**Type of indicators**
Classical: - probabilistic - analytical - numerical - iterative	**Economic:** -levelized cost of electricity (LCOE) -life cycle cost (LCC) -annualized cost of system (ACS) -total net present value (NPV)
Software tools: - Homer Pro - RETScreen, - PVSOL - Hybrid 2 - Transys	**Reliability**: - loss of power supply probability (LPSP) - loss of load probability (LOLP) - expected energy not supplied (EENS) - deficiency of power supply probability (DPSP) - loss of load expected (LOLE), - loss of energy expected (LOEE)
Hybrid methods: - combined dynamic programming and region-elimination technique algorithm (DP-RET) - hybrid Simulated Annealing–Tabu Search - hybrid Big Bang-Big Crunch algorithm (HBB -BC) - hybrid GA-mixed integer linear programming (GA-MILP)	Environmental: - carbon emission (CE) - embodied energy (EE) - carbon footprint of energy (CFOE) - life cycle assessment (LCA)
Artificial intelligence: - genetic algorithm (GA) - particle swarm optimization (PSO) - simulated annealing (SA) - ant colony optimization (ACO) - artificial bee colony (ABC)	**Social**: - human development index (HDI) - job creation (JC) - portfolio risk (PR) - social acceptance (SA) - social cost of carbon (SCC)

In general, according to the literature review, it can be noticed that there are still difficulties in the field of equipment capacity optimization:

1. improvements in load forecasting and adoption to methods are necessary;
2. calculation time step of power output is critical for the optimization of the results; thus, it should be reduced considerably as much as possible (less than 1 hour is preferable);
3. improved sizing methods equipment could be installed in the research area to obtain real-time data and verify simulation results;
4. new evaluation indicators may be used to provide more effective and overall assessment as the microgrids are emerging solutions for sustainability policy goals;
5. artificial intelligence sizing methods have advantages in accuracy and computation speed compared to traditional methods, while, on the other hand, those significantly increase optimization complexity;
6. as good practice equipment sizing is validated and improved also with more than one optimization tool.

It can also be concluded that existing

articles mainly focus on microgrid operation state; therefore, future research might have more efforts on the planning, construction state, and microgrid servicing.

The main aim of the present research 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 flexibility of already existing simulation tools. The developed tool is used to justify a composition and capacities of an off-grid system equipment for the real pilot project, which currently is under implementation. It is expected that this approach can be used and easily replicated for configurations that are more complex.

2. MODEL FOR THE HOUSEHOLD OFF-GRID SIMULATION

The simulation model described in the present research was developed for the real case evaluation. At that time, the information for the sizing of the system was rather insufficient. The model determined necessary generation and storage 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 or battery) and backup power generator. The model presented in this section is designed as a set of algorithms, which determine the operation of off-grid solution according to the load and supply power balances as indicated in Fig. 1 and Table 2.

Table 2. Parameter Abbreviations

Parameter	Abbr.	Parameter	Abbr.	Parameter	Abbr.
Electric load (kW)	P_l	Max amount of energy of the battery (kWh)	E_{bmax}	Power of PV modules (kW)	P_{gPV}
Generated power (kW)	P_g	Min amount of energy of the battery (kWh)	E_{bmin}	Power of wind generators (kW)	P_{gW}
Other generation capacities (kW)	P_n	State of charge of the battery (%)	SOC	Rated power of backup generator (kW)	P_r
Rated power of the battery (kW)	P_{br}	Max state of charge of the battery (%)	SOC_{max}	Minimal power of backup generator	P_{rmin}
Rated energy capacity of the battery (kWh)	E_{br}	Min state of charge of 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 backup generator are needed.

For simplicity, the time interval for modelling of off-grid system is assumed to be one hour; thus, the load and at the same time the required generation capacity are defined as Pl in the time interval t. Total power generated (kW) at the time interval i (excluding backup generator) $Pg(i)$ in Eq. (1) is defined as the sum of power capacity of solar modules, wind turbine and potentially other generation sources such as fuel cell, small-scale CHP unit, etc.

$$P_{g(t)} = P_{gPV(t)} + P_{gW(t)} + \ldots + P_{n(t)}. \tag{1}$$

As the off-grid system requires a battery energy storage system, it is necessary to determine its state of charge status at the time interval *t*:

$$\mathrm{SOC}_{(t)} = \mathrm{SOC}_{(t-1)} + \frac{E_{b(t)}}{E_{br}}, \tag{2}$$

where $\mathrm{SOC}_{(t-1)}$ is the state of charge of the BESS in the previous time interval, E_{br} is the rated energy capacity of the BESS, $E_{b(t)}$ is the amount of energy BESS charged or discharged in the time interval. In addition, the model calculates the maximum possible charge and discharge capacities (kW) of the BESS (4), which at the same time gives us the amount of energy per cycle. During the first cycle $\mathrm{SOC}_{(t)}$=SOC_{max}:

$$E_{bmax} = \left(SOC_{(t)} - SOC_{min}\right) \times E_{br}. \tag{3}$$

$$P_{bmax} = E_{bmax}, \text{ for time interval t = 1h.} \tag{4}$$

If there is a surplus or shortage of electricity (kW) at the time interval *t* in the off-grid system, Eq. (5) is used:

$$P_{(t)} = P_{g(t)} - P_{l(t)}. \tag{5}$$

In next equations (6 and 7), the model assesses whether to start-up the back-up generator and at what power:

$$\text{if } P_{bmax(t)} < P_{(t)}; \tag{6}$$

$$P_{r(t)} = P_{br} - P_{bmax(t)} - P_{(t)}. \tag{7}$$

If the BESS and other sources can cover the load, the backup generator will not be scheduled for operation. If not, the power output of the back-up generator during the time interval *t* is determined within the range P_{rmin}-P_r. The calculation is adjusted so that the back-up generator operates closer to the nominal (rated) output and charges the battery at maximum possible power during the time interval *t*.

The actual power rating (kW) of the BESS and its nature (charging / discharging) in the model is determined by Eq. (8):

$$P_{b(t)} = P_{(t)} + P_{r(t)}. \tag{8}$$

The actual charged or discharged energy rating (kWh) of the BESS E_b(i) at the time interval is determined by Eqs. 9–11:

$$if\, P_{b(t)} > 0, then\ k_{b(t)} = 0.9; \tag{9}$$

$$if\, P_{b(t)} < 0, then\ k_{b(t)} = 1/0.9; \tag{10}$$

$$E_{b(t)} = P_{b(t)} \times k_{b(t)} \times 1h, \tag{11}$$

where k_b is the efficiency of the BESS. The simulation cycle ends with Eq. 11) to initialize calculations for the next time interval *t*:

$$t = t + 1. \tag{12}$$

Fig. 1 shows a block scheme within the sequence of operations of the described off-grid system.

The annual costs and levelized cost of energy (LCOE) of the off-grid system are determined in a separate algorithm. Before using the algorithm, configuration of the model is necessary to set up the required dispatching strategy and input data.

The overall model optimization focuses on four aspects: off-grid system highest availability, lowest surplus generation, lowest operation hours of the backup generator, lowest LCOE.

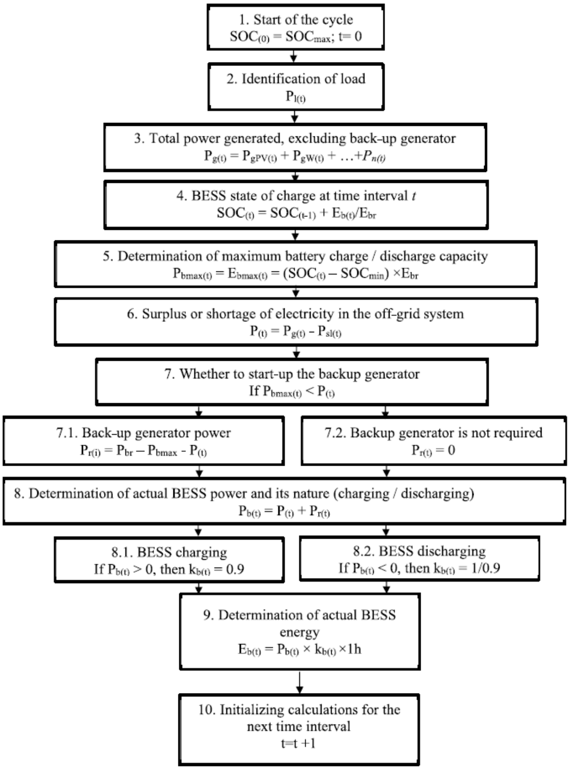


Fig. 1. Operational principles of the model of off-grid system.

3. ANNUAL COSTS OF OFF-GRID SYSTEM

The objective function in the calculations is minimization of the levelized cost of electricity (LCOE), which in this case is determined based on the method of the annual cost of system (ACS) [11].

ACS covers annual capital cost (ACC), annual operation and maintenance costs (AOM), annual replacement costs (ARC), annual fuel costs of backup generator (AFC) and annual emission cost (AEC). ACS (in EUR) is estimated as follows:

$$\mathrm{ACS} = \mathrm{ACC} + \mathrm{AOM} + \mathrm{ARC} + \mathrm{AFC} + \mathrm{AEC}. \qquad (13)$$

Annual capital cost (in EUR) of each unit which does not need replacement during project lifetime, such as PV system, wind turbine, back-up generator and inverter, is calculated as follows:

$$ACC = C_{cap} \cdot CRF(i, y), \tag{14}$$

in which

$$CRF = \frac{i \cdot (1+i)^y}{(1+i)^y - 1}, \tag{15}$$

where C_{cap} is the capital cost of each component in EUR, but y is the project lifetime in years. *CRF* is capital recovery factor, a ratio to calculate the present value of a series of equal annual cash flows, and i is the annual real interest rate.

The annual operation and maintenance cost as a function of capital cost, reliability of components (λ) and their lifetime (y) can be determined using the following equation:

$$AOM = C_{cap} \cdot \frac{1-\lambda}{y}. \tag{16}$$

ARC is the annual cost value (in EUR) for replacing units during the project lifetime. In this study, a unit that needs replacement is only battery banks. Other units do not require replacement because their lifetime is the same as project lifetime. Economically, annual replacement cost is calculated as follows:

$$ARC = C_{rep} \cdot SFF(i, y_{rep}), \tag{17}$$

where C_{rep} is the replacement cost of battery banks in EUR, but is the lifetime of battery banks in years. In this case, the replacement cost of battery banks is like its capital cost. *SFF* is the sinking fund factor, a ratio to calculate the future value of a series of equal annual cash flows. This factor is calculated as follows:

$$SFF = \frac{i}{(1+i)^y - 1}. \tag{18}$$

AFC of backup generator unit is estimated based on optimum dispatch of backup generator system. The fuel consumption (in liters) based on load characteristic of the back-up diesel generator is calculated for each time interval t using the following equation:

$$F(t) = 0.246 \cdot P_r(t) + 0.08415 \cdot P_r, \tag{19}$$

where is the rated power of backup generator in kW, $P_r(t)$ is the actual power generated at time interval t in kWh. The fuel cost (in EUR) is calculated for a year by multiplying hourly fuel consumption by fuel costs:

$$AFC = C_f \cdot \sum_{t=1}^{8760} F(t), \tag{20}$$

where C_f is the fuel cost per litre (EUR/l). To reach the maximum efficiency of operation the unit should be operated within rated power and specified maximum value.

AEC is the annual emission cost (in EUR) to capture CO_2 emission generated from backup generator system. The AEC can be expressed as follows:

$$AEC = \sum_{t=1}^{8760} E_f \cdot E_{cf} \cdot P_r(t)/1000, \tag{21}$$

where E_f is the CO_2 emission factor, kg/kWh, E_{cf} is the CO_2 emission cost in EUR/t.

By calculating the ACS it is possible to determine levelized cost of electricity (LCOE), which shows how much each kWh of electricity costs in the particular microgrid (EUR/kWh).

$$LCOE = \frac{ACS}{E_{AEC}}, \tag{22}$$

where is the annual energy consumption of a microgrid (kWh). Other parameters used in the calculations are shown in Table 3.

Table 3. The Economic Data Considered for Calculations

Parameter	Data	Parameter	Data	Parameter	Data
Project lifetime (years)	20	Reliability of PV panel (coef.)	0.98	Cost of Wind turbine (EUR/kW)	3500
Real interest rate (%)	4	Reliability of wind turbine (coef.)	0.8	Cost of battery bank (EUR/kWh)	540
PV panel lifetime (years)	25	Reliability of inverter (coef.)	0.98	Cost of battery bank (EUR/kW)	540
Wind turbine lifetime (years)	20	Reliability of battery (coef.)	0.98	Cost of inverter (EURkW)	1300
Inverter lifetime (years)	20	Reliability of backup generator (coef.)	0.9	Fuel cost (Cf) (EUR/l)	1.2
Battery lifetime (years)	10	Cost of backup generator (EUR/kW)	380	Emission factor (kg/kWh)	0.34
Backup generator lifetime (hours)	15 000	Cost of PV panel (EUR/kW)	1250	Emission cost (EUR/t)	30

The parameters shown in Table 3 can be changed as needed for other microgrids.

4. CASE STUDY

For the case study, real household hourly load data are collected, integrated in the model, and used in simulations. Household 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 transports needs can be considered the biggest consumers of electricity in this household. This type of household matches with aims for electrification, which has a critical role to play for achieving the European Union decarbonization policy targets.

Fig. 2 shows the typical daily load curve (for 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 the 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 were not an issue and always corresponded with the demand. Nonetheless, the connection allows the household not to consider load shifting.

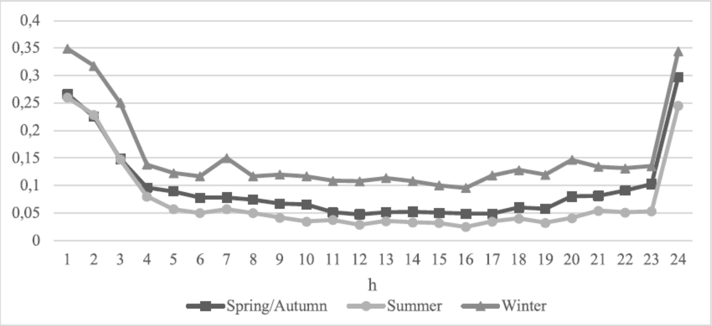


Fig. 2. Daily load curve in relative values for three seasons.

As shown in Table 4, five equipment sizing alternatives were evaluated. First three sizing alternatives are taken from the previous research on microgrid sizing with Homer software. The capacity of the back-up generator is at least 11 kW considering that system must cover the maximum daily load (which is around 9 kW), thus ensuring higher security of supply [4]. Two additional sizing options were developed to find the most sustainable and economically efficient solution.

Table 4. Average Equipment Size for All Alternatives

System equipment	1st alternative	2nd alternative	3rd alternative	4th alternative	5th 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 study, the results are displayed for the following alternatives: three dispatch strategies, different sizing options, power sources PV, wind, BESS, backup generator, the dispatch strategy is combined, and there is no capacity shortage.

5. RESULTS

Table 5 shows the results for all five equipment sizing alternatives considering three different dispatch strategies.

Table 5. 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, using a simulation tool it is possible to configure dispatch strategies to determine operating principles of how generation can provide the load.

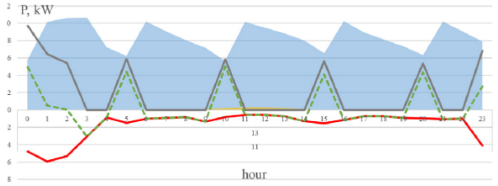
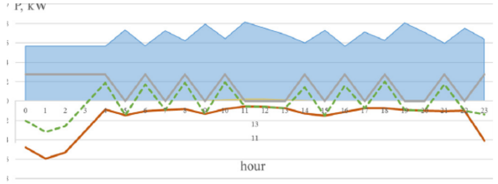
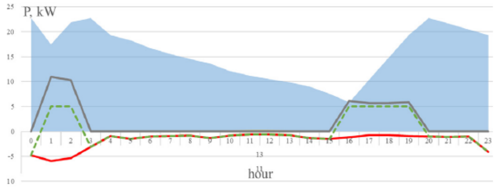
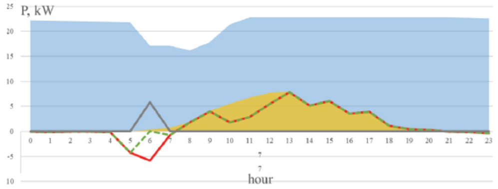
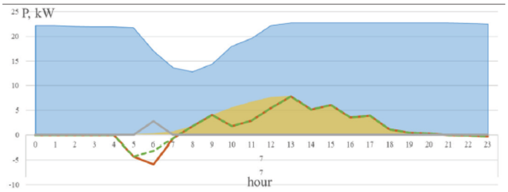
1) Combined charging dispatch strategy (CCDS) – intelligently switches between load following and cycle charging strategy. That way it can improve performance over the cycle charging and load following dispatch strategies by making more efficient use of back-up generator.

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

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 battery at the setpoint of battery state of charge. Cycle charging tends to be more optimal in off-grid systems with little or no renewable power.

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 day for two equipment sizing alternatives and three dispatch strategies is provided in Table 6 and 7. The graphs show the power source and amount of generation, energy storage capacity, load and its nature, battery power and its nature, backup generators power. The dates were chosen to represent the extreme situations where there was surplus or deficiency of renewable generation. During the observation period, there was low wind output on 7th July and low PV output on 13th November. By comparing the 2nd and the 5th alternatives, it is clearly visible that the microgrid benefits of diversified generation sources allow minimising the backup generators workload and maximising the share of renewables. Dispatch strategies pose the most impact on LCOE.

Table 6. Visualization of Off-Grid Operation for the 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	

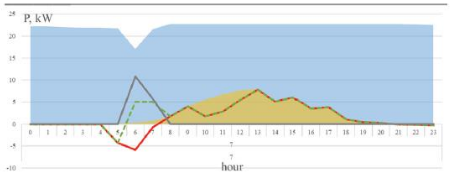
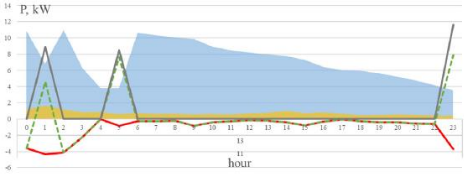
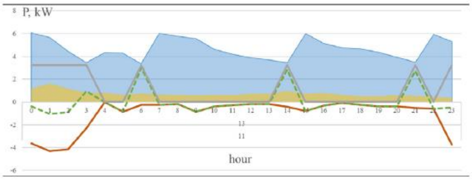
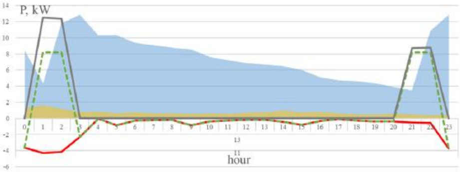
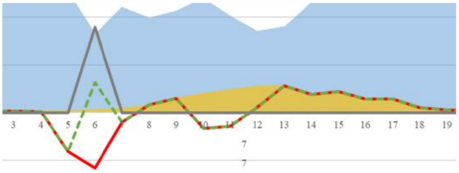
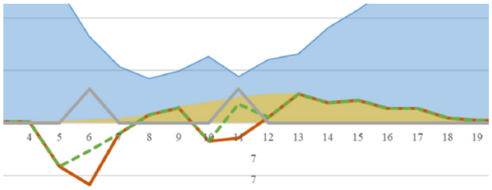
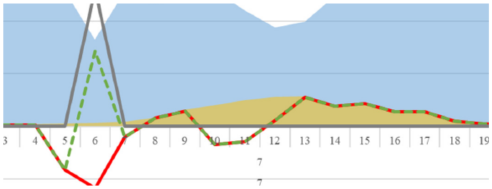
Cycle charging CCS	
LEGEND	🟨 Pg(i) 🟦 SOC(i) ― ∑P(i) - - - Pb(i) ― Pr(i)

Table 7. Visualization of Off-Grid Operation for the 5th Alternative and Dispatch Strategies

5th alternative: BESS power 8.2kW, capacity 16kWh, solar power 3 kW, wind power 2kW, diesel gen. 13 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	 Pg(i) SOC(i) ∑P(i) Pb(i) Pl

In addition to the analysis before, in the next three figures comparison of results between the new simulation tool and Homer Pro software is made.

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. 3, in all alternatives and dispatching strategies, the new tool displays more backup generator hours than Homer Pro software. The largest difference is observed at load following strategy (LFS). Nevertheless, both tools show that the generator hours will be the smallest for the 1st alternative at combined charging dispatch strategy (CCDS).

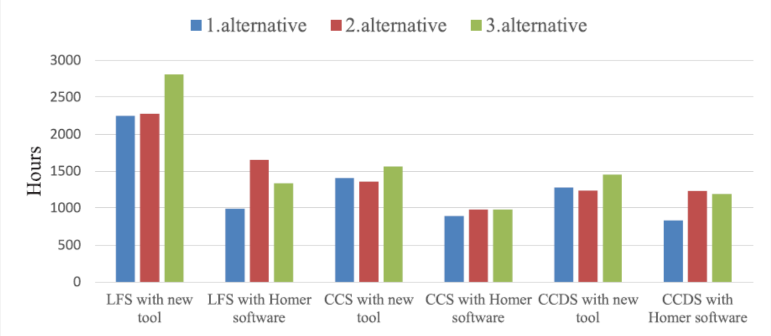


Fig. 3. Backup generator operating hours.

Secondly, “excess electricity” is analysed. Excess electricity occurs when surplus power in off-grid is produced (either by the back-up generator or by a renewable sources) and the battery or load is unable to take all electricity. Excess electricity as the percentage (%) of the total generation of three off-grid alternatives and three different dispatch strategies is shown in Fig. 4.

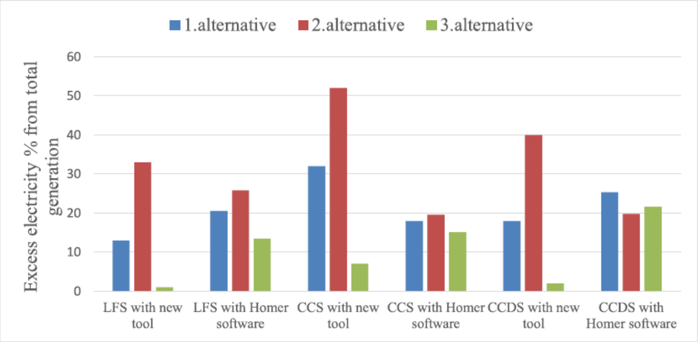


Fig. 4. Excess electricity in the all off-grid alternatives.

In 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 (%) differs 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. 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. We did not cover the LCOE in our previous publication, but we use the gained results this time.

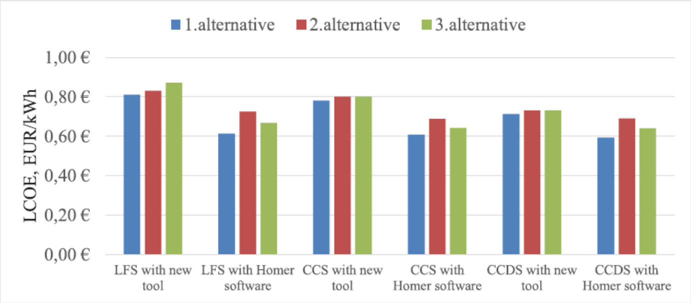


Fig. 5. Levelized cost of electricity for all off-grid alternatives.

As shown in Fig. 5, for the new tool average costs are between 0.72 EUR/kWh and 0.84 EUR/kWh, while in 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 difference in models themselves. In general, both simulation tools show similar trends, which confirms and validates their accuracy.

6. DISCUSION AND CONCLUSION

The case study and comparison of results to the authors' previous publication have shown that new multi-objective simulation tool can be used as an assessment tool for microgrid equipment sizing determination. It allows analysing potential generation by source, BESS charging / discharging versus the required load, calculating annual system costs and other parameters. It gives all the necessary key values to evaluate the possibility to create a microgrid solution.

By comparing simulation results of the new multi-objective simulation tool (considered in this publication) and Homer software (from the previous publication), it can be concluded that both tools show similar trends with regard to three parameters: backup generator operating hours, excess electricity and LCOE. The differences in results might be caused by additional emission cost (30 EUR/t), and only one capacity shortage level – 0 %, which was not the case in the previous publication using Homer Pro software. Another reason for the differences may be related to approaches/algorithms themselves which differ in both tools.

Furthermore, if we compare the two additional alternatives (4th and 5th), we see that the most sustainable and economically efficient solution would be using the combined charging dispatch strategy. However, there is no solution which would correspond to "the greenest and optimal solution". On the one hand, the 4th alternative is with fewer backup generator operating hours – 778; on the other hand, the 5th alternative has an LCOE of less than 0.09 EUR/kWh comparing with the 4th alternative. Thus, the end user must decide on dilemma whether to use a "sustainable" or "economically efficient" solution.

In this publication, the results again show that the dispatch strategy has great impact on the microgrid costs. Nevertheless, like Homer Pro software, the case study revealed that the combined charging dispatch strategy (CCDS) with both solar and wind sources is the most suitable one of all the alternatives.

Practically, both tools have their advantages and disadvantages. The Homer Pro allows highly automatizing the sizing offering, thus providing a quick multi scenario approach. While our own developed simulation model gives advantage to tweak the equipment sizing for very specific cases and can be further implemented on multiple software tools taking into account users' preferences. It can be used to validate results from other software tools as well.

The battery rated power should be at least as large as the sum of non-dispatchable generation. In case there is no load and there is full generation power, it is highly significant to store every generated kWh. At the same time, it should be greater than backup generator minimal power – in case of small load and empty battery, the generator will not be used sufficiently. As there is load from electrical vehicle in consumption the amount of energy the BESS should hold should be close to the battery capacity of the electric vehicle; otherwise, electric vehicle might be charged with diesel generator if no renewables are present.

For the further research it would be useful to compare the model against real case off-grid microgrid solution.

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

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

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

1. INTRODUCTION

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

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

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

1. useful development of project is possible in places where there are relatively high investments needed for the grid connection to the distribution networks [4];
2. due to reduced costs of new renewable energy technologies and fluctuating fossil fuel prices, a simplified off-grid system for household electricity supply in remote regions may be an efficient and cost-effective electrification way to the fight against climate change and to reach the European Union (EU) decarbonization targets [5]–[7];
3. to protect against electricity supply quality problems and overall reliability due to increased variable generation or decreasing conventional generation in the grid [8].

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

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

Initially, a special mathematical model was created to select energy sources, to size equipment and to further test the operation of this off-grid system in the Latvian climatic conditions. Thus, in this article not only we focus on evaluation of this real autonomous off-grid system performance, but also discuss aspects related to software computing techniques and mathematical models versus a real operational off-grid system.

As it is stated in [9], to ensure optimal design and that such renewable systems are affordable, careful planning preferably with high-resolution data on electricity generation and consumption is necessary. As it is one of research gaps identified in literature, and not delivered in a clear way, the objective of the article is to further increase knowledge of such system performance, planning and dimensioning in climatic conditions like it is in Latvia. It is expected to validate approaches which could be used in future and easily replicated for configurations that are more complex.

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

2. MATERIALS AND METHODS

2.1. Setup of Off-grid System

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

1. micro wind turbines and solar panels;
2. diesel generator;
3. battery electric storage system;
4. all of it is set up in or around a standard sea container (3.0 x 2.5 m, 2.5 m high) with other necessary equipment (sensors, cables, etc.) for the operation of the off-grid system.

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

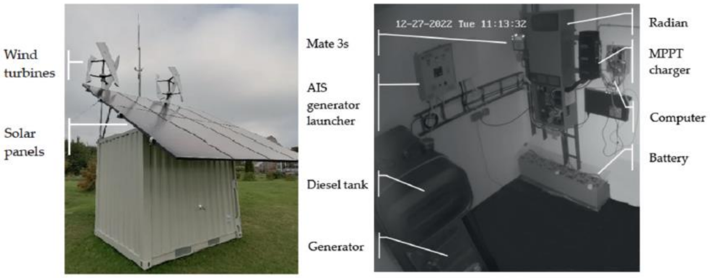


Fig. 1. Experimental autonomous off-grid system.

The basis of the off-grid system is a set of equipment manufactured by OutBack Power for microgrid implementation. System includes Radian GS7048E inverter/charger, system control equipment, panel MATE3, battery monitoring equipment FlexNetDC and solar panel (3.6 kW) charging controller FlexMax80. Separate charge controllers are used to transfer the electricity produced by micro wind turbines (2 x 1.1 kW) to the off-grid network, which are connected with the help of power relays depending on the battery charge level. In case of unavailability of renewable resources, a backup diesel generator is provided with automatic start-up according to the battery charge level. A LiFePO4 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 container, which hosts batteries, invertors and other electronic devices sensible to temperature, was insulated and equipped with devices for maintaining necessary microclimate: heater, conditioner and ventilation. The conceptual diagram of the off-grid system is given in Fig. 2.

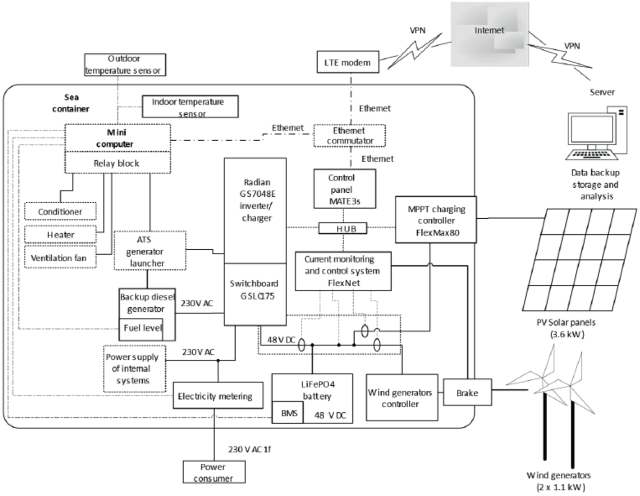


Fig. 2. Conceptual diagram of the installed off-grid system.

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

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. Household load data were collected using a power network analyser, and 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. The equipment survey results are summarised in Table 1.

Table 1. The Current and Planned Electricity Equipment in Household

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

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

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

2.2. Setup of the Off-grid System

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

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

The principle of power flow control in the off-grid system is based on voltage levels of the battery. Battery is charged from three sources using a two-phase charging method. During the first stage, constant current bulk charge is up to 0.5 C-rate or limited by resource availability, terminated at 58.4 V; and constant voltage absorption charge is terminated at return amps 0.03 C-rate. PV charger and AC charger using diesel generator are managed by a central system controller and obey rules descripted before. Wind turbine controller is a discrete device and, therefore, needs to be connected to DC bus if necessary, using power relay. If the voltage of the battery reduces below 52.0 V and solar energy is available, bulk constant current charging is started. In case solar energy is not available and voltage drops down to 57.6 V, wind turbines start to generate by connecting wind chargers to DC bus. If both wind and solar sources are insufficient or unavailable and voltage is below 52.8 V, a diesel generator shall take over the control and charge battery in that way avoiding power supply interruption. The operation of the diesel generator is set at 50 V.

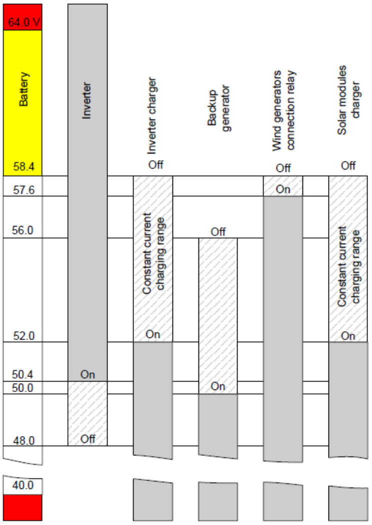


Fig. 3. Principle of power flow control based on a battery voltage level, source and power converter operating voltage ranges: red – voltage when battery damage occurs; yellow – charged battery voltage; grey – the device is working; dashed grey – switch-on or special charging mode.

When multiple sources are running simultaneously, priority is given to the source with the highest resource availability, i.e., for a charge controller that has a higher voltage and a proportionally larger amount of energy available from the renewable source. For example, if it is sunny with moderate wind, then due to higher installed capacity of the solar panels, charging will take place from them, the wind charge controllers will give a minimum current. In darker and windier weather, the situation will be the opposite. If the backup diesel generator is running, it will be able to charge battery at all times.

2.3. Data Collection

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

1. OutBack power MATE3 control panel – collects data from devices connected to OutBack Hub - FlexMax80, FlexNetDC and Radian GS7048E. Connected to a minicomputer via an Ethernet network.
2. The battery management system (BMS) has its own output data flow through the serial port to the minicomputer.
3. Power network analyser EM21 – Modbus RTU device connected to a minicomputer via RS485 network.
4. Minicomputer – collects information from connected sensors and analogue and digital inputs and outputs.

2.4. Data Analysis Method

Data analysis is made by using Python language in Jupyter notebook, which is a web-based interactive computing platform. The graph codes were written in Python using libraries like pandas, numpy, matplotlib, seaborn. A 31-day dataset from an off-grid system was collected between 18 October and 21 November 2022, with a minute-by-minute sampling frequency. The analysed dataset includes 37 input signals and high granularity data with a total of 48,301 data points.

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

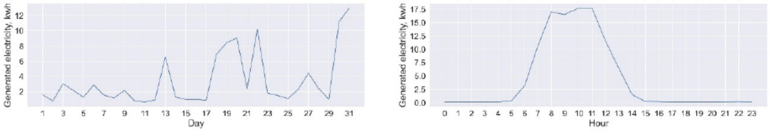
Various statistical methods are used in the present research – time series analysis, cumulative columns, and histograms.

3. RESULTS

The data analysis of the off-grid system was performed according to the previous sections. The off-grid system operating data are important and necessary to detect failures or faults of the system, especially in the initial stage of such off-grid system implementation. The results provide an insight for further studies and an indication of the importance of data availability and resolution.

3.1. Data Analysis Method

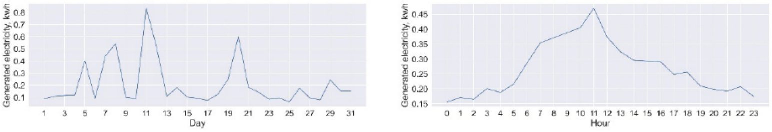
Figures 4–6 present daily and hourly production data curves of the off-grid system electricity between October 2022 and November 2022. The cumulative generation of electricity from solar, wind and diesel generator is covered.



(a) (b)

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

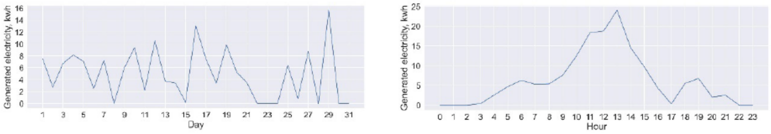
Figure 4 shows that solar power is generated on a relatively large scale and with a distinct tendency to take place from 6 a.m. to 3 p.m. Solar kilowatt hours (kWh) are calculated using data obtained from FlexnetDC.



(a) **(b)**

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

Figure 5 shows that wind power is generated on a relatively small scale and with no distinct tendency during the days. Also, wind kilowatt hours (kWh) are calculated using data obtained from FlexnetDC.

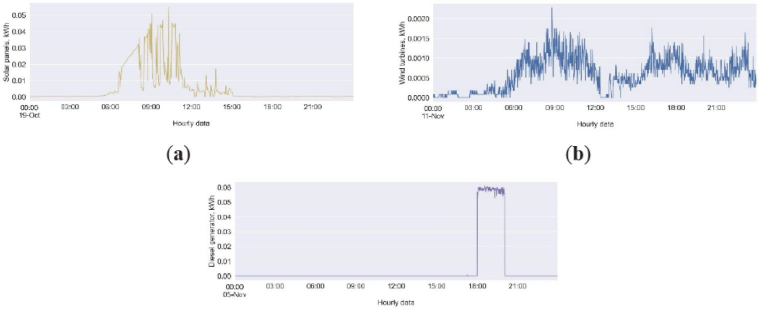


(a) **(b)**

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

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

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



(a) **(b)**

(c)

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

The data were taken on 19 October 19, 5 and 11 November. Thanks to the high granularity of the data, trend of each generation source can be seen in Fig. 7. It can be seen that renewable sources in these days show a lot of variability, while the diesel generator has been working for a specific period with a certain capacity.

3.2. Amount of Generated Electricity by Source Type

During 31 days of observation (see Fig. 8), most electricity was generated by the diesel generator (152 kWh), followed by solar (104 kWh) and wind generation (7 kWh). Later on, it was discovered that low output of wind generation was associated not only with insignificant wind velocity during the investigation period, but also due to inadequate operation of wind charger control logics. This is the challenge to be addressed during the course of experimental activity.

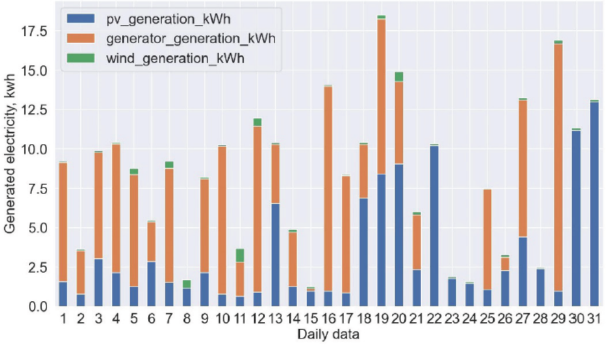


Fig. 8. Cumulative electricity generation by source type.

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

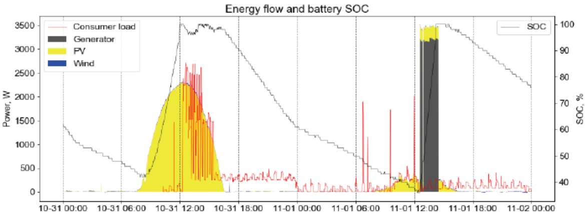


Fig. 9. Off-grid system characteristics during a sunny day at the end of October.

For example, Fig. 9 shows two sunny days at the end of October and at the beginning of November. During this time, the demand consumption was not logged in the beginning, indicating that the acquisition of data should be checked to ensure data continuity.

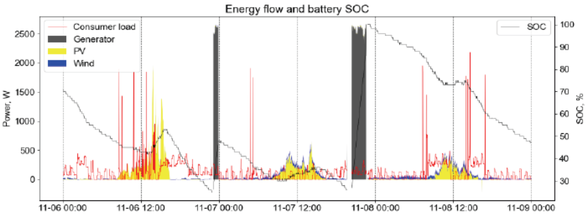
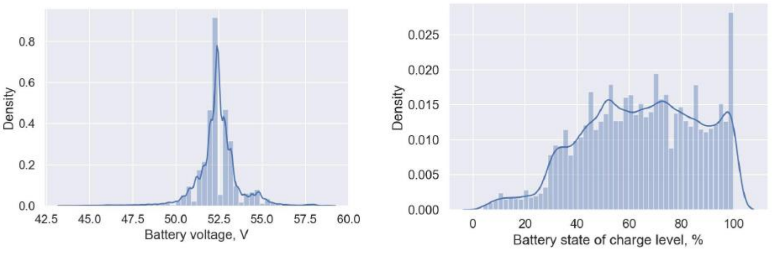


Fig. 10. Off-grid system characteristics during a sunny day at the beginning of November.

In Fig. 9 and Fig. 10, one can see the total contribution from each source. If the load capacity is greater than the total source contribution, the state of charge (SOC) of the battery falls, if less – battery charging occurs. When the generator is on, the SOC level climbs rapidly.

3.3. Electrotechnical Data: Voltage, SOC, Frequency

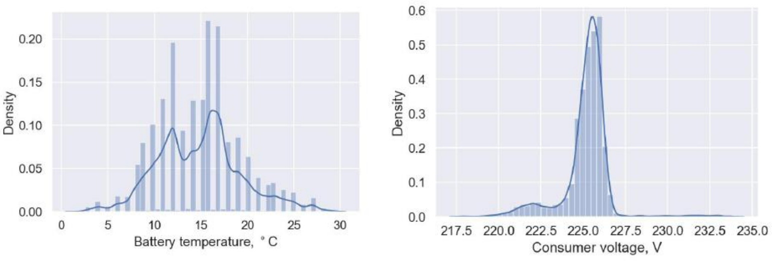
It was also important to observe electrotechnical data in the experiment. Figures 11 and 12 show the four histograms. A histogram divides the variable into bins, counts the data points in each bin, and shows the bins on the x-axis and the counts on the y-axis. In our case, we used Python library seaborn, which turns the y-axis as a density plot, which is the probability density function for the kernel density estimation. 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. 11. Electrotechnical data analyses: (a) for battery voltage; (b) battery SOC level.

According to the electrotechnical data shown in Fig. 11, it can be noticed whether the battery has any overvoltage or the battery is operated in the most efficient way to reduce the risks of degradation.



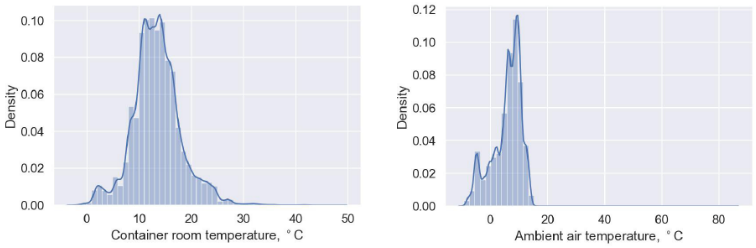
(a) (b)

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

It is important to monitor what happens to the battery temperature and whether the electricity consumer is provided with the appropriate voltage quality of electricity supply (see Fig. 12). Battery voltage data were obtained from inverter RadianGS, SOC and battery temperature data from system monitoring – FlexnetDC device, while consumer voltage from power network analyser – Carlo Gavazzi EM21.

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

During observations, the internal temperature of the off-grid container and the outside air temperature are monitored. Sensor DS1280 is used to determine both parameters. Results are shown in Fig. 13.

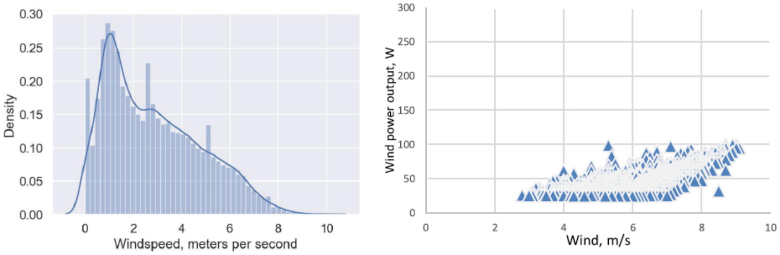


(a) **(b)**

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

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

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



(a) **(b)**

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

All the previous weather conditions were measured every minute at the site. Wind speed data were obtained from the anemometer above the sea container.

4. MODELLING TOOLS VERSUS REALITY

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

1. to obtain life data it would be required to test experimental off-grid system for at least 1-year period;
2. the off-grid system operation should be tested using more than one dispatch strategy (longer analysis than a 1-year period would be needed);
3. to obtain data to be later used in computer tools and mathematical models more measuring devices as planned before would be required, for example, regarding solar radiation;
4. as the off-grid project is still implemented, its true costs can only be clarified after a longer time period than now.

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

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

5. DISCUSSION AND CONCLUSIONS

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

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

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

tain level. Also, in order not to degrade the battery, it should not be completely discharged;
3. the high granularity operating data (in minutes resolution) from the off-grid system are essential for troubleshooting and assessing the performance of such a system;
4. Such an analysis showed that it was important to gather data on off-grid performance in a timely manner in order to later analyse the results obtained from the operating system.

High-quality power supply off-grid and microgrid systems will have to solve the same main tasks that are solved by large energy systems. The project developers must always have a complete understanding of the probable consumers' load values and appropriate combination of the energy generating sources. It is necessary to ensure protection of systems from accidents, short circuits, overvoltage and other factors of environmental impact on energy equipment, as well as that batteries and electronic devices operate at their appropriate preferable temperature (microclimate). The safe and efficient operation of the system must be ensured both when connected to the public power grid if there is such a connection and when it operates autonomously. The integration of different power conversion equipment, often supplied by different standards and different times, must be achieved, ensuring a continuous power supply of electric system for all time equipment that operates in all provided regimes.

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

ACKNOWLEDGEMENTS

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Appendix IV

JURISTA VĀRDS

16. AUGUSTS 2022 /NR. 33 (1247) SKAIDROJUMI. VIEDOKĻI

Jauni elektroenerģijas tirgus dalībnieki un tehnoloģijas – regulatīvie izaicinājumi

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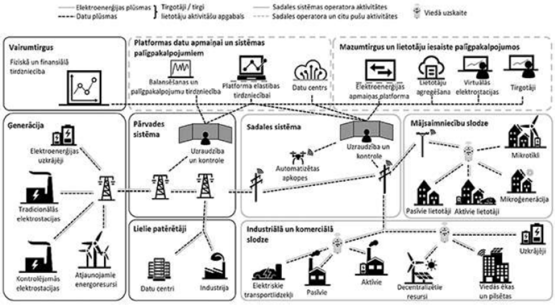
Eiropas Savienības (ES) mērķi un virzība klimatneitralitātes jomā rada iespējas plašākai izkliedētās ģenerācijas izmantošanai un jaunu tirgus dalībnieku iesaistei elektroenerģijas tirgū. Piemēram, jau šobrīd elektrotīklu sistēmas operatori veido savu darbības struktūru (skat. 1. attēlu [1]), iekļaujot un ņemot vērā tādas iesaistītās puses kā pasīvos un aktīvos lietotājus, energokopienas, mikrotīklus, agregatorus, virtuālās elektrostacijas, platformas balansēšanas enerģijas un citu elastības produktu palīgpakalpojumus, elektroenerģijas uzkrājējus u.c. iesaistītās puses, modelējot ne tikai enerģijas, bet arī datu plūsmas starp šīm pusēm, uzsverot jauno tehnoloģiju (*IoT*, *self-healing* u.c.) nozīmi.



1. attēls. Lietuvas sadales tīkla operatora (ESO) veidotā elektroenerģijas sistēmas struktūra 2030. gadā

Tādējādi pareiza sistēmu integrācija un normatīvo aktu ietvars būs svarīgs, lai vienkāršotu un vienlaikus lietderīgi izmantotu visus resursus un pieejamās tehnoloģijas, kā arī nodrošinātu augstāku sistēmas uzticamību un stabilitāti. Šajā rakstā analizēsim jaunos tirgus dalībniekus, apskatot tendences regulatīvajā vidē turpmākajos gados. Starp tiem:

- decentralizētie energoapgādes resursi;
- jauni tirgus dalībnieki kā energokopienas, aktīvais lietotājs u.c., kā arī elektroenerģijas kopīgošana, kas tiek ieviesta ar grozījumiem Enerģētikas un Elektroenerģijas tirgus likumā.

Decentralizēti energoapgādes resursi Latvijā

Par decentralizētiem energoresursiem (DER – *distributed energy resources*) parasti tiek uzskatītas mazas jaudas elektroapgādes tehnoloģijas, kas ražo, uzkrāj un pārvalda elektroenerģiju. Piemēram, saules moduļi, mazas vēja turbīnas, elektriskie transportlīdzekļi, mikrotīkli u.c.

Zinātniskā literatūrā diskutē, ka plašāka DER izmantošana varētu uzlabot sabiedrībai pieejamo resursu izmantošanas efektivitāti, palielinātu energosistēmas noturību (piemēram, lielu staciju izslēgšanas no tirgus gadījumā) un sniegtu patērētājiem un kopienām lielāku lomu dekarbonizācijas mērķu sasniegšanā. Tas atbilstu arī Eiropas zaļajam kursam un plāniem par drošu, pieejamu un tīru enerģijas plašāku izmantošanu. Tomēr DER pieaugums vienlaikus izjauks tradicionālos elektroenerģijas tirgus darbības principus, un bez pienācīga regulējuma to priekšrocības var nebūt vienādi jūtamas visā sabiedrībā. [2]

Lai gan nav noteikta decentralizētu energoresursu definīcija, Latvijā par mazas jaudas elektroapgādes tehnoloģijām var uzskatīt mikroģeneratorus, kas paredzēti maiņstrāvas elektroenerģijas ražošanai ar vienas vai trīs fāžu spriegumu un darba strāvu līdz 16 ampēriem. Vienas fāzes elektrotīklā tas atbilst 3,7 kW jaudai, bet trīs fāžu elektrotīklā – 11,1 kW jaudai (A tipa ražošanas moduļi). [3] Un arī elektrostacijas līdz 14,999 MW (kas iekļauj A, B un C tipa ražošanas moduļus), ko pieslēdz pie sadales operatora tīkliem – 0,4, 6, 10 un 20 kV spriegumā. [4]

Dažas industriju izpētes liecina, ka DER izmantošana Eiropā (tātad arī Latvijā) nākotnē varētu pat pārsniegt centralizēto ģenerācijas avotu proporciju. Piemēram, kā šajā izpētē, [5] kad pie DER iekļauj saules moduļus (<1 MW), vēja turbīnas (<500 kW), mikroturbīnas, ūdeņraža degvielas šūnas, dīzeļa ģeneratorus un gāzes katlus (<6 MW), elektroenerģijas uzkrājējus, mikrotīklus, elektroauto un pieprasījuma reakcijas izmantošanu.

Jāatzīst, ka īpaši lielu mikroģenerācijas attīstību Latvijā var novērot 2022. gada pirmajos četros mēnešos, ko noteica būtiski augstāka elektroenerģijas cena "Nord Pool" biržā, globālās ekonomikas atgūšanās no Covid-19 izraisītās ekonomikas lejupslīdes 2020. gadā dēļ. Tāpat ietekmi uz cenu rada ģeopolitiskā situācija – līdz ar Krievijas uzsākto karu Ukrainā būtiska neskaidrība valda pār turpmākām energoresursu piegādēm, meklējot alternatīvus piegāžu avotus. Mikroģeneratoru pieauguma straujā maiņa pārspējusi drosmīgākās prognozes – no janvāra līdz aprīlim ieskaitot, sadales elektrotīklam pieslēgti 970 mikroģeneratori ar kopējo jaudu 7,5 megavati (MW). Aprīļa beigās AS "Sadales tīkls" operatora tīklā pieslēgto mikroģeneratoru skaits sasniedza 3052 pieslēgumus ar kopējo uzstādīto jaudu 21,3 MW.

Ņemot vērā pašreizējās mikroģenerācijas attīstības tendences, AS "Sadales tīkls" eksperti prognozē, ka sadales elektrotīklam jaunpieslēgto mikroģeneratoru skaits 2022. gadā sasniegs 4000, taču visu sistēmai pieslēgto mikroģeneratoru kopsummai gada noslēgumā pārsniedzot 6000, bet kopējai jaudai – 45 MW. [6] Latvijā novērojama liela interese ne vien par mikroģeneratoru ieviešanu, bet arī saules parku attīstību. 2022. gada aprīļa beigās kopējā rezervētā jauda mikroģeneratoru un elektrostaciju attīstībai pārsniegusi 670 MW. Pēc pārvades sistēmas operatora datiem, Latvijas sistēmas maksimālā slodze 2020. gada ziemā sasniedza 1184 MW, bet minimālā slodze tika novērota vasarā – 463 MW. [7]

Politikas veidotāju, regulatora un citu tirgus dalībnieku galvenā loma ir sagatavoties izmaiņām attiecībā uz esošajiem elektroenerģijas tirgiem. Mainīgas un atjaunojamās enerģijas ģenerācija no vairākiem decentralizētiem avotiem būs izaicinājums elektrotīkla infrastruktūrai, kas izstrādāta un būvēta, plānojot tradicionālās centralizētās sistēmas darbības principus. Decentralizēta sistēma ar lielu atjaunojamo enerģijas avotu īpatsvaru ir mazāk paredzama nekā centralizēta sistēma, un elektrotīklu operatori var saskarties ar grūtībām, reaģējot uz maksimuma pieprasījumu un piedāvājuma mainīgumu un neprognozējamību.

Grozījumi Enerģētikas likumā

Pārejai uz tīrāku enerģētiku svarīgāka loma turpmākajos gados būs enerģētikas kopienām. Mājsaimniecības, privātpersonas un uzņēmumi kopīgi iegulda ar enerģiju saistītu aktīvu attīstībā un ekspluatācijā. Aplēses liecina, ka līdz 2030. gadam enerģētikas kopienām ES varētu piederēt aptuveni 17 % no uzstādītās vēja jaudas un 21 % saules enerģijas. [8] Šīs kopienas veicina vietējo ekonomisko attīstību, nodrošina drošu un pieejamu enerģiju un veicina vietējās kopienas savstarpējo sadarbošanos.

Tiesiskais regulējums enerģijas kopienām tika ieviests Eiropas tiesību aktos ar tā saukto Tīras enerģijas pakotni. Sīkāk termins "enerģijas kopiena" tiek lietots divās ES direktīvās saistībā ar:

- "iedzīvotāju energokopienu" Eiropas Parlamenta un Padomes 2019. gada 5. jūnija Direktīvā (ES) 2019/944 [9] (Direktīva 2019/944) par kopīgiem noteikumiem attiecībā uz elektroenerģijas iekšējo tirgu (pārstrādāta versija) un
- "atjaunojamās enerģijas kopienu" Eiropas Parlamenta un Padomes 2018. gada 11. decembra Direktīvā (ES) 2018/2001 [10] (Direktīva 2018/2001) par atjaunojamo energoresursu izmantošanas veicināšanu (pārstrādāta versija), kas pazīstama arī kā "RED II".

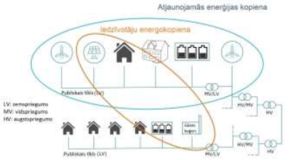
Abiem kopienu definīciju veidiem ir savas līdzības, piemēram:

- kopienas ir tiesību subjekts, kas izveidots kā juridiska persona (kā uzsvērts Direktīvā 2019/944, tā "veido jauna veida vienību, ņemot vērā to dalības struktūru, pārvaldības prasības un mērķus");
- tās efektīvi kontrolē to akcionāri vai dalībnieki, un
- to galvenais mērķis ir nodrošināt vides, ekonomisko un sociālo kopienas labumu, nevis finansiālu peļņu.

Savukārt galvenās atšķirības starp "iedzīvotāju energokopienu" un "atjaunojamās enerģijas kopienu" ir dalības kopienā jautājumos (pirmā ir daudz vairāk regulēta nekā otrā):

- "atjaunojamās enerģijas kopienas" sakarā ir papildu atruna privātiem uzņēmumiem, ka to dalība nedrīkst būt to primārā komerciālā vai profesionālā darbība;
- "atjaunojamās enerģijas kopienas" akcionāriem vai dalībniekiem jāatrodas "atjaunojamās enerģijas kopienas" piederošo un attīstīto atjaunojamās enerģijas projektu tuvumā.

"Iedzīvotāju energokopienas" sakarā šis subjekts ir atbrīvots no minētajām prasībām. Turklāt "atjaunojamās enerģijas kopienas" dalībnieki var kopīgi iesaistīties vairāku veidu atjaunojamās enerģētikas jomu pārvaldībā (ražošanā, patēriņa kontrolē un enerģijas pārdošanā, atjaunojamās gāzes utt.). Savukārt "iedzīvotāju energokopienu" darbības joma pašlaik ir ierobežota ar elektroenerģijas nozari, piemēram, elektroenerģijas ražošanu, sadali un piegādi, patēriņa kontroli, agregēšanu, uzkrāšanu vai energoefektivitātes un elektrisko transportlīdzekļu uzlādes pakalpojumiem utt. (tomēr tas var mainīties līdz ar jauno ES Gāzes direktīvas redakciju). No tīkla perspektīvas šo abu kopienu veidi attēloti 2. attēlā. [11]



2. attēls. Kopienas no sistēmas operatoru viedokļa

No iepriekš minētā var secināt, ka "iedzīvotāju energokopiena" ir tehnoloģiju neintrāla, kamēr "atjaunojamās enerģijas kopiena" ir limitēta ar atjaunojamās enerģijas tehnoloģijām.

2022. gada 14. jūlijā otrajā – galīgajā – lasījumā Saeima atbalstīja par steidzamiem atzītos grozījumus Enerģētikas likumā, [12] lai pārņemtu abu minēto ES direktīvu nosacījumus. Ar regulējumu energokopienām paredzēts veicināt Latvijas sabiedrības iesaisti elektroenerģijas ģenerācijai. Ar grozījumiem Enerģētikas likumā tiek paredzēts definēt jaunu tirgus dalībnieku jēdzienus:

– atjaunojamās enerģijas kopiena – energokopiena, kas nodarbojas ar atjaunojamās enerģijas ražošanu un kurai pieder vai arī tā attīsta vai apsaimnieko atjaunojamās enerģijas ražošanas iekārtas, kas teritoriāli saistītas ar atjaunojamās enerģijas kopienu;

– elektroenerģijas energokopiena – energokopiena, kas darbojas elektroenerģijas nozarē;

– energokopiena – juridiska persona ar atvērtu, demokrātisku un brīvprātīgu dalību, kuras mērķis ir sniegt vides, ekonomiskus vai sociālus labumus saviem biedriem vai daļu turētājiem, vai teritorijām, kurās tās darbojas; kura darbojas enerģijas, primāri no atjaunojamiem energoresursiem iegūtas elektroenerģijas, kā arī cita veida atjaunojamās enerģijas ražošanā, tirdzniecībā, elektroenerģijas kopīgošanā, patēriņā, pieprasījuma reakcijas pakalpojuma nodrošināšanā, elektroenerģijas uzkrāšanā, elektrisko transportlīdzekļu uzlādes pakalpojuma, energoefektivitātes vai citu energopakalpojumu sniegšanā.

Grozījumi Enerģētikas likumā noteic, ka energokopiena atbilst "atjaunojamās enerģijas kopienas" vai "iedzīvotāju energokopienas" nosacījumiem, kas nozīmē, ka energokopiena var atbilst vai nu vienam no minētajiem, vai abiem nosacījumiem. Tāpat ir noteikts, ka energokopienas biedri saglabā tiem noteiktos galalietotāja vai aktīvā lietotāja tiesības un pienākumus. Aktīvā lietotāja definīcija iekļauta grozījumos Elektroenerģijas tirgus likumā, [13] kas tika atbalstīti vienlaikus ar grozījumiem Enerģētikas likumā.

Tāpat arī energokopiena detalizētāk reglamentēta grozījumos Elektroenerģijas tirgus likumā (skatīt nākamo sadaļu). Elektroenerģijas energokopienas definīcija ir plašāka, kā direktīvā ietverot arī vidējos uzņēmumus. Tas darīts ar mērķi, lai iespējami vienādotu abu veidu energokopienu nosacījumus. Mazo un vidējo uzņēmumu definējums atbilst Eiropas Komisijas (EK) regulas Nr. 651/2014 [14] 1. pielikumā noteiktajai definīcijai.

Jāņem vērā, ka likumprojekts nenosaka vienu konkrētu energokopienu juridisko formu – līdzšinējā Eiropas pieredze liecina, ka šī forma var būt visdažādākā: (1) kooperatīvi, (2) sabiedrības ar ierobežotu atbildību, (3) nodibinājumi un fondi, (4) mājokļu asociācijas (īpašnieku/īrnieku biedrības), (5) bezpeļņas uzņēmumi (tipiski ciemu siltumapgādē Dānijā), (6) publiskās/privātās partnerības.

Latvijas gadījumā energokopiena var būt biedrība vai nodibinājums, kooperatīvā sabiedrība, kā arī kapitālsabiedrība, kas nodrošina atbilstību normatīvajos aktos noteiktajām prasībām energokopienai.

Lai energokopienu regulējums varētu darboties pilnā apmērā, Ministru kabinetam būs jānosaka energokopienu reģistrā iekļaujamās ziņas, reģistrācijas prasības un kārtība, reģistrācijas vai darbības izbeigšanas iesniegumā ietveramā informācija, energokopienas gada pārskatos sniedzamās ziņas, kā arī kārtība, kādā energokopienu izslēdz no energokopienu reģistra vai atkārtoti reģistrē. Šie noteikumi ietvers arī kārtību, kādā Būvniecības valsts kontroles birojs kā atbildīgā iestāde pieņems lēmumu par energokopienas iekļaušanu vai izslēgšanu no reģistra.

Savukārt Ekonomikas ministrijai turpmāk būs iespēja izstrādāt atbalsta shēmas energokopienām, kuras izmantotu atjaunojamos energoresursus, ievērojot komercdarbības atbalsta nosacījumus. Šajā gadījumā ir būtiski, ka atbalsts būtu iespējams arī energokopienām, kas atbilst tikai iedzīvotāju energokopienu nosacījumiem, bet vienīgi gadījumos, ja tās ģenerēs elektroenerģiju no atjaunojamiem energoresursiem.

Grozījumi Enerģētikas likumā vienlaikus kopīgi ar atbalstītajiem grozījumiem Elektroenerģijas tirgus likumā un atbilstoši izstrādājamajiem Ministru kabineta noteikumiem veidos juridisko bāzi, īstenojot energokopienu potenciālu. Papildus tam būs nepieciešamas investīciju atbalsta programmas un plaša sabiedrības informēšana, tajā skaitā grozījumos paredzētās vadlīnijas, ko būs jāizstrādā pašvaldību vajadzībām.

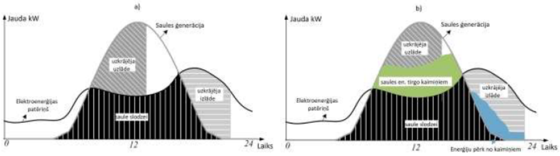
Grozījumi Elektroenerģijas tirgus likumā

Mājsaimniecību elektroenerģijas patēriņš veido daļu no kopējā elektroenerģijas patēriņa. Savstarpēja tirdzniecība (*peer-to-peer*), kā arī enerģijas kopīgošana starp enerģijas kopienām varētu veicināt Eiropas zaļo kursu, tirgojot enerģijas pārpalikumus lokāli vai uzkrājot lieko enerģiju vēlākai izmantošanai vai tirdzniecībai.

Savstarpējas tirdzniecības jeb *peer-to-peer* termins definēts Direktīvā (ES) 2018/2001: "Atjaunojamās enerģijas tirdzniecība ir starp tirgus dalībniekiem, izmantojot līgumu ar iepriekš paredzētiem noteikumiem, kas reglamentē darījuma automātisku izpildi un norēķinu tieši starp tirgus dalībniekiem vai netieši caur sertificētu trešo tirgus dalībnieku, piemēram, agregatoru. Tiesības veikt savstarpēju tirdzniecību neskar iesaistīto pušu tiesības un pienākumus, kas tām pastāv kā galalietotājiem, ražotājiem, piegādātājiem vai agregatoriem."

Kopienas un savstarpējā tirdzniecība atšķiras no tā sauktajām "virtuālajām elektrostacijām" ar to, ka, piemēram, elektroenerģijas uzkrājēji tiek izmantoti elastības nodrošināšanai, un elastība tiek izmantota kopienā, nevis dienas vai balansēšanas elektroenerģijas tirgos.

Grozījumi, kas paredz elektroenerģijas kopīgošanu kopienās, paver jaunas iespējas mikroģenerācijas attīstībai un saražotās elektroenerģijas optimālai sadalīšanai, kas ir uzskatāmi parādīts 3. attēlā. [15] Tajā ir attēlota savstarpējas tirdzniecības un elektroenerģijas dalīšanās kopienā ietekme uz mikroģenerācijas un elektroenerģijas uzkrājēju optimālu izmantošanu. Attēlā pa labi (b) ir parādīta enerģijas dalīšanās ietekme – atjaunojamās elektroenerģijas izmantošana palielinās, salīdzinot ar elektroenerģijas uzkrājēja izmantošanu, bez dalīšanās iespējām attēlā pa kreisi (a). Tirgojot enerģiju un daloties ar uzkrājēja aktīviem, enerģijas kopienai ir lielāka iespēja efektīvāk nosegt kopējo pašpatēriņu, nodrošināt pašpietiekamību, līdz ar to ir jāiegādājas mazāk enerģijas no ārējiem avotiem.



3. attēls. Elektroenerģijas patēriņa nosegšana ar mikroģenerāciju un elektroenerģijas uzkrājēju:

a) pa kreisi – atsevišķam patērētājam, b) pa labi – ar elektroenerģijas dalīšanos kopienā

Kā jau tika minēts, 2022. gada 14. jūlijā otrajā – galīgajā – lasījumā Saeimā atbalstīja arī grozījumus Elektroenerģijas tirgus likumā, [16] kura mērķis ir pārņemt Direktīvas 2019/944 un Direktīvas 2018/2001 nosacījumus. Grozījumi Elektroenerģijas tirgus likumā paredz elektroenerģijas neto uzskaites sistēmas pilnveidošanu un papildināšanu ar neto norēķinu sistēmu, kā arī nosaka principus elektroenerģijas energokopienu un aktīvo lietotāju darbībai.

Ar grozījumiem tiek paredzēts definēt jaunu tirgus dalībnieku jēdzienus:

- **aktīvais lietotājs** – galalietotājs, kurš ražo elektroenerģiju savām vajadzībām un var saražotās elektroenerģijas pārpalikumu pārdot, kopīgot, iesaistīties elastības pakalpojumos vai energoefektivitātes shēmās un kurš nav energoapgādes komersants;
- **elektroenerģijas kopīgošana** – aktīvā lietotāja saražotās un sadales sistēmā nodotās elektroenerģijas nodošana citiem galalietotājiem, tajā skaitā aktīvajiem lietotājiem, vai elektroenerģijas energokopienā saražotās un sistēmā nodotās elektroenerģijas nodošana elektroenerģijas energokopienas biedriem vai daļu turētājiem;
- **kopīgi darbojošies no atjaunojamajiem energoresursiem iegūtas enerģijas aktīvie lietotāji** – grupa ar vismaz diviem galalietotājiem, kas katrs atsevišķi ir pieslēgts pie elektroenerģijas sadales sistēmas un pēc savstarpējas vienošanās savām vajadzībām kopīgi ražo elektroenerģiju no atjaunojamajiem energoresursiem, un kuri rīkojas kopīgi vienā un tajā pašā ēkā vai teritorijā, kas atrodas vienā adresē;
- **no atjaunojamajiem energoresursiem iegūtas elektroenerģijas aktīvais lietotājs** – aktīvais lietotājs, kurš ražo elektroenerģiju savām vajadzībām no atjaunojamajiem energoresursiem.

Neto uzskaites sistēmas pilnveidošana un papildināšana paredzēs:

- veicināt juridisko personu, tostarp ražojošo uzņēmumu, iesaisti elektroenerģijas ražošanā pašpatēriņam;
- vienā lietotāja objektā saražoto elektroenerģiju varēs izmantot citos tā paša lietotāja objektos, kuriem elektroenerģijas tirdzniecību nodrošina viens tirgotājs un kas pieslēgti vienam sistēmas operatoram;
- neto norēķinu sistēmas ietvaros tiks noteikts 50 kW jaudas ierobežojums;
- likumprojektā noteikta Būvniecības valsts kontroles biroja kompetence administrēt komercdarbības valsts atbalsta piešķiršanu atbilstoši *de minimis* nosacījumiem elektroenerģijas galalietotājiem neto norēķinu sistēmas ietvaros;
- grozījumi paredz, ka neto uzskaite ir veicama tā gada ietvaros, kas sākas 1. martā un noslēdzas nākamā gada 29. februārī (iepriekš bija no 1. aprīļa līdz nākamā gada 31. martam).

Tiek paredzēti nosacījumi arī attiecībā uz Elektroenerģijas kopīgošanu:

- kopīgošanu nodrošinātu sistēmas operators atbilstoši noslēgtajam līgumam ar elektroenerģijas energokopienu vai kopīgi darbojošamies no atjaunojamajiem energoresursiem iegūtas elektroenerģijas aktīvajiem lietotājiem;
- elektroenerģijas kopīgošana notiktu viena tirdzniecības intervāla ietvaros. Tūlītēji nepatērētā elektroenerģija nav uzkrājama kopīgošanai citā tirdzniecības intervālā, tā ir pārdodama elektroenerģijas tirgotājam par vienošanās cenu;
- sistēmas dalībnieku objekti, kas piedalās elektroenerģijas kopīgošanā, vienlaicīgi nevarēs piedalīties neto uzskaites sistēmā, neto norēķinu sistēmā, kā arī elektroenerģijas izcelsmes apliecinājumu sistēmā;
- sadales sistēmu elektroenerģijas kopīgošanai izmanto par sistēmas pakalpojumu tarifiem, kuri noteikti likumā "Par sabiedrisko pakalpojumu regulatoriem" noteiktajā kārtībā.

Lai regulējums varētu darboties, Ministru kabinetam būs jānosaka:

- kārtība, kādā piemērojama neto uzskaites sistēma;
- neto norēķinu sistēmas izmantošanas nosacījumi, kārtība, kādā tā piemērojama neto norēķinu sistēma un veicama informācijas apmaiņa starp iesaistītajām pusēm tās administrēšanas nodrošināšanai, un *de minimis* atbalsta nosacījumu piemērošanas kārtība;

- kārtība, kādā īstenojama elektroenerģijas kopīgošana, un nosacījumi elektroenerģijas kopīgošanai.

Rekomendācijas nākamajiem grozījumiem Enerģētikas un Elektroenerģijas tirgus likumā:

- vai nevajadzētu detalizētāk atrunāt pretrunas starp abām kopienām – "iedzīvotāju energokopienu" un "atjaunojamās enerģijas kopienu", apvienojot tās vienā. "Iedzīvotāju energokopiena" ir tehnoloģiju neitrāla, kamēr "atjaunojamās enerģijas kopiena" ir limitēta ar atjaunojamās enerģijas tehnoloģijām, kam jābūt piederošo un attīstīto atjaunojamās enerģijas projektu tuvumā.

Likuma grozījumus veicot, būtu skaidri jākomunicē ar sabiedrību, jo īpaši par ieguvumiem dalībai vienā vai otrā neto sistēmā – "Elektroenerģijas neto norēķinu sistēmā" vai "Elektroenerģijas neto uzskaites sistēmā", uzskatāmāk parādot atšķirības starp tām. Piemēram, 4. attēlā ir parādīts piemērs par iespējamiem ieguvumiem, kad tiek uzskaitīta ne tikai ģenerētā elektroenerģija un patēriņš, bet arī noteikta elektroenerģijas vērtība, ņemot vērā attiecīgā brīža "Nord Pool" elektroenerģijas biržas tirgus vērtību. Šajā gadījumā ģenerētā elektroenerģija mājsaimniecībā – 27 kWh, patēriņš – 32 kWh, pārdotais apjoms tirgotājam – 15 kWh (par 3 eiro bez PVN, t.i., tikai par elektrības komponenti), un no tirgotāja iepirktais apjoms – 20 kWh (par 5,71 eiro bez PVN, t.i., tikai par elektrības komponenti). Pāreja no "Elektroenerģijas neto uzskaites sistēmas" uz "Elektroenerģijas neto norēķinu sistēmu" drīzāk ieviestu taisnīgāku ieguvumu sadalījumu pret tirgotāju, bet patērētājam tas varētu samazināt ieguvumus no saules enerģijas izmantošanas sistēmu uzstādīšanas. Šāds secinājums būtu spēkā pie cenu profila, kas attēlots 4. attēlā (šāda situācija Latvijā būs raksturīga nākotnē, kad uzstādīto saules sistēmu jauda būs vairākas reizes lielāka nekā šobrīd).

- Nosacījumos vai anotācijā varētu tikt skaidrots, kā tieši tirgotājam ļauts noteikt elektroenerģijas tirgus vērtību (t.i., vai tā var būt tā sauktā vienošanās cena, fiksēta cena vai līdzsvara cena). Viens no izaicinājumiem – kā izveidot taisnīgu ieguvumu sadalīšanas principu, kas būtu izdevīgs tirgotājam un aktīvajiem lietotājiem, gan arī kopienu dalībniekiem, jo pāreja no "Elektroenerģijas neto uzskaites sistēmas" uz "Elektroenerģijas neto norēķinu sistēmu" ir viens no mēģinājumiem, kā šādu problēmu risināt.
- Elektroenerģijas tirgus likuma grozījumos vai anotācijā būtu vēlams iekļaut plašāku vērtējumu par sistēmas operatora tiesībām noteikt neto uzskaites sistēmas administrēšanas maksu, tās apmēru un ietekmi uz pašu galveno neto uzskaites sistēmas uzdevumu – kā veicināt no atjaunojamiem energoresursiem iegūtas elektroenerģijas ģenerāciju.
- Abos likumu grozījumos tika saskatīti vairāki termini, kurus nākotnē būtu nepieciešams harmonizēt, vismaz starp Latvijas likumdošanu un politikas dokumentiem. Piemēram, "atjaunojamā" vai "atjaunīgā" enerģija, elektroenerģijas "ražošana" vai "ģenerācija" u.c.
- Ieviešot energokopienas sistēmu, sistēmas operatoram būtu nepieciešams izvērtēt jaunu tarifu aprēķināšanas principu izstrādi. Piemēram, gadījumā, kad elektroenerģijas sadalīšana notiek gan vienas kopienas ietvaros, gan starp kopienām. Vai papildus noteikumus, kas regulē kopienas atbildību pret radīto nebalansu. Sabiedrību vajadzētu arī informēt par to, kāds ieguvums būtu no dalības energokopienā vai elektroenerģijas tirdzniecībai starp šādām kopienām.
- Pieaugot aktīvo lietotāju skaitam un mikroģenerācijas sistēmu jaudai, nedaudz var samazināties sadales sistēmas operatora ienākumi no elektroenerģijas sadalīšanas pakalpojumu sniegšanas (vidēji par 1/3). Taču vienlaikus pieaug arī tīklā nodotais elektroenerģijas daudzums. Līdz ar to būtu nepieciešama tarifu izvērtēšana, kāds būtu taisnīgs regulējums, pieaugot aktīvo lietotāju skaitam un mikroģenerācijas sistēmu jaudai.

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TRANSITIONING TO DECENTRALIZED RENEWABLE ENERGY IN LATVIA: A COMPREHENSIVE PAYBACK ANALYSIS

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It is believed that the transition to renewable decentralized energy supply solutions (e.g., solar panels, storage of electricity in batteries) will help promote the decarbonization of the energy system. At the same time, it is expected to happen only when society is convinced of the environmental benefits and when there are enough economic incentives for it. This study analyses the economic feasibility of transitioning to decentralized renewable energy solutions, including solar panels and electricity storage, in Latvia. Our research explores potential savings of these solutions under various scenarios based on different factors, such as national NETO billing system, financial support scheme, electricity pricing, distribution network tariffs, energy storage options, as well as the impact of the battery energy storage system (BESS) discharging strategy. The results show that the potential savings can vary depending on these factors that are changing over time. Nevertheless, the rise in small-scale power generation at households shows that there is an increasingly rapid transition from centralized electricity supply to a decentralized supply system, which might indicate that society supports energy transition.

Keywords: *BESS economic feasibility, decentralized energy supply, NETO billing systems.*

1. INTRODUCTION

Decentralized power supply solutions, such as solar panels, electric vehicle (EV) charging stations, and electricity storage systems (batteries), are becoming increasingly more popular and widely recognized by numerous countries in their endeavours to promote environmentally friendly technologies. The adoption of these technologies is influenced not only by the national legislation, but also by other factors, such as high electricity prices, enhanced electricity reliability, and the desire to be more environmentally friendly.

For example, in Latvia, the swift adoption of solar panels in the past few years was most likely driven by two factors: firstly, the high electricity prices caused by geopolitical circumstances in neighbouring countries (see year 2022 in Figure 1) and, secondly, the support for renewable energy resources provided by the Latvian government. After the start of the Russia-Ukraine war, the average electricity price in Latvia increased to 226.01 EUR/MWh in 2022, in contrast to 46.28 EUR/MWh in 2019, or 34.05 EUR/MWh in 2020, and 88.78 EUR/MWh in 2021, respectively. In early 2023, however, the prices were slightly lower than those recorded in 2022 [1].

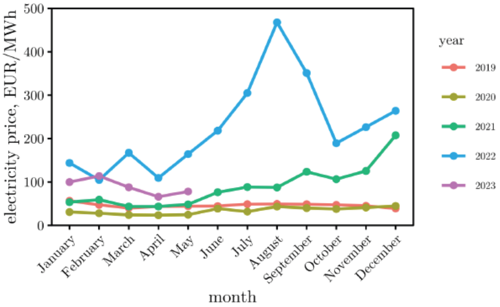

Fig. 1. Nord pool average day-ahead electricity price in the Latvian trade area [1].

By installing solar panels or small wind turbines, Latvian residents had the opportunity to receive financial support by means of the following two support programs:

- the support provided by the administered programme of ALTUM ranges from 700 to 4000 EUR, depending on the nominal power of the inverter.
- the support provided by the Emission Allowance Auction Instrument (EKII) also ranges from 700 to 4000 EUR, depending on the nominal power of the inverter.

Funding from the EKII support program is only available after the purchase and installation of the equipment. On the contrary, to receive the ALTUM support, one first needs to apply for the programme, await approval, and then commence the work. The EKII programme has a total funding of 40 million EUR, while ALTUM has a funding allocation of 3.66 million EUR [2].

These circumstances have led to a situation where, within a relatively short period, the total number of microgenerators (mostly solar) has surpassed 15,000 units (Fig. 2), with their combined production capacity already exceeding 120 megawatts (MW).

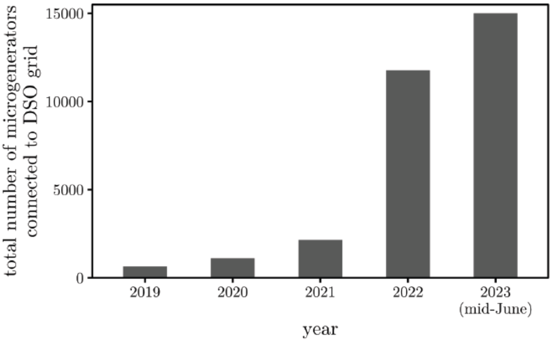

Fig. 2. Number of microgenerators connected to DSO (distribution system operator Sadales tīkls JSC) grid [3], [4].

The electricity generated by microgenerators is primarily directed towards enabling households to meet their own energy needs, including charging their EVs. EVs are widely recognized as one of the most promising solutions to mitigate environmental impact in the transportation sector and improve energy efficiency. When the electricity for EVs is sourced from a grid predominantly powered by fossil fuels, their life cycle emissions are comparable to vehicles with combustion engines. However, when renewable energy sources are predominant in the energy system, EVs emissions are slightly lower. To truly achieve sustainability in using EVs, it is required to shift the future of electricity towards renewable sources.

Among renewable energy resources, such as wind and solar power, solar energy is considered the most promising in the context of EV charging (see Table 1).

Table 1. Comparison of Charging EV from Wind or Solar Energy Source [5], [6]

Category	Wind energy	Solar energy
1	Onshore and offshore wind is far from where EVs can be charged	Close to where EVs can be charged. For example, rooftop photovoltaic (PV), so transmission is not needed
2	Different power scales: wind turbines in MW while EV chargers in kW. While on the other hand, with wind turbines it could be possible to charge several thousand EVs	Power scales are similar for rooftop PV and EV charger (both kW)
3	Generation is mostly in winter and night time	Generation is mostly in daytime and summer

In most scenarios, one advantage of solar energy as well as EV batteries is that those operate on direct current (DC) power. However, when it comes to grid integration, the standard is alternating current (AC). This leads to the need for unnecessary DC-AC-DC conversions, which can result in energy losses. In contrast, utilizing DC power directly, without conversion, proves to be more efficient [5].

In addition to the support available for installing microgenerators in Latvian households, there is also financial support available for individuals purchasing EVs. A grant of 4,500 EUR is provided when purchasing a new electric car, while a grant of 2,250 EUR can be received when purchasing used electric cars and new externally chargeable hybrid cars. However, there is a purchase price limit of 60,000 EUR for low-emission and zero-emission vehicles in their basic configuration, as stipulated by regulations. Additionally, there is an extra 1,000 EUR support available for beneficiaries, who choose to write off their existing vehicle and hand it over to a processing company [7].

However, unlike microgenerators and electric cars, electricity storage systems (batteries) have not yet been widely adopted in Latvia, and the government has not provided financial support for such equipment. This could be related to the existing NETO accounting system for microgenerators. The NETO accounting system has traditionally allowed for the virtual storage of electric energy produced by microgenerators, enabling its later use, for example, during winter months [8]. Perhaps this is one of the reasons why batteries have not been so popular so far.

However, Latvia has recently made amendments to the Electricity Market Law, resulting in the introduction of a new and improved system, called NETO settlement system. The new NETO settlement system not only records the amount of electricity generated and consumed by customers, but also assigns monetary value to this energy. The advantages of the new system have been communicated and include:

- applicability to both households and legal entities (the previous system included only private consumers);
- conversion of electricity produced and transferred to the grid into monetary terms, allowing for savings that can be utilized towards future bill payments or applied to electricity costs in other connections of the same customer, as per the conditions of the chosen electricity service provider;
- the net savings period is not limited by law;
- the freedom to select the most suitable service provider and the flexibility to switch between providers;
- active participation in the electricity market, enabling cost control by tying the value of energy transferred and received to market prices and settlement conditions. Encouragement of consumption habits that maximize the profitability of electricity production and consumption. These changes aim to empower consumers by providing greater control over their electricity usage and promoting a more economically advantageous approach to energy consumption [9].

Although there is extensive information regarding the new rules of the NETO settlement system in Latvia, there is a lack of detailed explanation for general public regarding the potential economic implications for owners of decentralized energy supply solutions [10].

This publication proposes three hypotheses. Firstly, the introduction of the new NETO system will reduce the homeowners' interest in switching to solar panels. Secondly, the implementation of the new system has the potential to motivate homeowners to actively invest in and utilize stationary batteries. And, thirdly, the smart BESS management system will determine the level of savings achievable by the storage. This publication could serve as a useful material for people and policy makers to evaluate new initiatives for the implementation of decentralized electricity supply solutions.

The publication 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 enactments on the economic viability of different situations.

The second chapter examines changes in the NETO accounting and settlement systems in Latvia. The hypotheses are defined and possible directions for future research are discussed. Section 3 defines the methodology and assumptions used in the two case studies for mathematical calculations to evaluate the NETO accounting and settlement systems, as well as BESS discharging strategy. Section 4 presents the calculation results, while Section 5 discusses the results and summarises conclusions from this work.

2. THE OVERVIEW OF THE CURRENT SITUATION

2.1. NETO Accounting and Settlement System in Latvia

According to the amendments made to the Electricity Market Law on 16 February 2023, significant changes have been implemented concerning microgeneration producers in Latvia.

NETO accounting system (pre-existing system; Fig. 3): 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. This system applies to the cases when the produced electricity is not immediately consumed but transferred to the grid. If the amount of electrical energy transferred to the grid exceeds the energy received from the grid, the excess energy is carried forward to the next billing period within a NETO year (starts on 1 March and ends on the last day of February). “Energy storage” can only be utilized within the same property (for the specific system connection) where it was generated. At the beginning of a new NETO year, all savings are deleted. It is important to note that the NETO accounting system is currently limited to households and is automatically applied after receiving permission to connect the microgenerator (when the amendments to the law take effect, it will be possible to join the scheme until 31 December 2023).

NETO settlement system (new system; Fig. 4): 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. If the total value of the electricity produced, but not immediately consumed (and transferred to the distribution network) exceeds the value of the electricity received from the same network, the surplus value can be credited in the subsequent settlement period or used for electricity payments in another connection of the same customer. Both households and legal entities will be eligible to participate in the NETO settlement system.

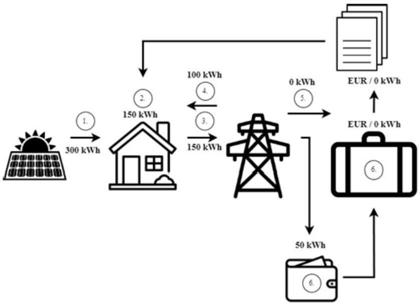

Fig. 3. Schematic representation of the NETO accounting system – the customer transferred 50 kWh more to the electricity network than he received from the network. The customer only has to pay the service fee of the distribution system operator this month, but does not have to pay for electricity [9].

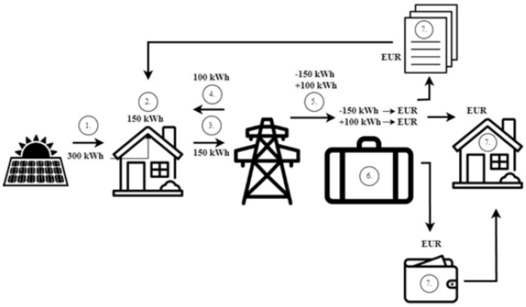

Fig. 4. Schematic representation of the NETO settlement system – the electricity trader determines the value of the electricity transferred to the common power grid and received from the common power grid [9].

The law mandates that electricity traders must include the NETO settlement system as part of their trading services. Currently, the Cabinet of Ministers is in the process of developing detailed operational guidelines for the NETO settlement system and determining the date when it will be made available to customers [9].

2.2. Definition of the Problem and Hypothesis

The authors propose three hypotheses regarding the impact of the new NETO settlement system:

- Hypothesis A: The introduction of the new NETO settlement system may reduce the economic viability of installing solar panels.
- Hypothesis B: The new NETO settlement system is expected to emphasize the importance of batteries in enhancing the profitability of investments in green technologies.

- Hypothesis C: The smart BESS management system will determine the level of savings achievable by the storage capacity.

2.3. Future Research Prospects

In the future, conducting research on the economic viability of various green technologies, particularly under scenarios such as energy arbitrage or their potential integration with energy communities, would offer significant advantages and insights. Currently, energy communities and the concept of electricity sharing have not gained significant popularity in Latvia. Moreover, there is a need for further exploration and understanding of the development and utilization of virtual power plants. By conducting additional studies in these areas, we can gain valuable insights into the potential benefits and feasibility of implementing decentralized energy solutions. This knowledge will play a vital role in facilitating the transition to a green economy in Latvia.

3. TWO CASE STUDY ASSUMPTIONS

The first 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. Figure 5 shows a block scheme of the case study.

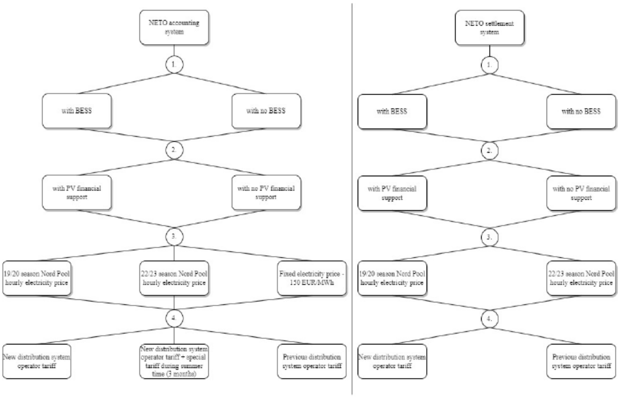

Fig. 5. Block scheme of the first case study which compares different operating scenarios of the NETO accounting system and the NETO settlement system.

The authors compare two NETO system alternatives 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. The authors have thoroughly analysed potential savings, considering the impact of the new distribution system tariff, which affects all current customers connected to the grid of the Latvian distribution system operator. Additionally, the implications of the newly introduced special tariff, which is available free of charge to any user, have been 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 JSC: date and time, electricity consumption, and electricity generation [11]. The yearly electricity demand of the household was 11.32 MWh, while solar energy injected to 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 [8], the level of direct consumption by households in Europe is 20–30 %.

Using input data described above (including Fig. 5), as well as in Table 2, the authors analysed all respective scenarios.

Table 2. Input Data and Assumptions of Household Power Supply System [8], [11], [12]

Characteristic	**Indicator or assumption**
Self-consumption	30 %
Solar system capacity and cost	5 kW, 1200 EUR/kw, 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

While the second case study considers a farm as an electricity consumer that is registered as a legal entity with access to the electric grid and installed solar panels. In this case study, the electricity storage system is added and evaluated for various operating scenarios of the NETO settlement system. Figure 6 shows a block scheme of the second case study scenarios.

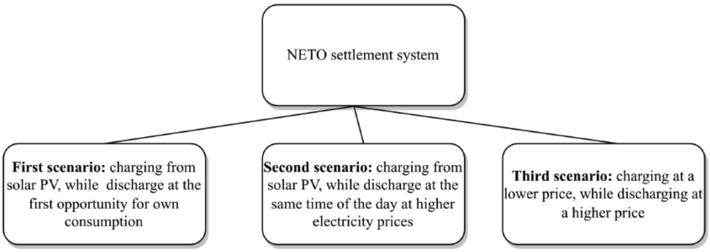

Fig. 6. Scheme of the second case study in which three scenarios of the NETO settlement system are investigated and compared using a farm with installed solar panels as an example.

In the second case study, the authors compare three alternatives to examine the best possible scenarios of BESS discharge possibilities and to evaluate savings that could be expected from the smart BESS system management. In all scenarios, annual data at a 1-hour resolution were obtained for one farm of an anonymous customer from Sadales tīkls JSC [11]. The yearly electricity demand of the farm was 8,279 MWh, while the solar energy injected to the grid reached 17,163 MWh on an annual basis (see Fig. 7). Unfortunately, like in the first case study, there is no information on the specific electricity consumption patterns at this facility, including information on a contract with an energy trader for the purchase of the produced electricity. As can be seen in Fig. 7, on average, the farm produced more than twice as much electricity as it consumed.

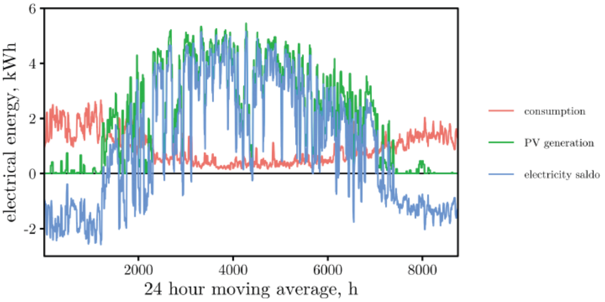

Fig. 7. Characteristics of electricity supply at the farm. 24 h moving average was plotted instead of the raw hourly data to improve the visual clarity of the plot [11].

Using data described above (including Fig. 6 and Fig. 7), as well as in Table 3, the authors have analysed all three scenarios.

Table 3. Input Data and Assumptions of the Farm Power Supply System [11], [12]

Characteristic	**Indicator or assumption**
Electricity storage systems (BESS) energy capacity, costs, and operation	Energy capacity 15-30-50 kWh, and 10 kW power capacity with capex 225 EUR/kW and 600 EUR/kWh accordingly. BESS charging and discharging efficiency – 95 %
BESS degradation	1.5 %
New distribution network tariff	• charge for electricity supply 0.03985 EUR/kWh • charge for IAA current magnitude 0.92 EUR/A/month
Electricity price	Three scenarios analysed with different electricity prices – the 2018 and 2022 season Nord pool exchange prices. Value added tax is not considered.

The significance of selecting the optimal operational mode and energy capacity for BESS is becoming a progressively more important topic for discussion. This analysis aims to approximate the advantages of installing a BESS in a power system that already incorporates solar panels.

4. ASSESSMENT RESULTS

4.1. The First Case Study – NETO Accounting System

In Figure 8, 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 a 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 of the government (assumed to be 2500 EUR).

Figure 8 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 Nord Pool prices of the 2022-2023 season 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 during 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.

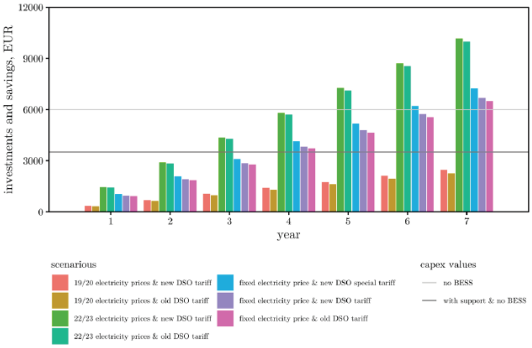

Fig. 8. Potential savings under NETO accounting system with no BESS in a 7-year period.

Figure 9 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. 8, 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.

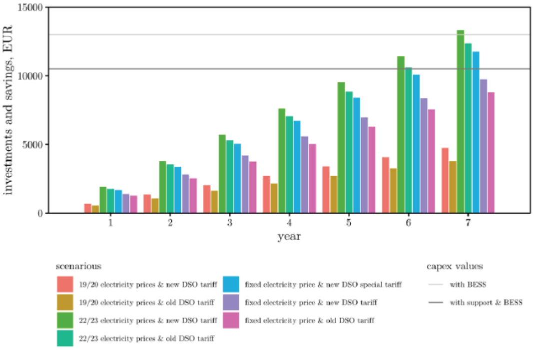

Fig. 9. Potential savings under the NETO accounting system with BESS in a 7-year period.

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.

4.2. 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. 10, 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. 10, 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 during 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.

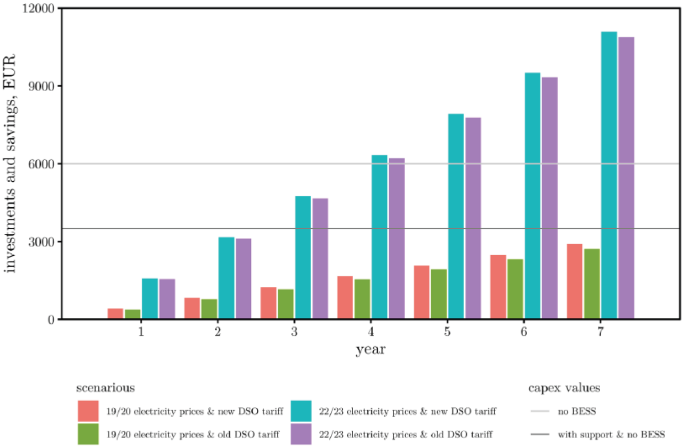

Fig. 10. Potential savings under the NETO settlement system with no BESS in a 7-year period.

Figure 11 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.

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.

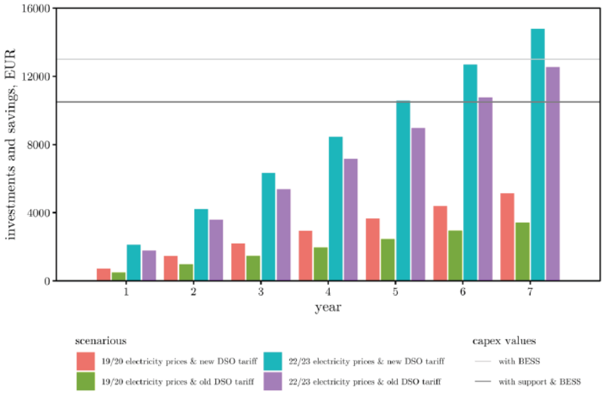

Fig. 11. Potential savings under the NETO settlement system with BESS in a 7-year period.

4.3. The Second Case Study – The BESS Management System

In the second case study, three algorithms have been developed to evaluate savings from different BESS discharge and charge management approaches. Energy storage capacities have been assumed and varied – 15, 30, and 50 kWh. This, the second case study, involves a farm operating under the NETO settlement system, equipped with a pre-existing solar panel system.

In the first scenario, the BESS is charged using solar PV, and discharge occurs as soon as there is an opportunity for self-consumption. The second scenario involves charging from solar PV but discharging during peak electricity pricing hours. In the third scenario, the BESS is charged at the lowest electricity rates and discharged when prices are higher.

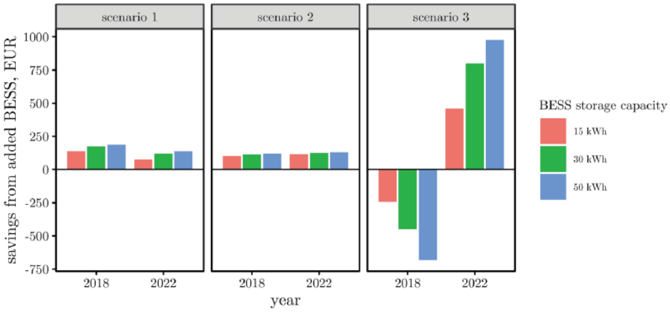

Fig. 12. Potential savings for three different scenarios with BESS. Years – 2018 and 2022 – represent different electricity prices based on which calculations have been made.

The analysis is conducted using the new tariffs of the DSO, as well as separately considering the 2018 and 2022 Nord Pool electricity exchange prices in the Latvian electricity trading area. Unlike the first case study, this analysis excludes the consideration of value-added tax. Figure 12 illustrates the potential savings of installing BESS across all three scenarios.

In the case of the first scenario, the results show that by creating an additional BESS system, marginally higher savings can be achieved in the case of a larger BESS capacity and lower electricity prices, which were lower in 2018 than in 2022 (the average price in 2018 was 49.89 EUR/MWh, while in 2022 it was 226.32 EUR/MWh).

When considering the second scenario, the results show that neither the BESS energy capacity nor the electricity prices of 2018 or 2022 lead to a significant difference in savings. Overall, the savings are very similar.

On the other hand, in the third scenario there is a significant discrepancy between savings made in 2018 and 2022, as a result of different electricity prices. At the prices of 2018, the savings were estimated to be negative, which could be related to the fact that in 2018 the changes in electricity prices during the day were relatively small, unlike in 2022. This scenario also highlights how the savings are affected by the choice of the energy capacity of the BESS system used; for example, in 2022, the difference in savings between the 15 and 50 kWh BESS is 500 EUR. In general, in 2022, the greater the installed BESS energy capacity was, the greater the savings were.

5. DISCUSSION AND CONCLUSIONS

Although the Cabinet of Ministers in Latvia is still in the process of developing detailed regulations (they have not yet come into effect) for the operation of the NETO settlement system, including the date at which the NETO settlement system will become available to customers, it is theoretically possible to predict how it will affect the potential savings from the use of decentralized electricity supply solutions.

When comparing yearly savings at the NETO accounting system without BESS to the NETO settlement system without BESS under the new DSO tariff, it is evident from the results that the difference in potential savings is not large and varies from +8 % to +15 % for the 2022/2023 and 2019/2020 electricity prices, respectively. For example, if we consider the 2022/2023 electricity prices, then in seven years one could save around 10 166 EUR and 11 079 EUR using the NETO accounting system and the NETO settlement system, respectively. Similarly, using the same approach, for the 2019/2020 electricity prices, the savings could be 2 459 EUR compared to 2 904 EUR. In the case of the NETO accounting system, it is worth considering a scenario with a fixed electricity price (150 EUR/MWh), which would result in potential savings of 6 690 EUR. Despite the significant potential for savings, the choice of the special tariff should be individually assessed with caution, as it offers benefits to the consumer only when their electricity consumption from the grid is exceptionally low.

The analysis has clearly shown that when electricity prices are higher, savings increase significantly. When this happens, there is less need for financial help from the government. Hence, it is reasonable to consider focusing the governmental support for cases when it is harder to make green solutions like BESS profitable, as this is where the help would be most effective. In addition, it can also be concluded from Figs. 8–11 that distribution tariffs can affect the payback of solar panels, but on a much smaller scale. In the case of the new DSO tariffs, the savings of the solar panel system will be higher compared to the old DSO tariffs.

When we compare the NETO accounting system with BESS to the NETO settlement system with BESS at the new or old DSO tariff, it is clear that the difference in potential savings is not very large either. For example, if we consider the 2022/2023 electricity prices and the new DSO tariff under the NETO settlement system around 14 800 EUR could be saved in seven years, while under the NETO accounting system it might be possible to save approximately 13 324 EUR. Similarly, using the same approach for 2019/2020, the savings could reach 5 127 EUR compared to 4 759 EUR. Under the NETO accounting system and with a fixed electricity price (150 EUR/MWh), it could be possible to achieve potential savings of 9 759 EUR. While there are cases when the savings could eventually cover the initial BESS system investment, in most situations, buying BESS may not lead to a quick payoff.

To improve the battery payback, different BESS management strategies have been considered, and the savings directly generated by an installed BESS system have been calculated.

In the first two scenarios, where BESS discharging is allowed at the first opportunity or during periods of higher electricity prices on the exchange for the relevant day, savings of 74 to 188 EUR (excluding VAT) could be achieved annually. While, if this BESS is allowed to charge from the grid and discharge at higher prices (by doing arbitrage), then BESS savings could reach 460–977 EUR per year. However, at the same time, it must be recognized that with the 2018 electricity prices, such a strategy would not pay off. On the contrary, it could cause losses that might have arisen from a not too large price difference on the electricity market. The results (see Fig. 12) indicate that the payback of BESS can be affected by both the energy capacity of the battery and price changes in the electricity exchange.

Based on the findings presented in this publication, it can be concluded that the hypothesis A has been neither right nor wrong. The savings from solar panels will mainly depend on the electricity market price rather than the NETO billing system. The evidence shows that the new payment system might be a slightly better economically when it comes to installing solar panels. On the other hand, the results support the confirmation of the hypotheses B and C. The analysis has demonstrated cases where installing BESS can actually save enough money to justify the investment. In addition, if BESS operations are managed effectively, it can result in even better savings.

ACKNOWLEDGMENTS

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Appendix VI

Towards climate neutrality: economic impacts, opportunities and risks

Friday, March 18, 2022 - Friday, March 18, 2022

Zoom

80th International Scientific Conference of the University of Latvia 2022

Report of Abstracts

/event/79/

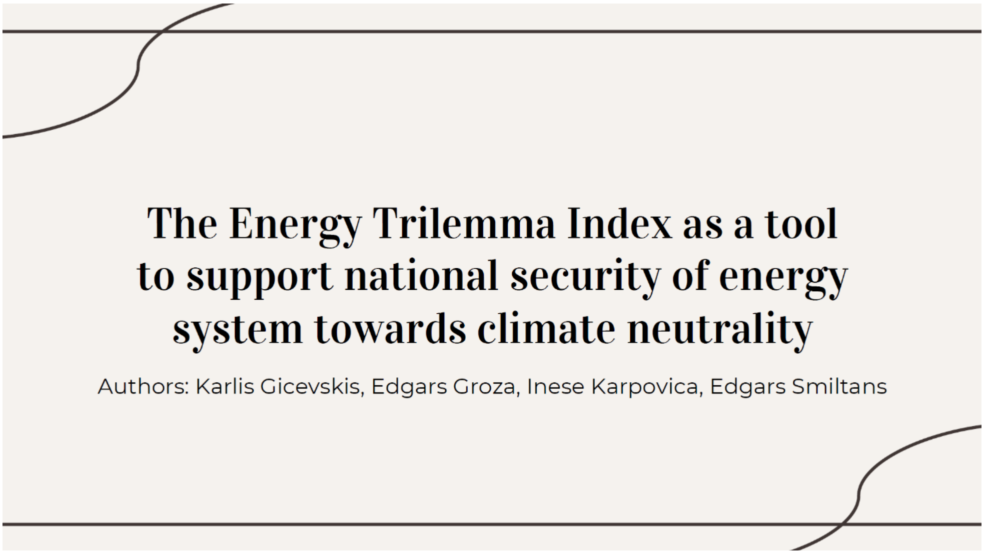
7

The Energy Trilemma Index as a tool to support national security of energy system towards climate neutrality

Author: Karlis Gicevskis[None]

Co-authors: Edgars Groza ; Inese Karpovica ; Edgars Smiltans

The World Energy Council's (WEC's) Energy Trilemma Index tool ranks 127 countries on their energy system performance through 3 dimensions: energy security, energy equity, environmental sustainability. The goal of the Index is to provide insights into a country's relative energy system effectiveness in each dimension and together. Highlighting challenges and opportunities for improvements, for example, regarding the transition to renewables, where new challenges might arise. Without disclosing original methodology of Energy Trilemma Index, this research reviews status quo of Latvian national energy security dimension. The aim of this study is to investigate Latvian energy security dimension to assist decision makers describing the key points that can move the energy sector onto safer ground. The dimension of energy security considers various sub-indicators that covers the effectiveness of management of domestic and external energy sources, along with the reliability and resilience of energy infrastructure. Up to ten-year period retrospective analysis of statistical records of those indicators as well as Latvian and foreign scientific and professional research studies was revised by authors and discussed with another 12 experts from a programme "The Future Energy Leaders Latvia" organized by the Latvian WEC committee. In conclusions, authors highlight most important opportunities and potential risks of no actions for Latvian energy security dimension. Authors also acknowledge need for new sub-indicators to represent an evolving energy system in transition.



The Energy Trilemma Index as a tool
to support national security of energy
system towards climate neutrality

Authors: Karlis Gicevskis, Edgars Groza, Inese Karpovica, Edgars Smiltans

Table of contents

01
Background
The Energy Trilemma
Index as a tool

02
Aim and methods
A look on how to upgrade
the energy sector

03
Analysis
Statistical records and
energy experts

04
Conclusion
Improvements still are
required

Background

<u>“The Energy Security Score“</u>

Country	Score
1.Canada	77.5
2.Finland	75.3
3.Romania	74.1
4.Latvia	**74.9**
5.Sweden	74.5

“The Energy Equity Score“

Country	Score
1.Qatar	99.9
1.Kuwait	99.8
1.UAE	99.8
2.Oman	96.6
2.Bahrain	99.6
44.Latvia	**78.1**

“The Environmental Sustainability Score“

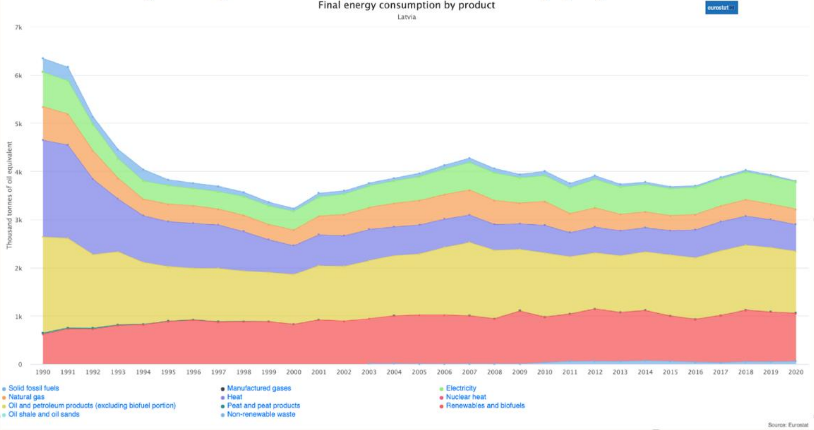
Country	Score
1.Switzerland	88.2
2.Sweden	86.3
3.Uruguay	85.4
4.Norway	84.4
5.Panama	83.7
34.Latvia	**70.9**

The aim and methods

Aim. The aim of this study is to investigate Latvian energy security dimension to assist decision makers describing the key points that can move the energy sector onto safer ground.

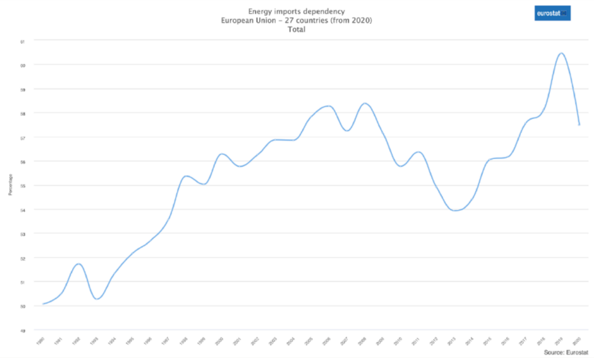
Methods. The dimension of energy security considers various sub-indicators that covers the effectiveness of management of domestic and external energy sources, along with the reliability and resilience of energy infrastructure. Up to ten-year period retrospective analysis of statistical records of those indicators as well as Latvian and foreign scientific and professional research studies was revised by authors and discussed with another 12 experts from a programme "The Future Energy Leaders Latvia" organized by the Latvian WEC committee.

Diversity of primary energy supply



Source: Eurostat

Import dependence

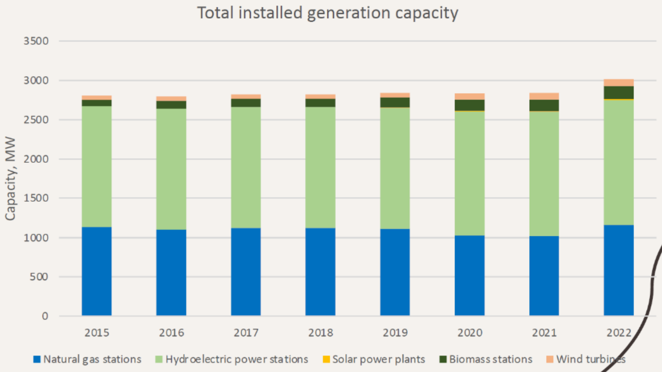


Diversity of suppliers

43 / 11

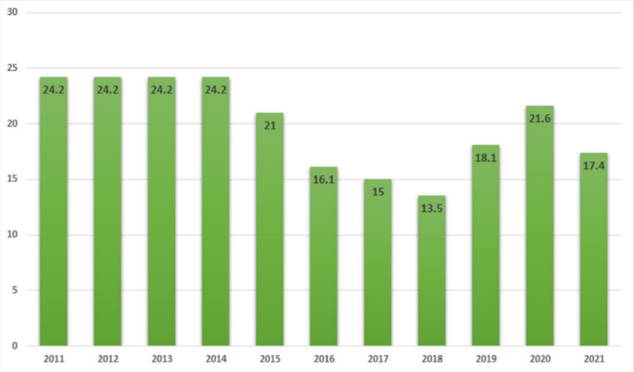
Increasing numbers of electricity and natural gas traders

Diversity of electricity generation



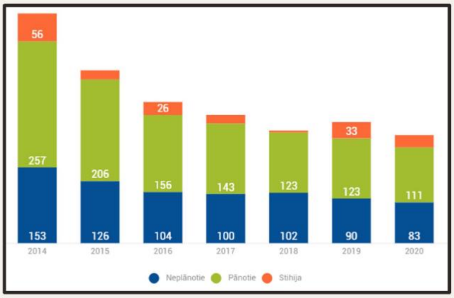
Energy storage for oil

Energy storage for gas

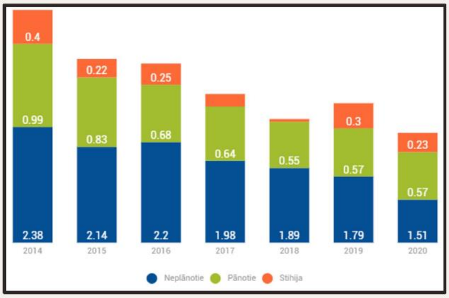


Amount of active natural gas at Inčukalns UGS after natural gas injection at the end of the season (TWh)

SAIDI and SAIFI

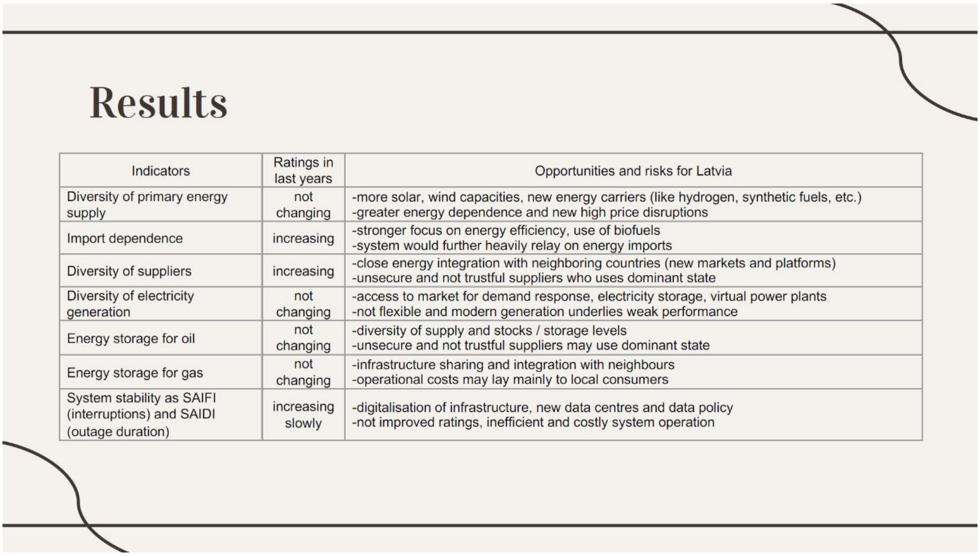


SAIDI:Average duration of power outages (min) per customer per year



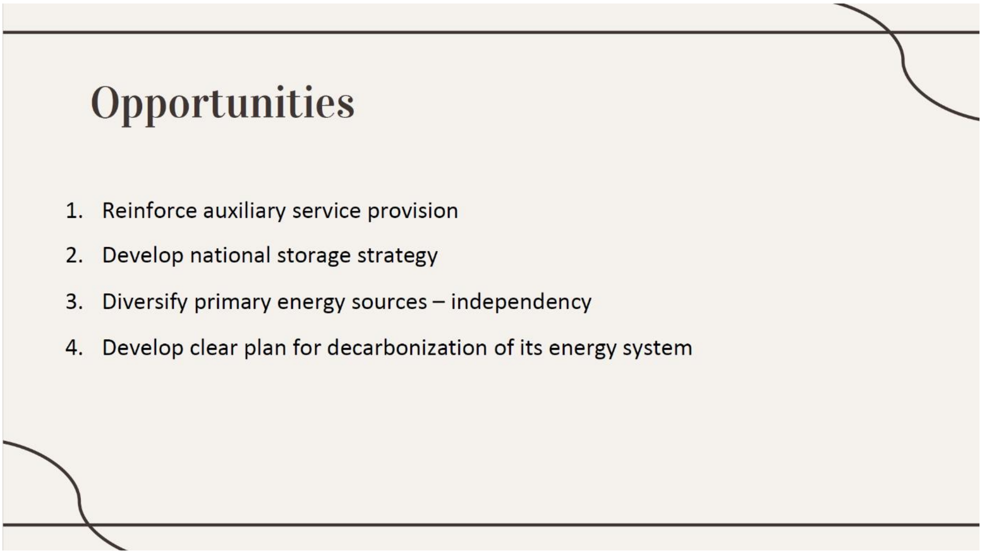
SAIFI: Average number of power outages per customer per year

- decreasing slowly



Results

Indicators	Ratings in last years	Opportunities and risks for Latvia
Diversity of primary energy supply	not changing	-more solar, wind capacities, new energy carriers (like hydrogen, synthetic fuels, etc.) -greater energy dependence and new high price disruptions
Import dependence	increasing	-stronger focus on energy efficiency, use of biofuels -system would further heavily relay on energy imports
Diversity of suppliers	increasing	-close energy integration with neighboring countries (new markets and platforms) -unsecure and not trustful suppliers who uses dominant state
Diversity of electricity generation	not changing	-access to market for demand response, electricity storage, virtual power plants -not flexible and modern generation underlies weak performance
Energy storage for oil	not changing	-diversity of supply and stocks / storage levels -unsecure and not trustful suppliers may use dominant state
Energy storage for gas	not changing	-infrastructure sharing and integration with neighbours -operational costs may lay mainly to local consumers
System stability as SAIFI (interruptions) and SAIDI (outage duration)	increasing slowly	-digitalisation of infrastructure, new data centres and data policy -not improved ratings, inefficient and costly system operation



Opportunities

1. Reinforce auxiliary service provision
2. Develop national storage strategy
3. Diversify primary energy sources – independency
4. Develop clear plan for decarbonization of its energy system

Conclusions

Table 3: Top 10 Rank Performers in Energy Security

TOP 10 RANK PERFORMERS		
Rank		Score
1	Canada	77.5
2	Finland	75.3
3	Romania	75.1
4	Latvia	74.9
5	Sweden	74.5
6	Brazil	73.5
7	United States	73.3
8	Bulgaria	73.1
9	Czech Republic	72.8
10	Germany	71.9

Source: World Energy Council

Improvements are required

New energy security issues

Clear plan for energy system development is needed

New indicators for security index assessment

Thanks

Do you have any questions?

https://www.facebook.com/NELLatvija

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Appendix VII

Pasaules enerģētikas trilemmas indekss: globālā pieredze lokālu risinājumu meklējumos

WORLD ENERGY COUNCIL | LATVIA

Pasaules Enerģijas padomes izstrādātais pasaules enerģētikas trilemmas indekss ir viens no pasaulē pazīstamākajiem indeksiem, ar kura palīdzību tiek mērīts dažādu valstu sniegums enerģētikā, un tas ļauj ērti salīdzināt tādas energoapgādes "disciplīnas" kā enerģētikas vides ilgtspēja, enerģētikas drošība un enerģijas pieejamība.

Bet vai indeksa izstrādē radīto metodiku un zināšanas ir iespējams izmantot par bāzi, lai veiktu vēl padziļinātāku analīzi un rosinātu precīzākus un fokusētākus rīcības ieteikumus jau konkrētas valsts līmenī? Pie šī jautājuma izpētes, risināšanas un priekšlikumiem ir ķērušies Pasaules Enerģijas padomes Latvijas komitejas paspārnē izveidotās programmas "Nākotnes enerģētikas līderi Latvijā" (NELL) dalībnieki – jaunie enerģētikas nozares uzņēmumu speciālisti.

Nav noslēpums, ka nereti valstis, neskatoties uz līdzīgu iegūto pasaules enerģētikas trilemmas indeksa vērtību, savu faktisko enerģētikas politiku īsteno ļoti dažādi, izvēloties daudzveidīgus politikas instrumentus. Spilgts piemērs tam ir Latvija un Lietuva, kuru uzrādītās indeksa vērtības ir samērā tuvas, turklāt Lietuva sasniegusi pat nedaudz augstāku vērtību, savukārt izvēlētie enerģētikas politikas instrumenti ir bijuši ievērojami atšķirīgi.

Jāatgādina, ka Lietuva vēsturiski lēnāk liberalizēja savu elektroenerģijas tirgu un elektroenerģijas apgādes jomā lielāku uzsvaru ir likusi uz pārvades jaudu attīstību un dabasgāzes infrastruktūras investīcijām. Savukārt Latvija ir veikusi salīdzinājumā lielākas investīcijas elektroenerģijas ražošanas jaudās un agrāk sākusi atvērt elektroenerģijas tirgu konkurencei. Kuri no politikas soļiem uzlabo valsts enerģētikas novērtējumu visstraujāk, un vai tie spēs nodrošināt labu sniegumu arī ilgtermiņā? Kuriem no politikas soļiem ir izrādījies vislielākais svars indeksa vērtības noteikšanā, un kā katrs no politikas soļiem ietekmē katru no enerģijas indeksa komponentēm, piemēram, ilgtspēju vai pieejamību? Tie ir tikai daži no jautājumiem, ar kuriem jāsaskaras pētniekiem, vērtējot un interpretējot valstu sniegumu, it īpaši paturot prātā, ka īsākā termiņā nereti līdzīgu rezultātu atsevišķās jomās var dot pat klaji atšķirīgi vai viens otru izslēdzoši politikas instrumenti.

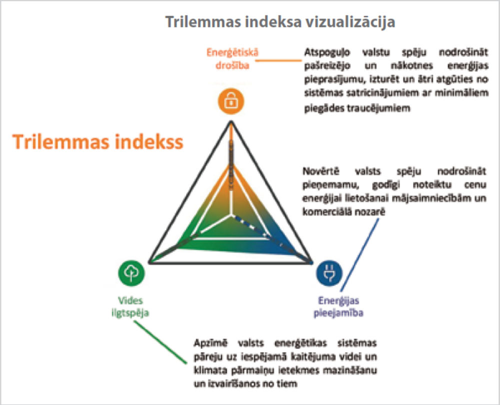
Piemēram, daudzu valstu pieredze rāda, ka enerģijas ekonomisko un sociālo pieejamību galalietotājiem var veicināt gan konkurences attīstība, gan cenu regulācija, gan arī nodokļu politika. Tomēr kurš no risinājumiem ir ilgtspējīgāks, industrijas un lietotāju intereses sabalansējošāks un kurš, savukārt, ir labvēlīgākais vides ilgtspējai?

Uz šiem jautājumiem atbildes bieži vien ir labāk meklēt jau nacionālā līmenī, jo tās var slēpties arī lokālos ekonomiskajos, sociālpolitiskajos un ģeogrāfiskajos faktoros, piemēram, valstij raksturīgajā klimatā, sociālajā struktūrā vai arī mājokļu kvalitātē. Tieši šo iemeslu dēļ enerģētikas trilemma ir neaizstājams instruments, kas mudina pētniekus un ekspertus no kopīgajām, globālajām un reģionālajām tendencēm un atziņām pakāpeniski pāriet uz jau lokālu atbilžu meklēšanu.

Kopš 2010. gada Pasaules Enerģijas padome (turpmāk – PEP) vērtē 128 pasaules valstis pēc vienotas metodoloģijas, lai izsekotu valdību pieņemto lēmumu ietekmi uz enerģētikas sistēmu kopumā un trim lielākajiem enerģētikas sektora izaicinājumiem, proti, enerģētikas drošumu, ilgtspēju un pieejamību.

Šo izaicinājumu novērtējumu kopums, kas ir atspoguļots ar noteiktiem statistikas rādītājiem no uzticamām datubāzēm, veido enerģētikas trilemmas indeksu. Pēc PEP enerģētikas trilemmas indeksa novērtējuma 2021. gadā Latvija ierindojās 20. vietā no 128 valstīm, pakāpjoties par divām pozīcijām salīdzinājumā ar 2020. gadu.

Atbilstoši PEP vērtējumam Latvijai ir ļoti laba situācija attiecībā uz “drošuma” dimensiju – Latvija ieņem ceturto no 128 vietām pasaules valstu reitingā. Latvijas enerģētikas trilemmas indeksa dimensijas “pieejamība” vērtība ir zemākā no Baltijas valstīm, aizņemot 44. vietu rangā. Savukārt “ilgtspējas” dimensijā Latvija ir ierindota 34. vietā.


Trilemmas indeksa vizualizācija

Atspoguļo valstu spēju nodrošināt pašreizējo un nākotnes enerģijas pieprasījumu, izturēt un ātri atgūties no sistēmas satricinājumiem ar minimāliem piegādes traucējumiem

Novērtē valsts spēju nodrošināt pieņemamu, godīgi noteiktu cenu enerģijai lietošanai mājsaimniecībām un komerciālā nozarē

Apzīmē valsts enerģētikas sistēmas pāreju uz iespējamā kaitējuma videi un klimata pārmaiņu ietekmes mazināšanu un izvairīšanos no tiem

Energoapgādes drošība

Veselīgas energosistēmas ir drošas, taisnīgas, ilgtspējīgas un videi draudzīgas, un tās demonstrē līdzsvaru starp visām trim trilemmas dimensijām: energoapgādes drošību, vienlīdzīgu pakalpojumu pieejamību un vides ilgtspēju [1].

Energoapgādes drošības dimensija nosaka valstu spēju apmierināt pašreizējo un turpmāko enerģijas pieprasījumu, izturēt un ātri atgūties no sistēmiskiem satricinājumiem ar iespējami mazākiem enerģijas piegādes traucējumiem. Šī dimensija aptver iekšējo un ārējo enerģijas avotu pārvaldības efektivitāti, kā arī enerģētikas infrastruktūras uzticamību un noturību [1].

Energoapgādes drošības indeksu veido trīs galvenie rādītāji:

- **imports** – valsts atkarība no energoresursu importa kopējā enerģijas patēriņā un piegādātāju dažādības;
- **elektroenerģijas ģenerācijas avotu daudzveidība** – ģenerācijas avotu daudzveidība, ar kuriem valstī tiek nodrošināta elektroapgāde;
- **enerģijas uzglabāšanas iespējas** – valsts spēja apmierināt savu enerģijas (dabasgāzes un naftas) pieprasījumu, ņemot vērā valstī pieejamo infrastruktūru, ieskaitot uzglabāšanas un pārstrādes jaudas [3].

Daudzas valstis joprojām lielā mērā paļaujas uz enerģijas importu, lai apmierinātu savu nepārtraukti augošo enerģijas pieprasījumu. Investīciju un resursu trūkuma, kā arī nestabilas elektroenerģijas ģenerācijas dēļ energoapgādes drošības līmenis tajās joprojām ir zems. Turklāt bieži vien starpvalstu politiskā neuzticēšanās apgrūtina starpsavienojumu un citu veidu enerģijas infrastruktūras attīstību.

Valstis, kuras koncentrējas uz izmantoto enerģijas veidu dažādošanu, energoefektivitāti un ieguldījumiem infrastruktūrā, uzlabo arī drošuma parametrus. Stabils resursu nodrošinājums, kā arī jau minētā enerģijas ģenerācijas avotu dažādošana un cieša enerģētikas infrastruktūras integrācija ar kaimiņvalstīm novērojama valstīs ar augstu energoapgādes drošumu. Ir skaidrs, ka šobrīd uzmanība jāpievērš arī tālākai iespējamajai dekarbonizācijai un zaļajam kursam, lai turpinātu resursu diversifikāciju un nodrošinātu lielākas iespējas valsts enerģijas pieprasījumu segt no vietējiem resursiem [2].

Latvija šobrīd ierindojas pasaules energoapgādes drošības *top 10* ceturtajā pozīcijā, kurā pārsvarā dominē citas Ekonomiskās sadarbības un attīstības organizācijas (OECD) un Eiropas Savienības (ES) dalībvalstis (skat. 1. tabulu).

Kanāda un Rumānija gūst labumu no tā, ka tās ir oglūdeņraža ieguvējas. Kanādai ir vairāk nozīmīgu un daudzveidīgu dabas resursu, savukārt Rumānija ir guvusi labumu no dalības ES, uzlabojot savu ener-

1. tabula

Pasaules energoapgādes drošības *top 10* (%)

	Valsts	%
1.	Kanāda	77,5
2.	Somija	75,3
3.	Rumānija	75,1
4.	Latvija	74,9
5.	Zviedrija	74,5
6.	Brazīlija	73,5
7.	ASV	73,3
8.	Bulgārija	73,1
9.	Čehija	72,8
10.	Vācija	71,9

Avots: PEP

ģētikas politiku un starpsavienojumu iespējas. Somija, iespējams, ir visinteresantākā no topa pirmo trīs pozīciju valstīm, tai ir mazāk dabas resursu, taču tā ļoti koncentrējas uz enerģētikas sistēmas dekarbonizāciju, samazinot fosilo un palielinot saules un vēja ģenerāciju. Savukārt mazākām Eiropas valstīm dalība ES ir izrādījies nozīmīgs veiksmes faktors enerģētiskās drošības uzlabošanai. Īpaši svarīgi tas ir bijis Baltijas valstīm, tajā skaitā arī Latvijai.

Enerģētiskā drošība kopumā tradicionāli centrēta ap naftu, bet trilemma piedāvā plašāku definīciju, ņemot vērā arī citus enerģētikas virzienus un noturības aspektus, kas rodas, enerģētikas sistēmām kļūstot decentralizētākām, digitalizētām un dekarbonizētākām. Bez šaubām, enerģētiskā drošuma definīcijai jāturpina attīstīties, ietverot jaunus risinājumus un iespējas, ko rada enerģijas pāreja.

Pandēmijas pieredze, iespējams, mainīs to, kā valstis uztver enerģētisko drošību. Enerģētikas sektors ir pierādījis, ka pandēmijas apstākļos spēj nepakļauties būtiskām svārstībām un nodrošināt pastāvīgu energoapgādi elektroenerģijas, siltuma un kurināmā veidā. Izgaismojas energosistēmas stabilitāte. Lai uzlabotu drošuma indeksu, būtu lietderīgi noteikt papildu kvantitatīvos rādītājus paralēli kvalitātes rādītājiem, piemēram, elastībai, līdzīgi kā tas ir ar SAIDI (vidējais elektroapgādes pārtraukumu ilgums (min.) vienam klientam gadā) un SAIFI (vidējais elektroapgādes pārtraukumu skaits vienam klientam gadā) [2].

Nesenais kiberuzbrukums *Colonial Pipeline* ir izgaismojis enerģijas piegādes sistēmu darbības traucējumu draudus un nepieciešamību apsvērt, kā attīstīt piemērotus un izmērāmus kiberdrošības darbības rādītājus. Līdz ar to būtiska loma tiek piešķirta arī kiberdrošībai, 2021. gadā pirmo reizi iekļaujot šo būtisko pozīciju padomes pasaules enerģētikas monitoringā [2].

Energoapgādes drošība Eiropā

No visiem trilemmā iekļautajiem rādītājiem energoapgādes drošībā vēsturiski vissliktākie rādītāji ir bijuši Eiropas reģionam. Tomēr kopējā energoapgādes drošības tendence ir augšupejoša, galvenokārt pateicoties enerģijas uzglabāšanas izmantošanas pieaugumam un elektroenerģijas ražošanas diversifikācijai.

Viens no būtiskākajiem energoapgādes drošības rādītājiem, kurā Eiropa joprojām nesasniedz globālo vidējo rādītāju, ir atkarība no importa. Kopš 2013. gada visas 27 ES dalībvalstis ir neto enerģijas importētājas. ES atkarības līmenis no enerģijas importa ir palielinājies no 56 procentiem 2000. gadā līdz 61 procentam 2009. gadā, un ES atkarība no trešām valstīm dabasgāzes piegādē pieaug ievērojami straujāk salīdzinājumā ar cieto fosilo kurināmo un jēlnaftu tajā pašā periodā.

Viens no ES Enerģētikas savienības pīlāriem ir palielināt starpsavienojumu jaudu, lai paaugstinātu pārrobežu enerģijas plūsmas. Savienojot pieprasījuma, piedāvājuma un uzglabāšanas jaudas lielos ģeogrāfiskajos apgabalos, starpsavienojumi sekmēs atjaunīgo enerģijas avotu izmantošanu, vienlaikus veicinot piegādes drošību. Arī energoresursu diversifikācija ir viens no energoapgādes drošības rādītājiem, kas jāuzlabo Eiropas enerģētikā.

Pieaugot bažām par elektroenerģijas pieprasījuma un piegādes līdzsvaru, ES var būt nepieciešami ilgtermiņa cenu signāli, kas veicinātu investīciju pievilcību. Ir vajadzīga arī enerģijas tirgus modeļu attīstība, lai nodrošinātu ilgtermiņa mehānismus, kas nepieciešami jaunām, dekarbonizētām ražošanas jaudām, stiprinot elektroenerģijas piegādes drošību Eiropā.

Izmantotie avoti

[1] https://www.worldenergy.org/transition-toolkit/world-energy-trilemma-index

[2]https://trilemma.worldenergy.org/reports/main/2021/World%20Energy%20Trilemma%20Index%202021.pdf

[3] https://trilemma.worldenergy.org/#!/country-profile?country=Latvia&year=2021

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Enerģijas pieejamība

Vēl viena no enerģētikas trilemmas dimensijām ir **enerģijas pieejamība**, kas ļauj izvērtēt valsts spēju nodrošināt vispārēju piekļuvi enerģijai, tās kvalitāti un cenu pieejamību gan mājsaimniecībām, gan komerciālajam sektoram. Enerģijas pieejamības dimensija tiek iedalīta trīs kategorijās – enerģijas piekļuve, piekļuve kvalitatīvai enerģijai, enerģijas cenu pieejamība un konkurētspēja – un tiek vērtēta pēc to rādītājiem (skat. 1. att.) [3].

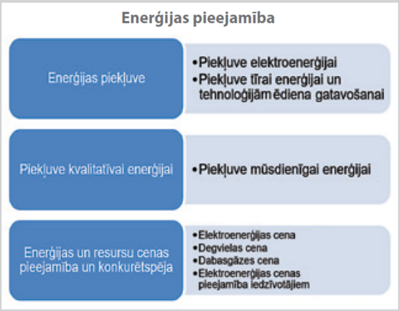
Piekļuvi enerģijai vērtē pēc šādiem rādītājiem:

- piekļuve elektroenerģijai – elektroenerģijas pieejamības nodrošināšana ir būtiska katras valsts ilgtspējīgai attīstībai un nabadzības samazināšanai. Rādītājs atspoguļo iedzīvotāju daļu, kuriem ir pieejama elektroenerģija;
- piekļuve tīrai enerģijai un tehnoloģijām ēdiena gatavošanai – rādītājs ir būtisks ilgtspējas attīstībai un nabadzības samazināšanai. Tas atspoguļo iedzīvotāju daļu valstī, kuri izmanto tīru kurināmo un tehnoloģijas ēdiena gatavošanai.

Piekļuvi kvalitatīvai enerģijai, savukārt, vērtē pēc rādītāja "piekļuve mūsdienīgai enerģijai". Tas atspoguļo informāciju par elektroenerģijas patēriņu mājsaimniecībā uz vienu iedzīvotāju gadā.

Enerģijas cenu pieejamību un konkurētspēju vērtē pēc šādiem rādītājiem:

- elektroenerģijas cenas – tiek ņemtas vērā mājsaimniecību elek-



Enerģijas pieejamība

Enerģijas piekļuve	•Piekļuve elektroenerģijai •Piekļuve tīrai enerģijai un tehnoloģijām ēdiena gatavošanai
Piekļuve kvalitatīvai enerģijai	•Piekļuve mūsdienīgai enerģijai
Enerģijas un resursu cenas pieejamība un konkurētspēja	•Elektroenerģijas cena •Degvielas cena •Dabasgāzes cena •Elektroenerģijas cenas pieejamība iedzīvotājiem

troenerģijas cenas un elektroenerģijas cenas industrijā;
- degvielas cenas – tiek ņemtas vērā benzīna un dīzeļdegvielas cenas;
- dabasgāzes cenas – tiek ņemtas vērā dabasgāzes cenas mājsaimniecībām un industrijā;
- elektroenerģijas cenu pieejamība iedzīvotājiem – atspoguļo iedzīvotāju spēju atļauties tērēt elektroenerģiju. Tas galvenokārt attiecas uz mājsaimniecībām, vietām, kurās iedzīvotāji uzturas ikdienā. Apakšrādītāju aprēķina tikai tām valstīm, kurās elektroenerģijas piekļuves līmenis ir lielāks par 90 procentiem.

Pirmajā tabulā sniegts pasaules valstu *World Energy Trilemma Index 2021 top 10* pēc enerģijas pieejamības rezultāta. Kā redzams, visaugstākais rezultāts ir Katarai, Kuveitai un Apvienotajiem Arābu Emirātiem (AAE), t. i., 99,9–99,8. Pārsvarā šajā topā redzamas valstis, kas ir bagātas ar fosilajiem un atjaunīgajiem energoresursiem. Gan Latvijas, gan Lietuvas un Igaunijas nav šajā sarakstā [4]. Atbilstoši aktuālajai informācijai par valstu profilu [3] Latvijā enerģijas pieejamība ir 78,1, kas atbilst 44. vietai pasaules valstu kopējā reitingā.

Tiesa, runājot par pieejamības rādītāja komponentēm, "fiziska pieejamība (piekļuve) enerģijai" Latvijā ir viena no labākajām pasaulē. "Piekļuve kvalitatīvai enerģijai" ir proporcionāli mazāks ietekmes rādītājs, un tas parāda mājsaimniecību elektroenerģijas patēriņu uz iedzīvotāju skaitu, tādējādi atspoguļojot elektroierīču daudzumu, ko iedzīvotāji izmanto, piesaistot to dzīves kvalitātei. Savukārt galvenais Latvijas izaicinājums ir saistīts ar "enerģijas dārdzību". [5]

1. tabula

Pasaules valstu *top 10* pēc enerģijas pieejamības rezultāta [4]

Rangs	Valsts	Enerģijas pieejamības rezultāts
1.	Katara, Kuveita, AAE	99,9–99,8
2.	Omāna, Bahreina	99,6
3.	Islande	99,2
4.	Luksemburga	99
5.	Īrija	98,4
6.	Šveice	98
7.	Saūda Arābija, Izraēla	97,4–97,4
8.	ASV	97,1
9.	Lielbritānija	96,8
10.	Dānija, Austrija	99,4

Enerģijas pieejamības vēsturiskā vērtējuma salīdzinājums

Enerģijas pieejamības pārmaiņas laika periodā no 2000. līdz 2021. gadam ir attēlotas otrajā attēlā, kurā 2000. gads ir bāzes gads (100%). 21 gada laikā enerģijas pieejamība Latvijā svārstījusies 5% robežās. Tādējādi var secināt, ka valstī enerģijas pieejamība ir stabila, pat ar mērenu uzlabojumu tendenci. Tā pamatā ir pieņemamas, lai gan ne īpaši zemas, benzīna un elektroenerģijas cenas (skat. 3. att.). Tomēr šajā periodā novērojams arī viens rādītāja pasliktinājums 2007. gadā.

Salīdzinot enerģijas pieejamības pārmaiņas Latvijā un kaimiņos – Lietuvā un Igaunijā –, var secināt, ka Latvijas pārmaiņu raksturs vairāk līdzinās Lietuvai. Kaut arī visās trijās valstīs pārmaiņu tendence raksturojama kā augoša, Igaunijā tas izteikts ievērojamāk. Tomēr visu triju valstu enerģijas pieejamības dimensija 2021. gadā novērtēta ar B līmeni.

Pašreizējās situācijas vērtējums Latvijā

Piekļuves elektroenerģijai rādītājs Latvijai tiek balstīts uz Pasaules Bankas datiem, un, kopš ir pieejama šī rādītāja vēsture, tā vērtība vienmēr sasniegusi 100 procentu, tātad šajā rādītājā Latvija vienmēr gūst augstāko iespējamo vērtējumu un spēj konkurēt ar jebkuru pasaules valsti.

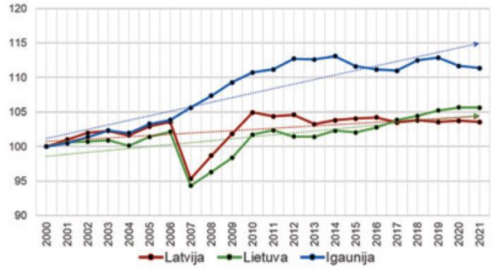
Arī apakšrādītājs "elektroenerģijas cenu pieejamība" Latvijas gadījumā ir stabils un nemainīgs ar vērtējumu 100 procentu. Saskaņā ar PEP metodoloģiju šī rādītāja vērtība pat pārsniedz noteikto diapazonu un līdz ar to saņem augstāko vērtējumu.

Starp reģioniem un dažādām ienākumu grupām reģionā var būt atšķirīga enerģijas pieejamība. Tas rodas no ļoti nevienmērīga ienākumu sadalījuma valsts iekšienē, sadales tīkla pārklājuma vai ģeogrāfisku aspektu dēļ. Pieejamība un pieejamības rādītāji ir nepārprotami attīstības rādītāji, un, vērtējot valsti kopumā, tie ir augstā līmenī. [6] Pēdējos gados ir vērojams alternatīvo energoresursu izmantošanas palielinājums, it sevišķi mājsaimniecību sektorā, ko stimulē draudzīgākas tehnoloģiju cenas un to fiziskā pieejamība Latvijas tirgū. Paredzams, ka 2021. gada elektroenerģijas cenu satricinājuma dēļ arvien plašāku popularitāti gūs elektroenerģijas piegādes diversifikācija un patēriņa cenas balansēšana.

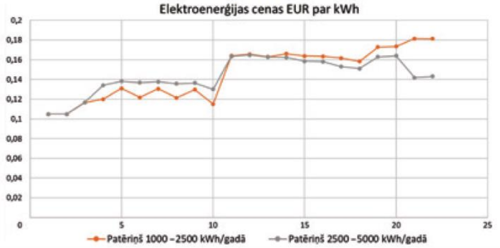
Avotu lietojums trilemmas dimensijas un tās rādītāju noteikšanai

Trilemmas rādītāju noteikšanai tiek izmantoti tikai jaunākie dati, kas ir ne vairāk kā divus trīs gadus veci. Tiek lietoti ārzemju, piemēram, Pasaules Bankas un Starptautiskās Enerģētikas aģentūras avoti. Datu avoti ir ļoti informatīvi: pirmkārt, tajos ir pieejama vēsturiskā informācija, otrkārt, datus ir iespējams lejupielādēt dažādos formātos, kā arī iegūt to grafisko attēlojumu, treškārt, var veikt salīdzinājumu un lejupielādēt gatavas atskaites, lietojot filtrus un izvēlnes. Informācija tiek iegūta gan no publiski pieejamajiem datu avotiem, gan no ierobežotas piekļuves materiāliem. Ņemot vērā, ka informācija par vienu un to pašu rādītāju dažādos datu avotos var atšķirties, nacionālā līmeņa trilemmas indeksu kopsavilkums atspoguļotu objektīvāku valstu vērtējumu ar lielāku precizitāti un aktualitāti.

Enerģijas pieejamības pārmaiņas laikā no 2000. līdz 2021. gadam Latvijā, Lietuvā un Igaunijā [3]



Elektroenerģijas cenu pārmaiņas mājsaimniecībām Latvijā 2010.–2021. gadā



Izmantotie avoti
[1] CSB dati
[2] World Energy Trilemma Index. Methodology
[3] https://trilemma.worldenergy.org/#!/country-profile?country=Latvia&year=2021
[4] World Energy Trilemma Index, 2021
[5] Latvijas produktivitātes ziņojums: http://eppi.lza.lv/wp-content/uploads/2021/01/LPZ_2020_.pdf

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Vides ilgtspēja

Nav nekāds noslēpums, ka jebkuram vides piesārņojumam ir sava cena. Gan vērtējot individuāli – cilvēka līmenī, kad par to maksājam ar veselību –, gan plašākā izpratnē – uzņēmumu līmenī, kad maksājums jau ir mērāms naudā. Pasaules Enerģijas padomes trilemmas indeksa sastāvdaļa – **vides ilgtspēja** – mēra valsts energosistēmas darbības ietekmi uz vidi un klimata pārmaiņām, novērtējot, cik valsts enerģētikas sektors ir spējīgs mazināt vai izvairīties no vides stāvokļa pasliktināšanās.

Vides ilgtspēju, līdzīgi kā iepriekšējās trilemmas sastāvdaļas, mēra pēc noteiktiem kritērijiem. Vides ilgtspējas kritēriji tiek iedalīti trīs lielākos blokos:

- resursu produktivitāte, kas ietver tādus kritērijus kā energoefektivitāte, enerģijas ražošanas, pārvades un sadales efektivitāte;
- dekarbonizācija, kas ietver siltumnīcefekta gāzu emisiju pārmaiņas un zemu oglekļa emisiju enerģijas ražošanu;
- emisijas un piesārņojums, kas ietver oglekļa dioksīda (CO_2) intensitāti, CO_2 daudzumu uz vienu iedzīvotāju, metāna (CH_4) emisijas no izlietotās enerģijas un cieto daļiņu emisijas.

Lai valsts uzlabotu savus rādītājus šajā trilemmas sadaļā, tai ir jāizstrādā stingra enerģētikas politika un, pats galvenais, jāpieturas pie tās ieviešanas. Svarīgs aspekts, kas spēj uzlabot ilgtspējas rādītāju, ir enerģijas ražošanas avotu dažādošana, par primāriem izvēloties atjaunīgos enerģijas avotus.

Vēsturiski trilemmas indeksa ilgtspējas topu augšgalā vienmēr ir atradušās Eiropas valstis, sevišķi Skandināvijas valstis, kuru enerģētikas politikā jau vairākas desmitgades tiek likts uzsvars uz atjaunīgajiem resursiem enerģijas ražošanā un CO_2 emisiju samazināšanu. Periodā no 2013. līdz 2017. gadam arī Latvija bija minēta starp piecām pasaules valstīm ar vislabākajiem sasniegumiem zema oglekļa elektrības ģenerācijas pieaugumā.[1] 2020. gada ziņojumā ar nelielu relatīvi negatīvu tendenci Latvijai ir atzīmēta gan energoresursu produktivitāte, gan dekarbonizācija, gan emisijas un piesārņojums. Šī tendence norāda uz faktu, ka arī turpmāk Latvijai svarīgi pievērst uzmanību ilgtspējas jautājumu risināšanai.

Ja raugāmies uz valstīm ar vislielāko progresu šajā jomā, šajos topos parasti nonāk valstis no Vidusāzijas un Āfrikas, jo salīdzinājumā ar 2000. gadu šīm valstīm rādītāji vienmēr bijuši krietni zemāki nekā attīstītajām Eiropas valstīm.

Rezultāti un attīstības virzieni 2021. gadā

Pasaules enerģētikas nozare pēdējos divos gados ir piedzīvojusi milzīgas izmaiņas, jo valstīm ne tikai jāturpina veidot ilgtspējīgu enerģētikas politiku, bet arī jāatkopjas no pandēmijas radītajām sekām un tiem procesiem, kas saistīti ar cilvēku paradumu maiņu.

Sakarā ar iepriekšminētajiem apstākļiem 2021. gadā vides ilgtspējības uzlabošana daudzām valstīm izrādījās problemātiska.

Viena no ievērojamākajām indeksa uzlabotājām ilgtspējības jomā bijusi Dānija, kura būtiski palielinājusi atjaunīgo enerģijas avotu izmantošanu. Šobrīd ar vēja stacijās saražoto elektroenerģiju tā spēj segt aptuveni pusi no valsts elektroenerģijas patēriņa. Ļoti labus rezultātus ir uzrādījusi arī Azerbaidžāna, kura ir uzlabojusi savu enerģijas un emisiju intensitāti. Savukārt Ķīna ir bijusi lielākā investore atjaunīgās enerģijas tehnoloģijās pēdējo desmit

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[1] World Energy Council, Wyman O. (2019) World Energy Trilemma Index 2020. London: World Energy Council, 2019 – 79 p. Pieejams: https://www.worldenergy.org/publications/entry/world-energy-trilemma-index-2019

1. tabula

Energoveiktspējas uzlabotāju *top 10* 2021. gadā

	Valsts	Uzlabojums, %
1.	Dānija	30
2.	Azerbaidžāna	28
3.	Ukraina	22
4.	Mjanma	22
5.	Taizeme	22
6.	Ķīna	21
7.	Īrija	20
8.	Panama	20
9.	Malta	20
10.	Serbija	19

gadu laikā, taču straujais enerģijas patēriņš enerģijas dekarbonizācijas procesu ir līdzsvarojis. *Top 10* ilgtspējas rādītājos joprojām dominē Eiropas valstis ar augstu atjaunīgās enerģijas ražošanas un energosistēmas efektivitātes līmeni.

Latvijas situācijas vērtējums

2021. gada ilgtspējas indeksa sarakstā Latvija ieņem 34. pozīciju. Salīdzinājumam jānorāda, ka mūsu dienvidu kaimiņi Lietuva ieņem 14. pozīciju, savukārt Igaunija – 39. pozīciju.

Laika posmā no 2000. līdz 2021. gadam vides ilgtspējas rādītājam Latvijā pārsvarā raksturīga mērena uzlabojumu tendence. Tomēr šajā periodā novēroti arī trīs rādītāja tendenču pasliktināšanās gadījumi 2005., 2013. un 2021. gadā (skat. 2. att.).

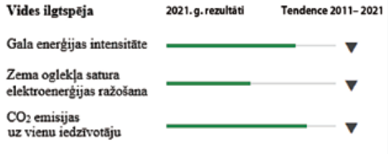
Detalizētāk izskatot Latvijas 2021. gada veikumu vides ilgtspējas kontekstā, būtu jāmin, ka visām trim tā sastāvdaļām – gala enerģijas intensitātei, zema oglekļa satura elektroenerģijas ražošanai, CO_2 emisijām uz vienu iedzīvotāju – bija raksturīga samazinājuma tendence, salīdzinot ar 2011.–2021. gada periodu (rādītāji tiek noteikti samērā ar citām valstīm, un pilna josla veido 100 punktus) (skat. 3. att.).

2. tabula

Energoveiktspējas līderu *top 10* 2021. gadā

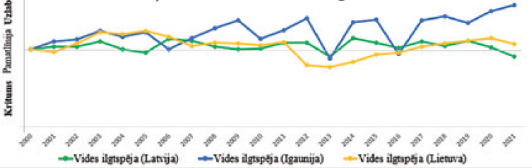
	Valsts	Vērtējums, p.
1.	Šveice	88,2
2.	Zviedrija	86,3
3.	Urugvaja	85,4
4.	Norvēģija	84,4
5.	Panama	83,7
6.	Brazīlija	83,4
7.	Dānija	82,9
8.	Francija	82,7
9.	Albānija	82,5
10.	Lielbritānija	81,3

2. att. Latvijas vides ilgtspējas rādītāja 2021. gada rezultāti



Latvijai ir lielākais ārpus emisijas kvotu tirdzniecības sistēmas (ETS) siltumnīcefekta gāzu (SEG) emisiju īpatsvars starp Baltijas valstīm, kas ir arī otrs augstākais rādītājs Eiropas Savienībā. SEG emisijas ārpus ETS darbībām galvenokārt veido lauksaimniecības un transporta jomas. Oglekļa izmešu mazināšanai ir ārkārtīgi svarīgi izveidot un uzturēt vienotu (harmonizētu) skatījumu par dekarbonizācijas iespējām Baltijas valstīs un vienotu pieeju dekarbonizācijas pasākumu īstenošanai. Tomēr vienotas pieejas izmantošana dekarbonizācijas pasākumu īstenošanai varētu būt sarežģīta, jo katrā valstī ir atšķirīgas enerģijas struktūras un galvenie SEG emisiju avoti.

3. att. Baltijas valstu vides ilgtspējas rādītāju tendenču izmaiņu virzieni, 2000. – 2021. gads [1]



Turpmāk darba grupa plāno padziļināti analizēt Latvijas negatīvo ilgtspējas tendenču rādītājus, kā arī sniegt priekšlikumus to uzlabošanai.

Izmantotie avoti

[1] WEC. Country Profile. Latvia. https://trilemma.worldenergy.org/#!/country-profile?country=Latvia&year=2021
[2] WEC. World Energy Trilemma Index 2021 Report

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Kopsavilkums

NELL programmas dalībnieki tuvākajos mēnešos veiks dziļāku PEP enerģētikas trilemmas indeksa metodikas izvērtējumu un pievērsīsies Latvijas trilemmas indeksa analīzei, pieejamajiem statistikas datiem, indeksa sastāvdaļām un to tendencēm. NELL dalībnieki jau ir identificējuši vairākus neskaidrus jautājumus gan par datu avotiem, gan par to interpretācijas iespējām un ir apkopojuši jomas, kurās ir iespējams veikt metodikas labojumus un piedāvāt risinājumus.

Savukārt ilgtermiņa mērķis ir izstrādāt Latvijas enerģētikas trilemmas metodoloģiju un veikt Latvijas situācijas vērtējumu, tai skaitā apskatot vēsturiskos datus. Enerģētikas trilemmas indekss var kļūt par papildu instrumentu Latvijas enerģētikas novērtējumam, prioritāšu definēšanai, risinājumu meklēšanai un nozares politikas plānošanai. E&P

**Edgars Groza, Kārlis Gičevskis, Edgars Smiltāns,
Inese Karpoviča, Gunārs Valdmanis**

Latvia's energy supply and security

The paper focuses on one of the Trilemma Index dimensions – Energy security. The criteria that are impacting the energy security dimensions score the most are reviewed. The review focuses on the current state of the energy system, the current and future issues, possible solutions and suggestions to maintain and increase the energy security dimension's score. The data mostly are obtained from public sources, market reviews, statistical databases. The authors would like to express their gratitude to an executive committee of programme "Future Energy Leaders in Latvia". This research was also supported by Riga Technical University's Doctoral Grant programme.

1. Energy Security Trilemma Index

Energy systems security defines the energy systems ability to satisfy current and futures energy demand. It shows its ability to maintain stability in different scenarios, to recover from disruptions with the least outages of power supply. Energy systems security covers the efficiency of the management of local and external energy sources, as well as the reliability and sustainability of energy infrastructure[1]. World energy council (WEC) has developed a methodology how to measure country's ability to maintain energy security.

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[1] World Energy Council (2022). World Energy Trilemma Index 2021. Available: https://www.worldenergy.org/publications/entry/world-energy-trilemma-index-2021

2. WEC methodology

Latvia is among the top 5 countries in the world according to the current Trilemma score on the Energy security index. Globally, energy security index is focusing on oil and other fossil fuels. Although fossil fuels have been a resource Latvia is importing, well diversified power generation portfolio has granted this high score. Energy security index includes other important criteria that have a positive effect on overall system and its stability.

Three main pillars can measure energy systems security in the context of Trilemma Index:

a) import – national dependency on resource import in the total energy consumption and supplier diversification;
b) energy generation capacities and their diversity – country has well balanced and diversified generation portfolio;
c) energy storage capabilities – countries ability to satisfy its energy demand, in accordance with the available infrastructure.

Energy resource availability, economic development, technological development, investment flow, well designed energy market, ability to react on disturbances: these are few aspects that characterizes energy systems security index and are evaluated within WEC methodology.

Daniel Yergin, an American author, economic researcher and energy analyst, has argued that energy security cannot be viewed as independent criteria in separate country: it needs to be seen in a broader context between different countries, and attention needs to be paid to how the energy system between these countries interact[2]. Therefore, also in the context of Latvia, one of the directions of the research is regional cooperation, which is at the same time one of the basic principles of the Energy Union. It is the case of the Baltic states that demonstrates that the integration of energy infrastructure through the interconnection of pipelines and the interconnection of electricity networks between the EU Member States is necessary for the functioning of the EU's common energy market and the strengthening of energy security in the region.

3. Case of Latvia: The current state of energy system

Latvia's final energy consumption consists of the following resources: solid fossil fuels, electricity, natural gas, heat, oil products, peat products, renewable resources and biofuels, non-renewable waste. Based on Eurostat data, Latvia has reduced its

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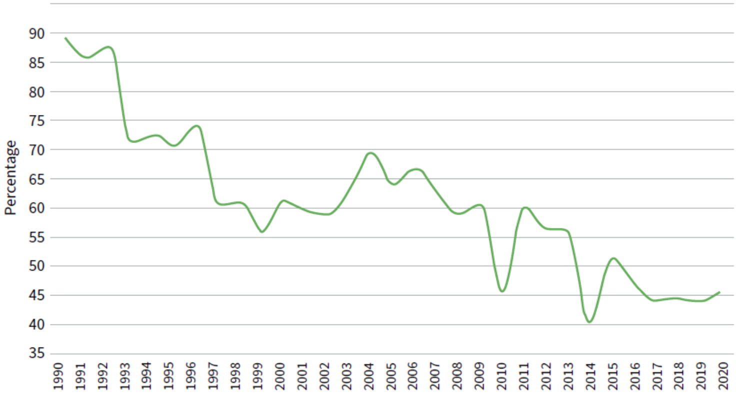
[2] Yergin, D. (2006). Ensuring Energy Security. *Foreign Affairs, 85*(2), 69–82. https://doi.org/10.2307/20031912

Figure 1. **Energy imports dependency of Latvia**



Source: Eurostat

solid fuel consumption by 50% since 2015. There are also changes in the use of renewable resources and biofuels. Consumption of other resources has not changed significantly in the last five years.

Looking at the total consumption of energy resources, it can be observed that the total consumption of renewable energy resources in Latvia is increasing, which allows to approach the goals set by the European Union ensure at least 50% share of renewable energy in Latvia's final energy consumption until 2030 and become climate neutral by 2050.

According to Eurostat data, Latvia has an average high dependence on energy imports (~45%). The most important imported resources are natural gas, oil products, biofuels and electricity, which a few years ago had not such a huge impact on energy security.

4. Raw resources

4.1. Gas

Within ten years (2011–2020), the share of natural gas consumption decreased by 8.7 percentage points and in 2020 was 20.6%. Along with the decrease in natural gas consumption, the volume of imported natural gas has also decreased, which is largely related to the use of alternative fuel resources and the promotion of energy efficiency measures as well as increase of CO_2 emission price for gas users. Despite the decrease in this share, natural gas still plays an important role in Latvia's total energy consumption. Most natural gas is used to produce electricity and heat in boiler houses and cogeneration plants. At the same time, it should be kept in mind that natural gas consumption in Latvia is seasonal, as, for example, the high demand for natural gas in 2020 can be explained by relatively low outdoor temperatures during the months of the heating season. Additionally, the overall natural gas demand was influenced by several other factors – low natural gas price in first two quarters of the year, which contributed to the higher usage of natural gas in power production, and malfunction of one of largest natural gas power plants in Latvia in the last two quarters of the year, which limited the usage of natural gas for power production in respective period. In 2021, the volume of gas consumed for the needs of Latvian users was 12.5 TWh[3], which represents 8% over the indicator of 2020. Increase in consumption was influenced by climatic conditions in winter, as the average air temperatures dropped to –2.8 °C, which is 0.4 °C below the seasonal norm, furthermore, January and February saw the harshest frost in the recent years[4]. At the same time, the cold climatic conditions raised natural gas consumption for electricity production – the year of 2021 shows higher volume of electricity produced by thermal power stations – JSC Augstsprieguma tīkls (AST) data)[5].

An integrated and liquid natural gas market between LV, EE and FI exists since beginning of 2020, and Lithuania is planning to join in 2023[6].

As there is reasonable amount of gas suppliers around the globe, the lack of their diversity can be seen as a threat in a short term. The Baltic states have quite good pipeline grid and at the same time the problem is that the infrastructure is built mostly for gas supply from Russia, after the completion of Klaipeda LNG terminal in 2014, Balticconnector gas pipeline between Estonia and Finland in 2020 and the GIPL pipeline interconnection between Lithuania and Poland this year. But still in conditions where gas supply is used as a weapon, reorientations cannot happen so smooth and fast. Shortage of infrastructure capacity in Baltics (as well as in Finland and Poland) is rather high – the capacity of Klaipeda LNG terminal is insufficient to cover consumption of the region – Lithuania, Latvia,

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[3] AS "Conexus Baltic Grid" (2022). Dabasgāzes pārvades sistēmas operatora ikgadējaā novērtējuma ziņojums par 2021. gadu. Rīga. Available: https://www.conexus.lv/uploads/filedir/Zinojumi/PSO_zinojums_2022_LV.pdf

[4] SLLC Latvian Environment, Geology and Meteorology Centre (2022). Available: https://klimats.meteo.lv/laika_apstaklu_raksturojums/2021/gads/

[5] AS "Augstsprieguma tīkls" (2021). Available: https://www.ast.lv/lv/electricity-market-review?year=2021&month=13

[6] Connexus Baltic Grid (2021). Available: https://conexus.lv/vienotais-dabasgazes-tirgus

Estonia and Finland. Additional terminal is needed. Consequently, there is a plan to build it in Estonia as well as in Finland. There are discussions and feasibility study exploring the potential for development of LNG terminal also in Latvia, however, thus far no decision has been made. It can be expected that the share of Russian pipeline gas will be replaced mostly with LNG and biomethane until the end of 2022.

4.2. Electricity

4.2.1. Market

At the end of 2021, electricity prices set new historical monthly average price records, resulting in 2.6 times higher average yearly electricity price (88.78 EUR/MWh). The rise in electricity prices was driven by several factors including rise of natural gas and CO_2 emissions prices (setting record price 92.37 EUR/MWh and 80.10 EUR/tCO_2), low wind power generation in Europe, lower water levels in Scandinavia.

On 22 May 2022, electricity trading with Russia has been stopped, leaving only technical capacities for grid balancing.

Specifically, in Latvia in year 2021 the generated amount of electricity has risen by 1.8% what is 5.6 TWh and the demand has risen by 3.5% reaching 7.4 TWh. Hydro power stations have generated 4.2% more and cogeneration stations 10.7% more than in 2020. All other generation capacities have shown much smaller contribution comparing to the previous years, which can be explained with changes in subsidized energy scheme as well as with the depletion of some of production capacities. These events in combination with situation in neighbouring countries has led to increase of electricity import to Baltics to around 50%.

On 17 August 2022, Baltic electricity market set new record on highest ever electricity price reaching 4000 EUR/MWh. The sharp rise in prices is caused by the limited supply of electricity in the Baltic market – it is limited both by the repair of the dams of the Daugava HPP, as a result of which the large hydropower plants in Latvia produce little due to the low water level, the availability of gas and its high prices for the production of electricity in cogeneration plants, and also the decision to stop importing electricity from due to the sanctions imposed on it by Russia.

The limited volume of production contributed to the increase in imports to the Baltic states. From the countries of the European Union, a total of 1 138 716 MWh of electricity was imported into the Baltics[7].

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[7] AS "Augstsprieguma tīkls" (2022). Available: https://www.ast.lv/lv/electricity-market-review

4.2.2. End users

The Latvian electricity market has been fully liberalized since 1 January 2015, which means that households and commercial electricity users are free to choose a trader by agreeing on an electricity price. Based on the data of the Electricity Trade Register of the Public Utilities Commission, a total of 43 electricity traders were registered in November 2021.

Electricity market participants, which include electricity producers, traders, aggregators, end-users, operate in the electricity market and their trading transactions cover the supply of electricity from the electricity producer to the user. The above transactions take place in the wholesale of electricity and then in the retail sale of electricity. Amendments in the Electricity Market Law identifies new entities – prosumers and energy communities, which expands the market participant options to involve in the electricity generation. End users in Latvia can cover their consumption by installing microgeneration and work in cooperation with distribution system operator (DSO).

4.2.3. Generating capacities

The installed generation capacity in Latvia has not changed much in recent years in total 3015 MW. Since 2015, generation capacity has increased by 209 MW. Of which RES capacity has risen by 183 MW in the last 7 years, but natural gas power plant capacity – by 26 MW.

It should be mentioned that the distribution (DSO) and transmission system operator (TSO) have issued technical regulations for the connection of new generating capacity of more than 4 GW, including solar and wind power plants.[8]

Latvia's power generation portfolio consists of hydro powerplants, natural gas power plants, biogas power plants, wind power plants and sun power plants (see Figure 3) all together crafting well diversified and balanced generation portfolio. This list excludes microgeneration (around 36 MW[9]). Unfortunately, the installed capacity now is insufficient to completely cover internal countries electricity demand.

4.2.4. Electricity import

By looking at the load of generation units by months, it can be observed that the generation capacity is the least loaded in June, July and August – respectively, when there is the lowest water flow in local river Daugava and it is not profitable to operate gas power plants (neither cogeneration nor condensation mode).

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[8] AS "Augstsprieguma tīkls" (2022). Available: https://ast.lv/lv/content/pieslegumu-ierikosanas-un-atlautas-slodzes-izmainu-statuss

[9] AS "Sadales tīkls" (2022). Elektroapgādes apskats. Available: https://sadalestikls.lv/lv/elektroapgades-apskats

Figure 2. Total installed electricity generation capacity

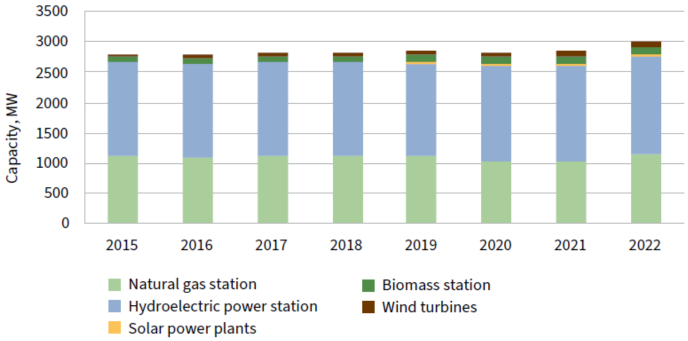
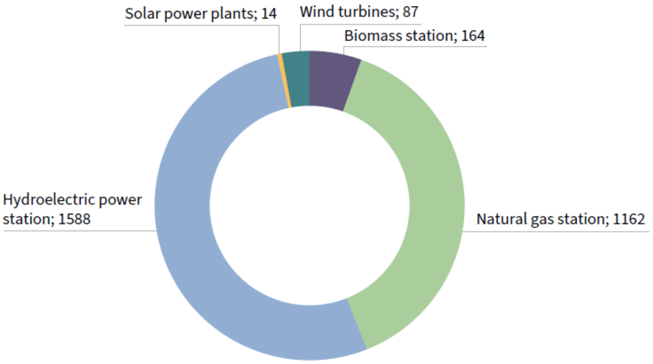
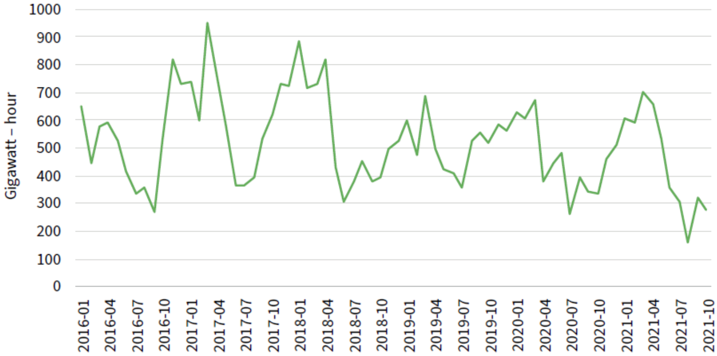


Figure 3. Generation capacities in 2022 (MW)



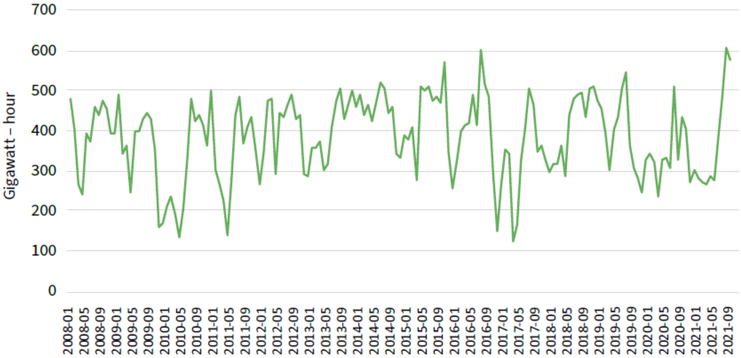
The amount of electricity produced in these months is low, so electricity is imported through interconnectors. Net electricity imports are shown in the Figure 5. In 2019, the maximum interconnection capacity of the Latvian transmission network available for electricity import/export was 947 MW from Estonia to Latvia and 879 MW from Latvia to Estonia. 684 MW from Lithuania to

Figure 4. **Net electricity generation in total**



Source: Eurostat

Figure 5. **Net imports of electricity in Latvia**



Source: Eurostat

Latvia and 1302 MW from Latvia to Lithuania. Since May 2022, there is no import from the third countries. Only necessary technical flows are current to operate the network

4.2.5. Interconnections (BRELL)

The operator of the Latvian electricity transmission system operator AST is responsible for the reliability of electricity supply and for the modernization and development of the transmission network. The most important realized and ongoing development projects can be seen in the table.

Table 1

Project	Kurzeme arc	Riga TEC-2 – Riga HES	EE-LV interconnection	Synchronization Phase 1			Synchronization Phase 2
				Valmiera-Tartu	Valmiera-Tsirgulina	Systems synchronous and intertia equipment	
Planned impl. year	2019	2020	2021	2023	2024	2025	2025
Planned CAPEX	128 MEUR	15 MEUR	83 MEUR	23 MEUR	22 MEUR	32 MEUR	100 MEUR
Total length	214.3	13	180	49	49		

In order to ensure safe operation of the Latvian electricity system, efficient functioning of the electricity market, and to prevent equipment obsolescence, the Latvian electricity TSO reconstructs and modernizes high-voltage substations and electricity distribution points. Observing the development trends of electricity systems of Latvia and neighbouring countries, Latvian electricity TSO evaluates and decides on the development of interconnections of the Latvian electricity transmission system, as well as the need to strengthen and modernize the internal network[10].

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[10] AS "Augstsprieguma tīkls". Available: https://ast.lv/lv/development-projects/parvades-tikla-modernizacija-un-attistiba

The Baltic states have historically worked and are currently working synchronously with the electricity systems of Russia and Belarus. The goal of synchronization is to start the Baltic electricity system's synchronous work with Europe and reduce dependence on decisions made outside the European Union. Synchronization will increase the ability of Baltics to constantly manage its electricity system, ensuring the balance between production and consumption, managing the necessary safety reserves, as well as regulating electricity flows and frequency without the involvement of countries outside the European Union. The most important benefit is security, because as a result of synchronization, the Baltic electricity transmission system will become a part of the European system, which means significant independence from Russia and more secure electricity supply[11].

4.2.6. Storage

Latvia has unique geological conditions which would allow in 11 locations to develop underground natural gas storage (UGS) facilities with capacity to cover approximately 10% of whole Europe's demand. The only operating underground natural gas storage facility in Baltics is located in Inčukalns with capacity to store 2.32 billion m^3 (~24 TWh) of natural gas. Mostly, storage is used seasonally – the gas is mainly injected in summer for the coming winter season.

Prior to the liberalization of the natural gas market in Latvia, the Inčukalns UGS was filled to its maximum technical capacity every season. As market liberalization approached, the Russian natural gas group Gazprom reduced until it stopped storing natural gas for Russia, significantly reducing the total amount of natural gas stored at the Inčukalns UGS thus reducing the usage of the storage. An important factor was the completion of modernization projects of natural gas storage facilities in Russia, increasing the natural gas storage capacity in the country. The Lithuanian lawsuit against Gazprom also played an important role, which adversely affected Gazprom's desire to store natural gas in the Baltic region.

The liberalization of the market did not oblige natural gas traders to use the Inčukalns UGS, relying on market mechanisms, which have been reflected in the sharp decline in stored volumes in 2017. The decline in the volume of stored natural gas continued in 2018, and taking into account the technical structure of the Inčukalns UGS, created a rickshaw for the energy crisis as extraction capacity correlates with volume of natural gas left in the storage.

In 2020, with the establishment of the common natural gas market between Estonia, Latvia and Finland and the introduction of an inter-operator compensation mechanism that abolished tariffs for natural gas flows between market interconnections, the stored natural gas in Inčukalns UGS and the energy security of Latvia and the Baltic region increased significantly.

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[11] AS "Augstsprieguma tīkls". Available: https://ast.lv/lv/projects/sinhronizacija-ar-eiropu

Figure 6. **Amount of active natural gas at Inčukalns UGS after natural gas injection at the end of the season (TWh)**[12]

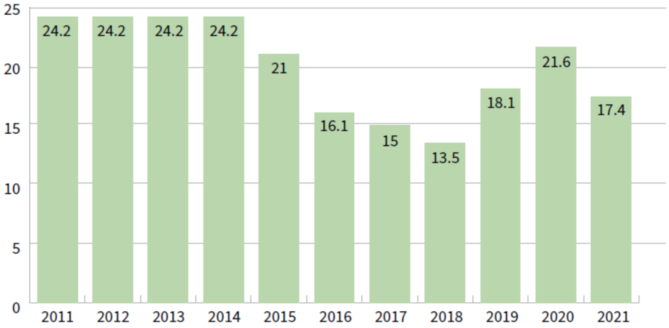
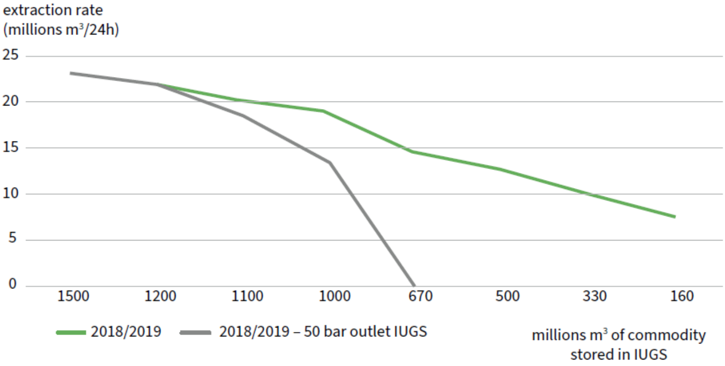


Figure 7. **Inčukalns UGS natural gas extraction productivity in relation to stored volume**[13]



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[12] AS "Connexus Baltic Grid" (2021). Dabasgāzes pārvades sistēmas operatora ikgadējā novērtējuma ziņojums par 2020. gadu. Available: https://www.conexus.lv/uploads/filedir/Aktualitates/Parskati/Dabasg__parv_sist_operatora-zinojums_par_2020_JUN_ready2.pdf

[13] AS "Connexus Baltic Grid" (2018). PCI project 8.2.4. Investment Request. Inčukalns Underground gas storage enhancement. Available: https://www.google.com/url?q=https://www.conexus.lv/uploads/filedir/iugs_pci_investment_request_20181002.pdf&sa=D&source=docs&ust=1655143083818440&usg=AOvVaw2oVDZx0gNG-D7GXGrTvFShC

Situations in which the filling of Inčukalns UGS is relatively low, but the demand for natural gas is reaching its peaks, there is a risk of an energy crisis. This risk can be explained by the decrease in the technical pumping capacity of Inčukalns UGS due to the decrease in the amount of stored natural gas (see Figure 7). The storage system operator JSC Conexus Baltic Grid has started the modernization project of Inčukalns UGS, as a result of which the modernized compressor will ensure the removal of natural gas from the storage facility with increased, stable and predictable daily removal capacity even at low natural gas balances and storage pressures[14].

Steep changes in geopolitical situation promoted role of Inčukalns UGS as one of main pillars for security of supply in whole Baltic region. Particular statement is supported by high demand for Inčukalns UGS storage capacities by natural gas traders in the region. In order to ensure sufficient natural gas stocks for upcoming winter, Inčukalns UGS switched its working regime to injection in an atypically timely manner – in February. The unusual practice resulted in unusually high level of stock, which is crucial to ensure security of supply. Practical tool for mitigation of risks concerning security of supply is creation of strategic stocks. Latvian government via national electricity concern Latvenergo has ordered creation of such stock in amount of 1.8–2.2 TWh[15, 16, 17, 18].

In Latvia, safety reserves of oil products are established in accordance with the requirements of Directive 2009/119/EC, which have been transposed into Latvian legislation by the Energy Law. The EU regulation requires to ensure the fuel reserves for up to 90 days of consumption of the country. As can be seen in the Figure 8, Latvia's reserves of energy products of oil origin have more than doubled in the last decade, in 2020 they are 162% higher than in 2011, which nevertheless is connected with the rise of consumption. The increase in oil product reserves strengthens Latvia's energy security.

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[14] AS "Connexus Baltic Grid" (2021). Inčukalna pazemes gāzes krātuves modernizācija būtiski uzlabo Latvijas dabasgāzes apgādes stabilitāti. Available: https://www.conexus.lv/aktualitates/incukalna-pazemes-gazes-kratuves-modernizacija-butiski-uzlabo-latvijas-dabasgazes-apgades-stabilitati

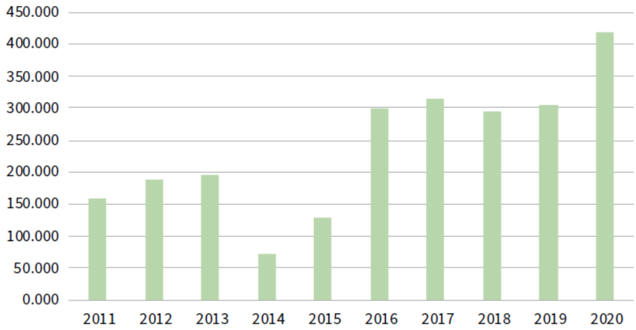
[15] Saeima (2022). Saeima noteic energoapgādes drošuma rezerves apjomu gāzei. Available: https://www.saeima.lv/lv/aktualitates/saeimas-zinas/30936-saeima-noteic-energoapgades-drosuma-rezerves-apjomu-gazei

[16] AS "Connexus Baltic Grid" (2022). Available: https://conexus.lv/zinas-presei/conexus-pirmajos-tris-gada-menesos-incukalna-pgk-noglabats-rekordliels-dabasgazes-apjoms

[17] AS "Connexus Baltic Grid" (2022). Available: https://conexus.lv/zinas-presei/incukalna-pazemes-gazes-kratuve-sagatavota-iesuknesanas-uzsaksanai

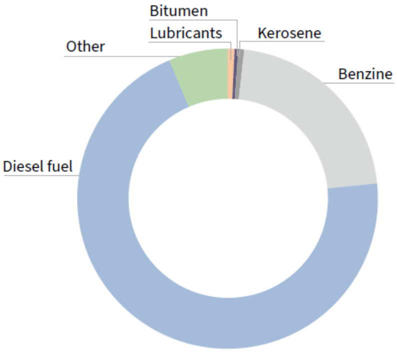
[18] Latvijas Sabidriskie mediji (2022). Valdība nolemj Inčukalnā veidot dabasgāzes rezerves par aptuveni 230 miljoniem eiro. Available: https://www.lsm.lv/raksts/zinas/ekonomika/valdiba-nolemj-incukalna-veidot-dabasgazes-rezerves-par-aptuveni-230-miljoniem-eiro.a452974/

Figure 8. Reserves of oil products stored in Latvia, tons



Source: Eurostat

Figure 9. Proportion of oil product reserves held by Latvia by type



Source: Eurostat

In total, more than 400 thousand tons of stored oil products contain around 70% of diesel, and about 22% of gasoline. The other product types, each individually, account for a relatively small percentage of total oil product reserves. Considering the aspect of dependence on certain oil products, it can be concluded that diesel and petrol play the most important role in ensuring energy security.

4.2.7. Possible solutions

One of the most efficient solutions how to improve the security of Latvian energy system in reference to Trilemma Index methodology would be to implement new electricity generation capacities.

Latvia has developed National Energy and Climate Plan for 2021–2030 that highlights national ambitions on energy sectors development in four pillars:

- resourcefulness;
- self-sufficiency and diversity of resources;
- reducing consumption of fossil and non-sustainable resources;
- use of sustainable renewable and innovative resources;

which concludes in a developed and climate neutral economy.

Latvian electricity TSO has developed a map with information about the transmission lines on availability to connect generation or consumption. The map in combination with project list of issued connection permits, it can be concluded that there is around 2GW of renewable projects under development in different stages.

The closest power station to commissioning in 2022 is 58.8 MW wind park in Ventspils parish. Two wind parks after long struggle have obtained positive Environmental impact assessment which is big leap on wind park development and few parks are performing the environmental impact assessment. There are several developers who have granted the connection technical requirements in summer 2020 but yet not decided on finalizing.

Increasing renewable non-dispatchable energy resources in the total generation portfolio can also have negative consequences if dispatchable capacities are not increased at the same time. In a situation where the country has a high share of renewable resources and low dispatchable capacities, windless cloudy weather, large amount of generating power has no production, which can impact the balance between supply and demand.

Dispatchable capacities with synchronous generation provide system services such as system rotating reserve, the insufficiency of which may result in frequency fluctuations and power system instability. Therefore, to increase the resilience of the energy system from the point of view of generation diversity, the generation portfolio must be balanced, including sufficient dispatchable capacity.

4.2.8. Estonian-Latvian offshore wind park

In the Latvian National Energy and Climate Plan 2021–2030 (NEKP 2030) the task of implementing an international project for the construction of an off-shore wind farm in the period up to 2030 has been confirmed. Such a task was included in NEKP 2030, because Latvia has committed to achieve a 50% share of renewable energy in the total final energy consumption by 2030, as well as to ensure a reduction of Latvia's total greenhouse gas emissions by 65%, compared to Latvia's GHG emissions in 1990.

In 2020, Latvia approved the marine spatial planning map, where the potential construction sites of offshore wind farms, as well as the possible connections of the power transmission infrastructure, are also planned. Latvian electricity TSO, together with other institutions, participated in the marine spatial planning process organized by the Ministry of Environmental Protection and Regional Development.

Latvian and Estonian transmission system operators Latvian and Estonian electricity TSOs, respectively, as responsible for infrastructure development and connections to the power transmission network, are also involved in the implementation of this project. At the beginning of 2021, TSOs carried out preliminary calculations of the distribution of power flows for the construction and reinforcement of the power transmission network if new wind farms are connected. Both TSOs plan to conduct a detailed route study for possible connection options, while the ministries and LIAA plan to conduct a cost-benefit analysis of the entire project, including wind farms and infrastructure. CEF RES European co-financing opportunities may appear after 2022. The auction of the wind park project to a potential investor may take place around 2025, and the implementation of the project itself, together with the infrastructure, is scheduled for 2030. [19]

In order to achieve climate neutrality of the energy sector, it is essential to introduce new technologies. Currently, one of them is the use of hydrogen, which has several advantages and development prospects in the industry. Latvian utility company is working on pilot project to implement hydrogen in energy portfolio. It envisages that green hydrogen will be produced using polymer electrolyte membrane electrolysis equipment and electricity from TEC-2 solar batteries or from the planned AS Latvenergo wind power plant in Priekule district, or from Daugava hydroelectric plants. The produced hydrogen will be stored or used immediately for combustion in gas turbines TEC-2. Before burning the produced hydrogen will be mixed with natural gas in a mixing unit.[20]

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[19] AS "Augstsprieguma tīkls" (2021). Elektroenerģijas pārvades sistēmas attīstības plāns 2022–2031. Available: https://ast.lv/sites/default/files/AST_Attistibas_plans_2022-2031.pdf

[20] AS "Latvenergo" (2022). Elektroenerģijas tirgus apskats. Available: https://latvenergo.lv/storage/app/media/uploaded-files/ETA_jan_2022.pdf

Conclusion

Although Latvia is scoring high in Energy Security Trilemma Index by WEC methodology, it is necessary to highlight that even short but focused bursts of specific issues (gas supply interruption, lack of generating capacities in the region) can dramatically impact the energy security as whole and leave significant footprint in further development. Therefore, it is critical to prioritize the energy security determining factors and purposely act on the improvements.

Latvia should set a clearer plan for decarbonization of its energy system with explicit actions for humanizing energy transition. For example, starting with development of national hydrogen strategy. In authors' view, Latvian energy security dimension should be more decentralized, distributed, digitalized, and decarbonized, and at the same time maintain balanced share of dispatchable baseload capacities in generation portfolio. Authors also acknowledge the need for new sub-indicators to represent an evolving energy system in transition.

energies

Article

Modelling of Battery Energy Storage System Providing FCR in Baltic Power System after Synchronization with the Continental Synchronous Area

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Abstract: This paper presents the case study of provisions of frequency containment reserve (FCR) with a battery electric storage system (BESS). The aim of the case study is the evaluation of the technical possibility to provide FCR in Latvian power systems after all Baltic power systems will synchronize with the Continental Europe Synchronous Area (CESA). To simulate the dynamics of BESS capacity and its state of charge (SOC), authors have developed an algorithm and mathematical model (it can be realized in different calculation programs). The case study calculations verified the model. The algorithm is conditionally divided into two parts—FCR provision and SOC recovery–which in turn is divided into three possible models of BESS state of charge recovery options: (1) overfulfillment—exceeding the specified FCR amount, (2) deadband utilization, and (3) BESS charging or discharging through scheduled transactions in intraday power market. The modelling was performed using historic frequency data of Latvian and French power systems. The case study of BESS with charging capacity of 12 MW and stored energy volume of 7 MWh for provision of determined FCR for Latvian power system was considered. The obtained results from the simulation were used in the separate model to evaluate economic feasibility of BESS for FCR.

Keywords: frequency control; FCR; battery electric storage; simulation; algorithm; state of charge recovery

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1. Introduction

Historically, power systems of Estonia, Latvia, and Lithuania were operated in parallel with power systems of Russia and Belarus based on the so-called BRELL agreement (abbreviation of Belarus, Russia, Estonia, Latvia, Lithuania) [1,2]. Frequency control was centralised and provided by Russian United Power System (UPS). Transmission system operators (TSOs) in BRELL were responsible for minimize frequency mitigation by maintaining power generation and demanding equilibrium. According to the existing Network Codes in Baltic States, frequency must be maintained between 49.95 Hz to 50.05 Hz.

In 2018, a political decision was made on the synchronization of the power system of the Baltic States with the continental European electricity system, and the disconnection (desynchronization) from the electricity systems of Russia and Belarus. As desynchronization from the BRELL and synchronisation to the Continental Europe Synchronous Area (CESA) is an approved goal for Baltic States, it will be crucial to maintain the frequency stable for each TSO of the Baltic States [2,3]. It is expected to be a rather difficult task, so the solution for this problem is complex. While connected to BRELL the frequency control is centralised. After synchronisation with CESA, each of the Baltic States' TSOs must be able to maintain power equilibrium and frequency control—activation of frequency containment reserves (FCR) immediately after a difference in the balance between generation and demand. Both the construction of new interconnections and the reconstruction of existing ones, as well as the strengthening of the existing network, network management, and control systems in each country, require large-scale investments. At the same time, the decarbonization goals are highly responsible for large renewable power penetration in the power system, thus decreasing conventional generation; this could affect the power equilibrium and loss of system inertia [4–7]. There are several methods for system inertia control. The research conducted by the Institute of Power Engineering in Riga Technical University concludes that synchronous condensers in AC power systems can respond with active power injection during a loss of generation, and–in combination with novel load shedding method–show promising results for further investigation, thus opening new methods for system stability control [1].

To carry out this ambitious plan, the Baltic States TSOs have signed the "Memorandum of understanding on development of the Baltic load-frequency control block" [3,8]. The memorandum explains a high-level concept for balance management, FCR technical requirements, concept of FCR prequalification process, and FCR dimensioning rules. The situation in Baltic power system management will also change with the introduction of new Grid Codes and Guidelines for new pan-European platforms or markets for ancillary electricity services (MARI (go-live planned for 2022), PICASSO, TERRE), according to Regulation (EU) 2017/2195 of November 2017. Therefore, after the synchronization with CESA, there will be an opportunity to offer new ancillary services in the Baltic power market including active power reserves for frequency control.

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

The European Commission Regulation EU 2017/1485 on guidelines for the operation of the electricity transmission system, and the European Commission Regulation (EU) 2017/2195, establishing electricity-balancing guidelines provided for four-level frequency regulation processes or platforms. The platforms are dedicated to frequency containment reserves, automatic and manual frequency restoration reserves (aFRR/mFRR), and replacement reserves (RR). All of them (see Table 1) are introduced into the system in a certain chronology after the occurrence of active power imbalance, as shown in Figure 1.

Table 1. Active power reserves in the Continental Europe Synchronous Area.

Power Reserve	Aim
Frequency containment reserve—FCR	Reserves of active power to maintain stability of systems frequency after power imbalance. The purpose of FCR is to stop the frequency deviation after a disturbance in the power system, achieving a new balance between electricity supply and demand.
Frequency restoration reserve– FRR	Reserves of active power to firstly recover frequency to normal state, and secondly to restore the power balance in individual frequency control zones to specific value. aFRR—automatically activated FRR; mFRR—manually activated FRR.
Replacement reserve—RR	Reserves of active power (including generation power) for restoring the required FRR level to be ready for additional imbalances in the system.

The amount of FCR is determined annually according to the amount of generation and consumption in the synchronous zone. The total amount of FCR, aFRR, and mFRR must be equal to the largest possible cut-off unit in the Baltics (700 MW in 2025). The distribution of FCR, aFRR, and mFRR among the Baltic States calculated in 2020 is given in Table 2. As can be seen, the estimated amount of FCR for Baltic power system is ±30 MW. The estimated amount of aFFR in the Baltics in 2025 will be 100 MW (the distribution is based on the current imbalance in the Baltic States). Manually activated FRR is determined as the remaining amount of the total amount of FRR; in 2025, it will be 600 MW in the Baltics.

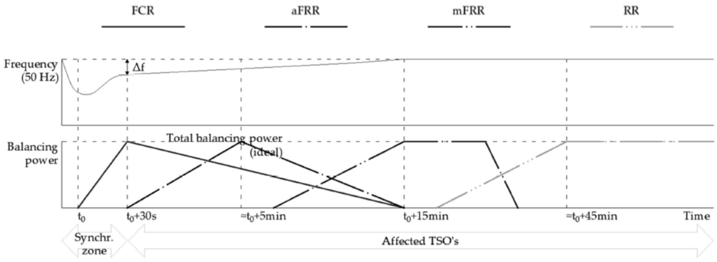


Figure 1. Chronology of frequency control process [9].

Table 2. Active power reserve volumes in Baltic power systems calculated in 2020 after synchronization with CESA [10].

	Lithuania	Latvia	Estonia	Baltic States
FCR	±12 MW	±11 MW	±7 MW	±30 MW
percentage	40%	33%	27%	100%
aFRR	±45 MW	±23 MW	±32 MW	±100 MW
percentage	45%	23%	32%	100%
mFRR (up)	+243 MW	+148 MW	+218 MW	+600 MW
percentage	39%	25%	36%	100%
mFRR (down)	−300 MW	−21 MW	−279 MW	−600 MW
percentage	50%	3.5%	46.5%	100%

Recently, the European Green Deal and decarbonisation goals of energy systems have led to a growing interest in energy storage systems (ESS). ESS are a versatile tool with different technical characteristics that can provide many options of application, such as services to support generation, TSO's or distribution system operator's infrastructure, customer energy management, and ancillary services [11,12].

For the determined Latvian TSO's reserve volumes, lithium-ion battery ESS (BESS) is expected to be the most suitable option. The main advantages of lithium-ion batteries in electricity system applications compared to other battery technologies are fast response time, high capacity, and long life in partial cycles. In addition, lithium-ion batteries have the potential for different power/capacity combinations. Nevertheless, the energy capacity of all batteries is limited, which limits the maximum power delivery time. Therefore, lithium-ion batteries are best suited for FCR applications characterized by short-term power supply [13,14]. The possibility to install BESS in almost any place gives this technology a noticeable advantage. Thus, in this research, other ESS technologies are not considered.

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 needed response speed to provide FCR. Regulation capability and ancillary services' price have vast influence on BESS economics and operation. The algorithm should be tailored for specific power systems and electricity market needs. Reviewed studies have not addressed the problems Baltic TSO's will encounter in the nearest future, thus the proposed methodology and conclusions could be used as guidelines in the decision-making process [15–19].

In following sections, authors propose methodology to determine the possibility to use battery systems for FCR service. The background of the mathematical model, the analyses of the frequency data from Latvian and French power systems, the assumptions on the BESS used for calculations, and the tailored algorithm are described in Section 2. In Section 3, authors review the results. To evaluate the viability and feasibility, economic assumptions and sensitivity analyses are described in Section 4. In Section 5, authors give the conclusions and proposed discussion questions of the research.

2. Methodology

To understand whether it is possible to maintain frequency stability with BESS in the power system of Latvia, the research team conducted a case study, developed a calculation model, and tested the system's frequency containment option for previously recorded frequency deviations.

2.1. Mathematical Modeling of BESS FCR

The modelling of BESS operation for providing FCR is based on the Latvian TSO planned conditions for the implementation of ancillary services considering synchronization with the CESA until 2025 [9]. The characteristics of the planned FCR product are summarized in Table 3.

Table 3. FCR product characteristics [9].

FCR amount	±11 MW
Time	15 min
Minimum bid	1 MW
Maximum bid	All necessary FCR amount
Minimum duration between successive activations	0 min
Maximum activation duration	Non limited
Capacity pricing	Pay-as bid

Some principles of the German integrated market for ancillary services have been considered as well. One of these states that all FCR bids must be symmetrical, i.e., up and down regulation must be provided [20].

The FCR provision process or so-called primary frequency control is based on a load-frequency characteristic, as shown in Figure 2. FCR is not intended to restore the frequency to a nominal value (50 Hz), but to restore the balance of generated and consumed power in the system and to keep the frequency at a stable limit. This historically has been done by automatically adjusting the output of generating units. The amount of active power required to restore this balance or prevent the further frequency increase or decrease is proportional to the system's frequency deviation from the nominal value.

According to the proportional load-frequency characteristics, the current battery power $P_{BESS(t)}$ for FCR provision is defined mathematically as following:

$$P_{BESS(t)} = \pm P_{FCR(t)} = \frac{\Delta f}{|\Delta f_{max}|} \cdot P_{FCR\_max} \tag{1}$$

where $\pm P_{FCR(t)}$—actual necessary positive or negative power for FCR provision according to frequency deviation, $\Delta f = f - f_{nom}$—deviation of actual frequency f from the nominal frequency $f_{nom} = 50$ Hz, P_{FCR_max}—maximal FCR power defined in Table 3, and Δf_{max}—maximal frequency deviation at which total prequalified FCR power should be activated. In the synchronous grid of Continental Europe, the maximum steady-state frequency deviation is ±200 mHz, at which full FCR power must be activated in 30 s. The frequency band or deadband in which FCR delivery is not required is ±10 mHz [21,22].

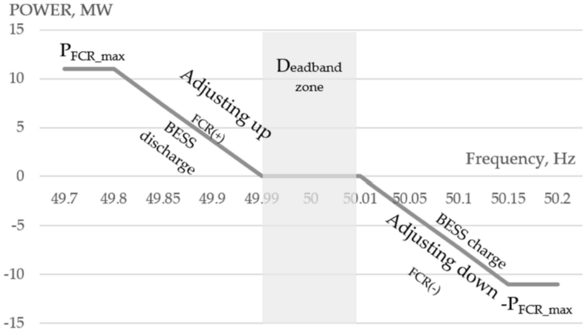


Figure 2. Primary frequency control load-frequency curve.

As the frequency deviation increases, the required active power increases linearly. If the frequency deviation is above 50 Hz, there is active power surplus in the network. This means generated active power must be reduced, or negative FCR provision (FCR (−)) is required, and vice versa—when frequency is below 50 Hz generated active power must be increased or positive FCR power (FCR (+)) is required. In the BESS case the positive FCR is provided by discharging the BESS and negative—by charging BESS. In the calculations, BESS power is assumed to be positive if BESS is charged, and negative if BESS is discharged.

In the event of the frequency deviation, the generating units that provide the FCR automatically activate them within a few seconds; therefore, primary frequency control is the fastest way to control the power system (Figure 1).

2.2. Frequency Data

Frequency data provided by the Latvian TSO for 2018 and 2019 were used in the calculations of BESS operation, as well as the calculations with French power system (RTE) data [22] for 2019 were used for comparison. Frequency measurements are summarized at 1-min intervals.

In the Latvian power system, the frequency dynamics have been similar in both analyzed years. For purpose of better perception, Figures 3 and 4 show Latvian and French power system frequency deviations at 4-h and one-month periods accordingly. Figure 5 shows the frequency histogram of Latvian and French power systems. Although the primary frequency regulation is currently provided by the Russian UPS, the frequency characteristics were analysed in the context of the requirements of EU network codes and guidelines. Most of the time, the frequency was within the allowable limits from 49.99 to 50.01 Hz–61% of all cases in 2018 and 63% in 2019. Approximately 37% of the time in 2018, and 39% in 2019, the frequency was outside the normal frequency deviation limits of ±0.01 Hz–when no primary frequency control should be performed. In both years, the frequency was above 50 Hz (51%) most of the time.

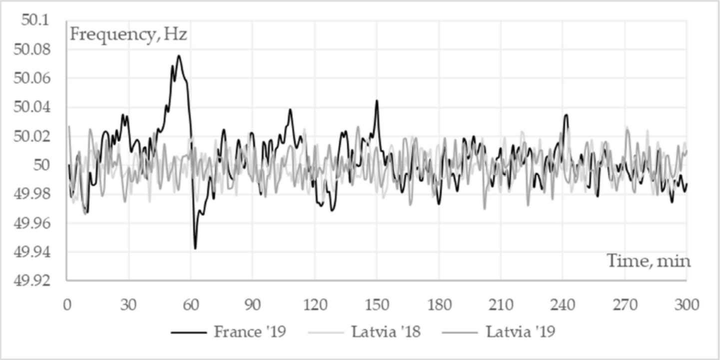


Figure 3. Frequency changes in Latvian and French power systems during 4-h period from 00:00–04:00 in 5 February.

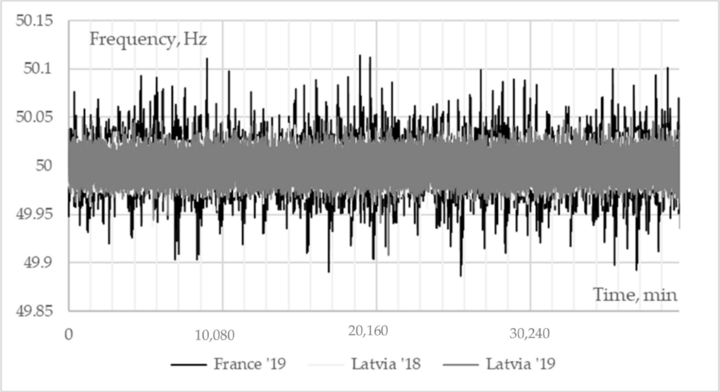


Figure 4. Frequency changes in Latvian and French power systems on monthly (February) basis.

In contrast, the French power system, which is part of CESA, had significantly larger frequency deviations from the nominal value. The frequency was outside the permissible limits 49% of the time (Figures 3–5). As the frequency data are rapidly changing, the following pictures are used to display the large difference in frequency variability and dynamics in Latvia and France. In Figure 3 the time scale is 4 h on 5 February, and Figure 4 the time scale is whole month of February 2019 (major gridlines represent one week, minor gridlines represent one day).

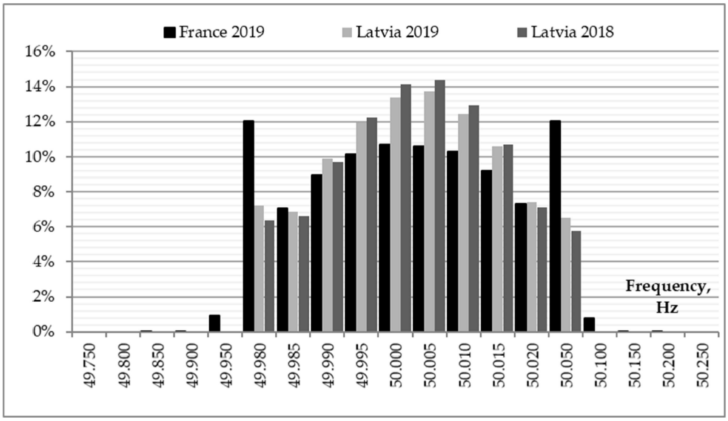


Figure 5. Frequency histogram of Latvian and French power systems.

2.3. BESS Life Cycle and Degradation

Battery life is one of the most important factors in any BESS application, as it will greatly affect the cost-effectiveness of the project. BESS life cycle is basically evaluated according to two criteria—calendar life and cycle life. At these particular circumstances, the end-of-life criterion is considered to be a 20% reduction in capacity, which is facilitated by both processes—calendar and cycle aging. As more recycled products are becoming available for stationary cases, the BESS life could be extended up to values lower than 70% of the initial installed capacity, which could lead to better feasibility results. Battery life depends mainly on temperature, time, state of charge, and number of cycles [14]. To simplify the calculations, authors assumed that the decrease of the lithium-ion BESS capacity is linear over time and amounts to a 2% reduction from the initial nominal capacity each year. Thus, the technical life of BESS is assumed to be 10 years.

2.4. Calculation Algorithm of the BESS Model

The algorithm (Figure 6) is conditionally divided into two parts—FCR provision and SOC recovery–which in turn is divided into three parts according to the above-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.

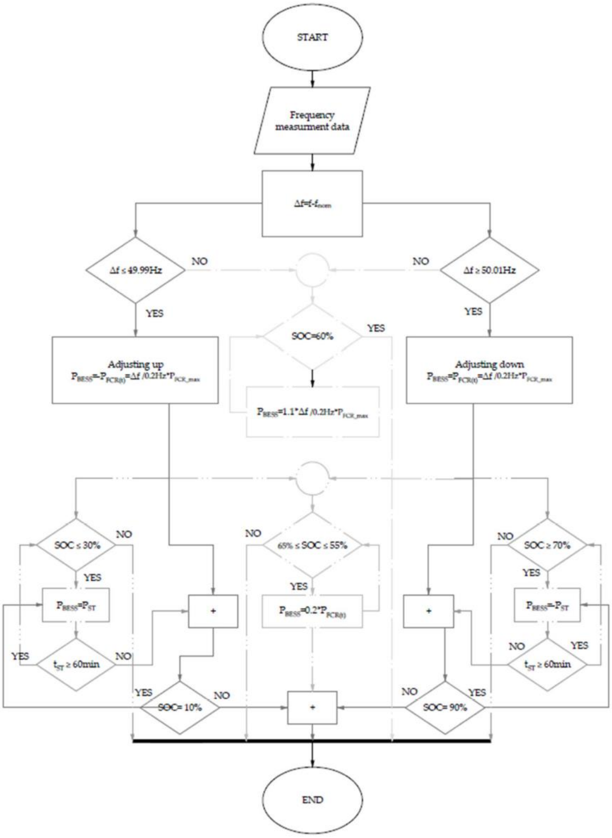


Figure 6. Blocksheme for the BESS operation.

2.5. Selection of BESS Parameters and Operating Principle

The choice of BESS nominal power (P_{BESS_nom}) is determined by the required amount of FCR for the Latvian power system after synchronization with the CESA, which is ±11 MW (see Table 2). Table 4 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 provision 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 that must be observed to ensure that the life cycle specified by the BESS are maintained. The developed BESS model assumes that the maximum SOC (SOC_{max}) is 0.9 or 90% of the nominal capacity (E_{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_{BESS_fact}).

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

$$E_{BESS\_nom} = P_{BESS\_nom} \cdot 0.5 / DOD_{max} \quad (2)$$

where 0.5—defines half of 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 the Equation (2) 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 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%.

The state of charge of the battery is calculated and the model verifies whether the SOC lies within the permitted SOC bandwidth as follows:

$$\text{for charging } SOC(t) = SOC(t-1) + \frac{P_{BESS(t)} \cdot \eta_{BESS} \cdot \Delta t}{E_{BESS\_nom}}, \quad (3)$$

$$\text{for discharging } SOC(t) = SOC(t-1) + \frac{P_{BESS(t)} \cdot \Delta t}{\eta_{BESS} \cdot E_{BESS\_nom}}, \quad (4)$$

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

The round-trip efficiency of BESS for charging and discharging processes–also considering the efficiency of the inverter and step-up transformer–is assumed to be 92% [23].

Due to the continuous operation of the BESS with insignificant periods of downtime, the overall self-discharge of the BESS is not considered in the calculations. BESS self-consumption is also not considered in the calculations.

Table 4. Selected BESS parameters.

Nominal power	P_{BESS_nom}, MW	11.0
BESS nominal electrial capacity	E_{BESS_nom}, MWh	7.0
Available BESS electricity	E_{BESS_fact}, MWh (0.8*E_{BESS_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%

2.6. Maintaining Normal State of Charge

While providing FCR reserves, the BESS is charged and discharged continuously. At some point–at higher frequency deviations–it may reach full charge or discharge, and at that point it will no longer be able to provide symmetric FCR service. Therefore, a BESS state of charge management strategy is required to ensure that BESS will supply FCR capacity throughout the contracted timeslices. Here, authors have considered some options to maintain normal SOC level, as practiced in the German FCR market.

The German FCR market legislation allows in certain cases to deviate from the proportional frequency regulation curve. This is especially important for BESS operators, as they can use these options to restore state of charge levels. Typically, the battery operator has three options to balance the charge level and maintain the normal operating range of the BESS during primary control operation [21,22].

First option is overfulfillment when it is allowed for battery operators to exceed the specified FCR power up to 120% of the load-frequency curve P(f), as shown in Figure 7. This option can be used to selectively charge or discharge the battery as needed.

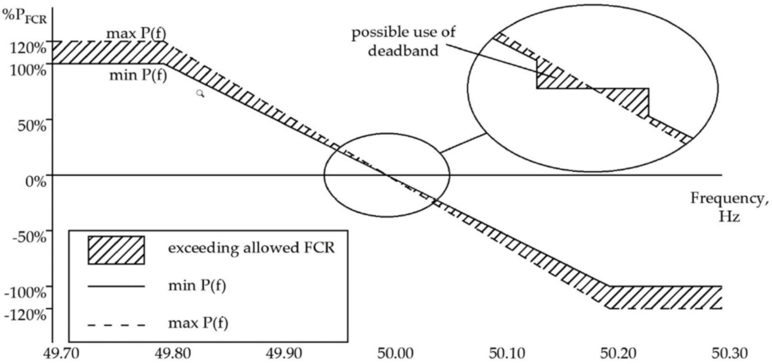


Figure 7. Exceedance range and deadband of the specified FCR [15].

Second option is deadband utilization. BESS operators have the option of resetting the charge level in the frequency deadband, which is ±10 mHz (Figure 7). They may choose to comply with or deviate from the P(f) curve. However, the opposite control is not allowed—BESS should not be discharged when the FCR is positive, and BESS should not be charged when the FCR is negative. In this case the accuracy of the frequency measurement equipment and the control measurement must be high.

The third option is BESS charging or discharging through scheduled market transactions. This means that the balancing energy can be purchased or sold in the intraday market to restore the desired BESS charge level. It must be ensured that the net FCR supply (battery capacity minus capacity purchased/sold on-the-spot market) continues to comply with FCR regulations. When the BESS is charged or discharged with the planned energy, its operating point is changed to enable the primary control operation at the same time. The BESS operator must present the concept to the responsible TSO and notify the TSO 15 min before the change of operating point.

The intraday market is a part of the wholesale electricity market in which electricity is traded in relatively small volumes with a short delivery time. Products available on the intraday market include hourly and quarterly electricity supply contracts.

In the first and second options, the electricity consumed from the grid to recharge the battery depends on the system frequency, but the energy bought or sold on-the-spot electricity market (third option) does not depend on the system frequency and can be used to significantly adjust the SOC of BESS. On the other hand, the first and second options are free of charge, but on-the-spot market electricity must be purchased at a fixed price, which increases BESS's operating costs, while electricity sold on-the-spot market generates additional income.

The authors use all three options simultaneously in the calculations of BESS operation to maintain the normal state of charge (Table 5). Therefore, the following characteristics were defined:

- The deadband utilization is used in the ±10 mHz frequency range.

- FCR overfulfillment starts when the state of charge decreases to 55% (SOC_{OF_min}) or increases to 65% (SOC_{OF_max}). When these limits are reached, the required amount of FCR is exceeded by 20%, thus speeding up BESS charging or discharging.
- Scheduled market transactions are activated at 30% state of charge level (SOC_{ST_min}) and 70% (SOC_{ST_max}), respectively. An important aspect to be considered to ensure the SOC management through the scheduled market transactions is the planned transaction capacity (P_{ST}), which should be additionally accounted for the BESS investment costs. In the calculation model, authors assume additional capacity of 1 MW for market transactions, which will be sold or purchased on the spot market for 1 h as the SOC level reaches defined limits.

Table 5. Parameters for SOC management.

Planned transaction capacity	P_{ST}, MW	1
Minimum state of charge for activation of FCR overfulfillment (OF)	SOC_{OF_min}	0.55
Maximum state of charge for activation of FCR overfulfillment (OF)	SOC_{OF_max}	0.65
Minimum state of charge for activation of scheduled transaction (ST) for charging	SOC_{ST_min}	0.3
Maximum state of charge for activation of scheduled transaction (ST) for discharging	SOC_{ST_max}	0.7

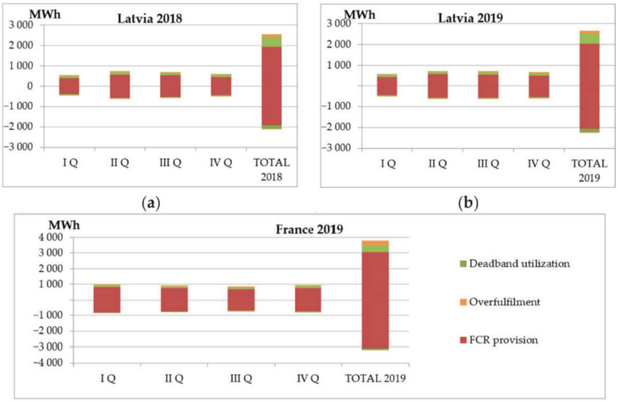
3. Results

The research team used the developed calculation algorithm to study BESS performance at three cases of frequency fluctuations in the Latvian power system in 2018 and 2019, as well as in the French power system in 2019.

Figure 8 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 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 Latvian example by almost 70%. Therefore, in the calculations with frequency fluctuations of French power system, the capacity required for the scheduled market transactions was increased to 2 MW. Results in Figure 8 show that in this case, BESS transferred around 3160 MWh to the network and consumed around 3800 MWh of electricity for charging.

Figure 9 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. Figure 9 shows that the planned market transactions took place differently on a quarterly basis. In 2018, in case of frequency changes of 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.



(**a**) (**b**)

(**c**)

Figure 8. BESS performance for FCR provision and SOC management: (**a**) in Latvia 2018, (**b**) in Latvia in 2019, (**c**) in France in 2019.

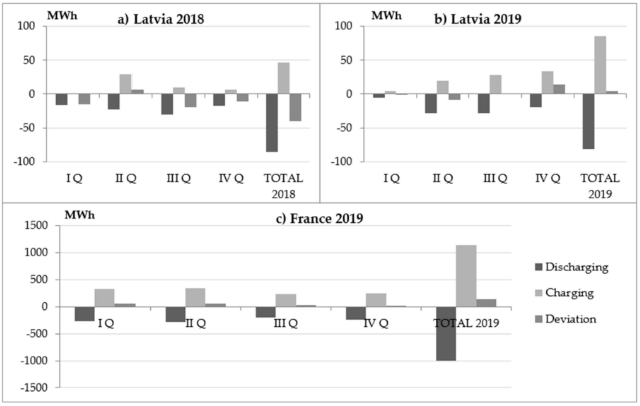


Figure 9. Scheduled market transactions to restore the SOC.

The dynamics for a certain period of time for BESS active power and state of charge in the case of Latvian power system frequency in 2018 are shown in Figure 10. 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 Figure 10 shows how the operating point of the actual BESS power shifts.

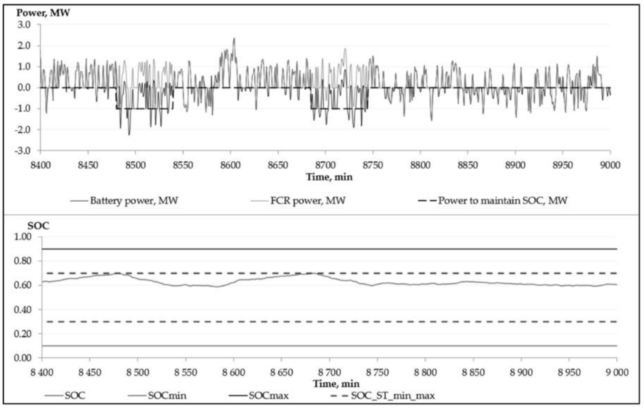


Figure 10. Dynamics of battery power and state of charge in the example of frequency changes in the Latvian power system in 2018 (I quarter, 06.01.18 at 20:00–07.01.18 at 06:00).

In the example of the French power system, the dynamics of battery power and SOC are shown in Figure 11. Fluctuations of SOC are more frequent, with larger discharge depths, according to frequency fluctuations. Performed SOC management ensures its maintenance within permissible limits.

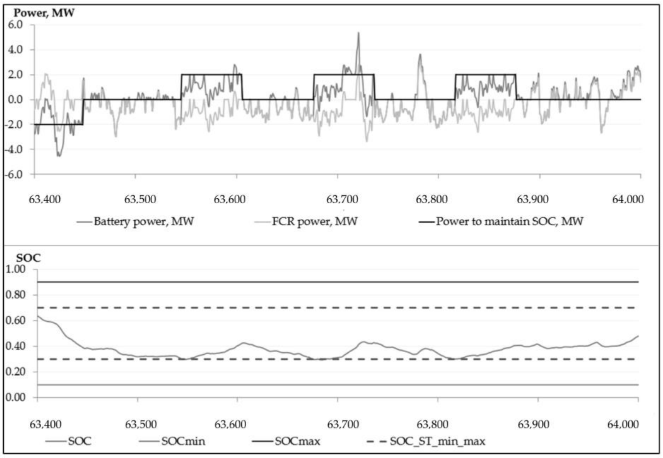


Figure 11. Dynamics of battery power and state of charge in the example of the French power system (II quarter, 15.05.19 at 00:40–10:40).

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, 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 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 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 Figure 12.

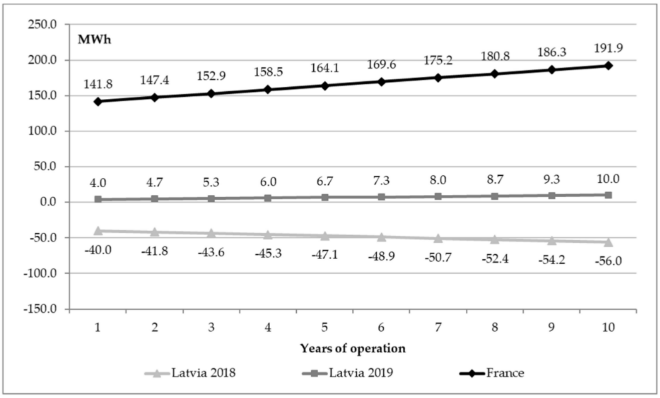


Figure 12. Annual electricity consumption for SOC renewal during the technical life of BESS.

However, Latvia's two-year observations (for 2018 and 2019) do not allow reliable predictions to be made about the future costs or income of BESS 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 the 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.

4. Economic Assumptions

To assess the economic efficiency of the BESS project, authors determined the net present value (NPV) of the project, as well as the internal rate of return (IRR) and the discounted payback period. To assess the capital investments of the BESS project, authors assumed the specific capital costs for energy and for power as 359 EUR/kWh and 445 EUR/kW accordingly. Considering this, the expected capital costs of BESS are estimated at EUR 7.85 million for the example of Latvian power system with 12 MW/7 MWh BESS, and at EUR 8.30 million for the example of French power system with 13 MW/7 MWh BESS. Annual operating expenses amount to 1.5% of the initial investment, or EUR 0.12 million in the Latvian example and EUR 0.13 million in the French example.

Authors also considered additional costs for SOC renewal via scheduled transactions in the intraday market, although the renewal of SOC was not always required to purchase electricity. As can be seen from Figure 12, there was necessity to sell surplus electricity in the intraday market for SOC renewal. However, the amount of additional costs of EUR 6.2 thousand with an annual increase of 3.93% during battery life cycle were assumed in base calculations. The costs are calculated based on the forecasted electricity price (2022 is the start of BESS operation).

In turn, the revenue from the provision of FCR service amounts to EUR 0.95 million annually at the assumed base price of FCR service of 10 EUR/MW per hour. In calculations, the base price of the FCR service is assumed to be the average of the existing FCR service prices in the German and Finnish FCR markets.

Economic calculations assume that continuous provision of FCR service during the contract period is ensured, as well as the right to provide full FCR service yearly–except for two weeks for BESS maintenance–will be won. The discount rate is assumed to be 5.5%.

Considering all the above basic economic assumptions, the BESS project does not pay back during its technical life. The calculated NPV in year 10 for the Latvian example is −1.7 MEUR and IRR 0.64%. The BESS project would require at least 25% co-financing to ensure a payback period of 10 years. In the case of the French energy system, for example, there is correspondingly lower return on investment.

As FCR prices are not predictable, the impact of changes in the price of the FCR service on the payback of the BESS project has been further assessed. FCR price changes are assumed to be ±20% and ±40% of the base price. According to economic calculations, the BESS project can payback within 10 years without additional co-financing, if the price of the FCR service is at least 14 EUR/MW/h. The respective NPV curves for the frequency deviations of the example of the Latvian power system are shown in Figure 13.

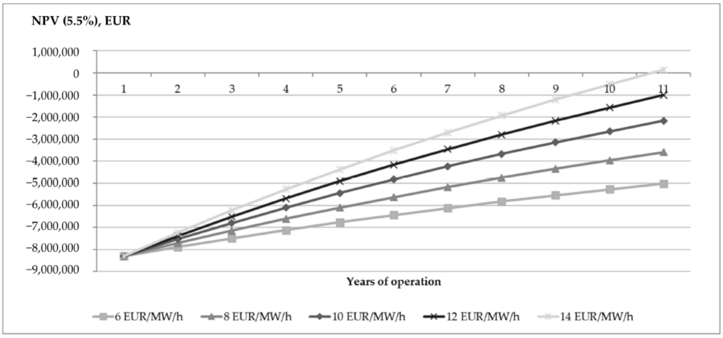


Figure 13. NPV curves of the BESS project for the example of Latvian power system at different FCR prices.

5. Discussion and Conclusions

Authors evaluated the operation of BESS by developing a mathematical model based on operational principles of the CESA, as well as projections planned by Latvian TSO. The main objective of the research was to observe technical possibilities of a battery energy storage system to provide frequency containment reserves in the Latvian power system after synchronization with CESA.

Comparing the frequency deviations in the Latvian (BRELL) and French (CEN) power systems, the BRELL system has smaller frequency deviations from the nominal value than in the Central European power system. The choice of BESS parameters was influenced by different frequency characteristics in different synchronous zones. Although the BRELL system proved to be more stable, the situation in Latvian power system after desynchronization from BRELL will be quite unique, and the frequency dynamics in the Latvian power system may change. Possible frequency dynamics cannot be predicted; however, authors assume that most likely, higher frequency deviations are expected.

Considering the frequency data of the Latvian power system for 2018 and 2019, the indicative amount for frequency containment reserve could be provided by BESS with at least 11 MW installed power and with a storage capacity of 7 MWh. In addition, 1 MW of installed power should be provided to maintain a normal charge level through planned market transactions. Thus, 12 MW and 7 MWh should be provided in total.

In the event of greater frequency fluctuations, as observed in France in 2019, more power capacity could be required to maintain the SOC level and to ensure continuity of FCR services. The calculations estimated the need for 2 MW of additional power capacity. Thus, the BESS with 13 MW and 7 MWh in total could be installed. However, here the intraday market organisation principles are important. The intraday market in France closes 30 min before the operating hour, while participants in the Latvian intraday market can submit their requests and proposals for transactions on the current day, no later than one hour before the operation hour. One hour for frequency deviations as in the French power system would be too long to keep the SOC levels at permissible limits, and there are risks suspending the provision of FCR. This will require a greater capacity of BESS to keep the provision of FCR until starting the scheduled transaction for SOC renewal.

The BESS project will payback during the technical life of the battery (10 years) as long as the price of the FCR service is at least 14 EUR/MW per hour. At this price, the planned BESS revenue will be EUR 1.32 million per year. However, there are currently no clear forecasts for the future development of FCR service prices. There is currently no FCR market in the Baltic power system, so the costs of the region's FCR service are difficult to predict. For example, with the introduction of daily auctions, the price of the FCR service in the German market decreased from 14.6 EUR/MW/h in 2017 to 8.7 EUR/MW/h in 2019. The price of the FCR service will be determined by the marginal price of the bids offered in the auction.

All calculations were performed under certain assumptions and under certain selected parameters to assess the possible operation of the BESS for the provision of the FCR service and the potential income and costs of the BESS. Changing the parameters of the BESS model may change the overall results.

In general, in 2025 or after synchronization with the Continental Europe Synchronous Area, it is worth to consider battery electric storage systems as alternative equipment to provide sufficient levels of frequency containment reserves. Feasibility study may discover that for viability reasons it is necessary to maintain an option to use the BESS, as well as for other ancillary services.

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Conflicts of Interest: The authors declare no conflict of interest. The publication consists of algorithm, technical calculation, and open methodology for calculating technical parameters.

Nomenclature

Δf	Deviation of actual frequency f from the nominal frequency
Δf_{max}	Maximal frequency deviation at which total prequalified FCR power should be activated
Δt	Time moment of 1 min in the studied case
aFRR	Automatic frequency restoration reserve
BESS	Battery electric storage system
BRELL	Belarus, Russia, Estonia, Latvia, Lithuania
CAES	Compressed Air Energy Storage
CEN	Continental European Network
CESA	Continental Europe Synchronous Area
DOD_{max}	The coefficient of maximum depth of discharge
E_{BESS_fact}	Actual available capacity of the battery
E_{BESS_nom}	Nominal battery electrical capacity
ESS	Energy storage systems
f	Actual frequency
FCR	Frequency containment reserve
f_{nom}	Nominal frequency f = 50 Hz
FRR	Frequency restoration reserve
mFRR	Manual frequency restoration reserve
$P_{BESS(t)}$	Battery power at time moment t
$P_{FCR(t)}$	Actual necessary positive or negative power for FCR provision according to frequency deviation
P_{FCR_max}	Maximal FCR power
PHES	Pumped hydro stations
PST	Planned transaction capacity
RR	Replacement reserve
SMES	Superconducting Magnetic Energy Storage (SMES)
SOC	State of charge
$SOC_{(t)}$	The state of charge of the battery at time moment t
$SOC_{(t-1)}$	State of charge at previous time moment
SOC_{max}	Maximum SOC
SOC_{min}	Minimum SOC
SOC_{norm}	Normal state of charge
SOC_{OF_max}	Maximum state of charge for activation of FCR overfulfillment
SOC_{OF_min}	Minimum state of charge for activation of FCR overfulfillment
SOC_{ST_max}	Maximum state of charge for activation of scheduled transaction
SOC_{ST_min}	Minimum state of charge for activation of scheduled transaction
TSO	Transmission system operators
t_{ST}	Duration of scheduled transaction
UPS	Russian United Power System
η_{BESS}	Round-trip efficiency of battery storage system

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THE ROLE OF DECENTRALIZED ELECTRODE BOILER IN ANCILLARY SERVICES AND DISTRICT HEATING: A FEASIBILITY ASSESSMENT

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This article evaluates the feasibility of using electrode boiler in grid ancillary services and district heating scenarios. Electrode boilers in the context of electricity grid management can be considered as a relatively new technology. This study assesses the technical and economic viability of electrode boiler by considering various factors such as energy demand, technical feasibility, economic viability, and regulatory market conditions. The simplified mathematical model has been developed for simulation of electrode boiler use for grid services and heat production. The results have shown that electrode boiler have the potential to be a cost-effective solution for heating and grid balancing services in certain scenarios. However, it may not be applicable or economically viable in all situations or regions; thus, further research and development is needed to fully realize their potential.

Keywords: *Balancing markets, CHP, electrode boiler, heat and power production.*

1. INTRODUCTION

It is widely acknowledged that combined heat and power plants (CHPs) can play a significant role in providing resilient energy systems. This is due to their ability to switch generation between electricity and heat, as well as operate in cyclic modes [1], [2]. Considering the rapid development of renewable energy sources and the emergence of new balancing markets, there is still a need for a comprehensive study on individual power-to-heat technologies that could further enhance the flexibility provided by CHPs. One such technology is the electrode boiler (EB).

EB is a device that uses electricity to generate heat for individual or district heating systems, or other industrial processes. Regarding electrode boilers, two types are typically distinguished: those with an electric heater (known as electric resistance boilers) and those with electrodes. Due to their larger capacity, electrode boilers are most often used for district heating purposes. EBs can provide hot water as well as steam with efficiencies up to 99 % (η^{EB}_{avg}) and capacity of 5–70 megawatt (MW) [3], [4]. Other characteristics of electrode boilers are shown in Table 1.

Table 1. Electrode Boiler Characteristics [2], [5]

Parameter	Electrode boilers	
Ramp rate up/down, s	from less than 30 s	
Operating temperature level input, °C	10-110	
Operating temperature level output, °C	water: 70–140, steam: < 300 at 45 bar	
Investments for different EB capacities, million EUR/MW	Voltage and installed capacity	Net investments
	400 V and 1–3 MW	0.13–0.16
	10 kV and 10 MW	0.06–0.09
	10 kV and 20 MW	0.05–0.07
Total operations and maintenance (O&M)	-	
Fixed O&M, EUR/MW per year	1100	
Variable O&M, EUR per megawatt hour (MWh)	0.5	

As it can be seen in Table 1, the investments are decreasing with the increasing of EB capacity. To address potential cost fluctuations, including those attributed to inflation, this publication will incorporate a sensitivity analysis, considering cost adjustments of +15 % and +30 % for EB investments. Besides, valuable characteristics mentioned in Table 1, integrating EBs in CHPs is often associated with accommodation of large shares of variable renewable energy. Study [6] argues that despite an increased need for balancing renewables and the technology being available, initiatives to use them, for example, in Sweden district heating systems as flexibility sources are rare because the potential gain is considered low and unpredictive.

Nevertheless studies [7]–[10] emphasize importance of flexibility services provided by EBs. Most efforts of reviewed studies were focused on the electricity day-ahead market. Even though the number of works studying the participation in the balancing markets is limited, EBs still demonstrate the potential to increase the flexibility provided by CHPs, due to their high ramp rate from minimum to full load and high efficiency.

In this publication, the installation of EB is evaluated. The aim is to assess different EB capacities and the potential benefits from participating in heat and Baltic balancing markets. More specifically, restoration reserves with manual activation (mFRR) are evaluated in this paper, 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 [2], 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.

The remaining part of this publication is structured as follows: Section II provides an overview of the current situation and CHP operation, as well as outlines the research problem and formulates the hypothesis. Section III presents and explains the mathematical model used for evaluation and calculation. Section IV presents results of mathematical simulation and feasibility assessment. Finally, Section V draws up the main conclusions of the research.

The study provides a reference for interested parties, including policy makers, foreseeing the landscape for power to heat system development.

2. AN OVERVIEW OF THE CURRENT SITUATION

A. Insight into the Energy Sector of Latvia and Other Baltic States

As studied in [11], [12], the Baltic States for the period up to 2030 can face the following: (1) supply of electricity balancing reserves is expected to decrease because the oldest conventional generators are expected to exit the market; (2) due to high geopolitical tensions in relations with ongoing war from Russia since February 2022, natural gas prices hit records – in the Netherlands Title Transfer Facility reached 345 EUR/MWh in March 2022; (3) the growing share of intermittent and distributed generation in the Baltic power system; (4) rising price of carbon dioxide (CO_2) emission allowances; (5) synchronisation of the Baltic power system with the grid of Continental Europe, which will further increase demand for balancing reserves – frequency containment reserves and automated/manual frequency restoration reserves (mFRR and aFRR).

According to a balancing roadmap of the Baltic transmission system operators (TSOs), TSOs have committed to implement and make operational European platform for the exchange of balancing energy from mFRR (the so-called MARI platform) and exchange of balancing energy from aFRR (the so-called PICASSO platform). Baltic TSOs have to join MARI platform no later than 24th July 2024, and the introduction of PICASSO is planned to be concluded by the end of 2024. To ensure necessary reserves for operation of the Baltic States, Baltic TSOs also plan to procure reserves (FCR, aFRR, mFRR) as capacity products. Procurement of all three types of reserves will start at the end of 2024. The main parameters for all three types of reserves are shown in Table 2 [13].

Table 2. Three Types of Reserves – FCR, aFRR and mFRR

Standard product	**FCR**	**aFRR**	**mFRR**
Activation type	Automatic	Automatic	Manual
Activation time	< 30 s (2 s reaction)	< 5 min	< 12.5 min
Minimum volume	1 MW		
Direction	Symmetrical	Up and down	
Preparation period	0 min	0 min	< 7 min
Linking of bids	No		Yes
Activation command	- (based on local frequency measurement)	Signal (from TSO frequency restoration controller)	Message (WebService)

This study considers EB aligned integration in JSC Latvenergo natural gas combined heat and power plant one and two (CHP-1 or CHP-2) operation. Both CHPs not only hedge Latvia against possible shortages of electricity supply, but also provide heat energy for the right bank of Riga district heating system. CHP-1 has two gas turbines (P = 158 MW and Q = 145 MW) combined with three gas heat only boilers (HOB, 3 × 116 MW). While CHP-2 consists of two combined-cycle gas turbines CHP - 2/1 (P = 412 MW and Q = 275 MW) and CHP - 2/2 (P = 419 MW and Q = 270 MW) combined with five gas HOBs (Q = 5 × 116 MW) [2].

B. Definition of the Problem and Formulation of the Hypothesis

In [2], two hypotheses were proposed: (A) Replacing natural gas fired boilers with EB can lower power plant production costs during periods of low electricity price in Europe’s power market – Nord Pool; (B) Using EB can enhance the competitiveness of CHP plants. Both hypotheses generated positive incomes, although Hypothesis B was with lower income, making the installation of EB less attractive, while Hypothesis A showed more promise. This time, we will evaluate the benefits of providing regulation services to the transmission system operator through an EB. Therefore, the authors state the following hypothesis: The use of EB can not only reduce the heat production costs of CHPs, but also generate revenues from the Baltic balancing market, more precisely mFRR market, thus confirming the economic feasibility of EB integration in CHP operation, and making EB application more attractive.

C. The Baltic Balancing Market Volumes and Prices

Since 1 January 2018, a single balancing market has been operating in the Baltic States. Operation of the common Baltic balancing market takes place using balancing energy products: Baltic mFRR standard product and Baltic emergency reserve (ER) mFRR product. The total activated energy from mFRR and ER mFRR products in the Baltic balancing market for the four years can be seen in Fig. 1. On average, upward balancing electricity was activated in the amount of 193361 MWh during these years, and 210355 MWh for downward regulation.

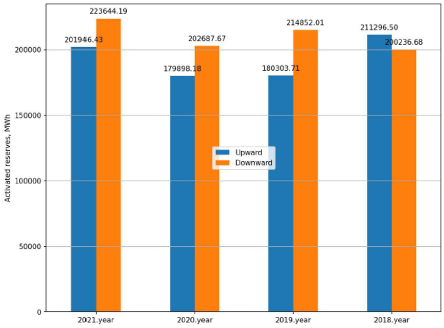


Fig. 1. Activated mFRR and ER mFRR volumes in the Baltic balancing market [14].

This study assumes that the EB will only be used for downward mFRR regulation, and the balancing market data and CHPs operation calculations are based on the year 2021. The reason for choosing 2021 is that CHPs units have been operating less than usual since 2022, due to the uncertainty surrounding gas availability following Russia's invasion of Ukraine.

Figure 2 shows the average annual reserve prices from normal activations for both upward and downward regulation in all three Baltic countries. The price of the ER mFRR specific product is not available on the Baltic Coba platform and not included in these statistics.

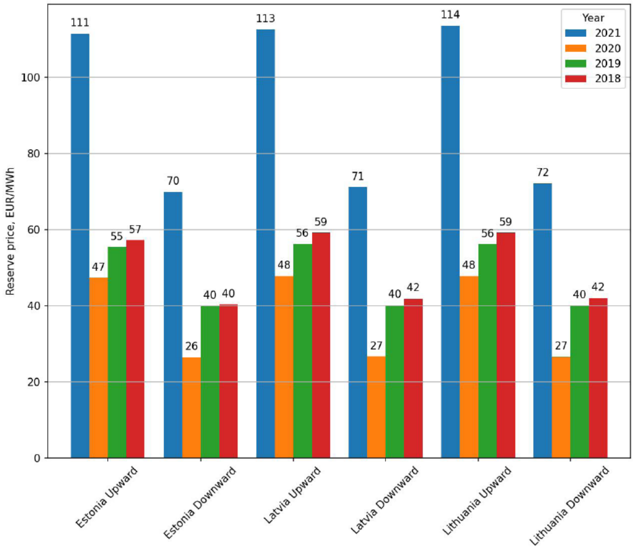


Fig. 2. Average annual reserve prices from normal activations [14].

It can be observed in Fig. 2, the downward reserve price is relatively lower than the upward reserve price. The EB can theoretically be used in the upward direction, but this study will not consider it. According to the Baltic balancing market rules, downward activation (or negative balancing energy) is balancing energy bid activation to reduce generation or increase consumption.

D. Future Research Prospects

The growth strategy of JSC Latvenergo focuses on ambitions plans which include the development of new renewable energy capacities, i.e., solar, wind parks. The company plans to implement renewable energy projects domestically and abroad, aiming for a capacity of 600 MW by 2026 and 2300 MW by 2030 [15]. Such a plan could be a reason to further analyse the use of EB to balance the ambitious renewable capacities in the portfolio of JSC Latvenergo. It is not under consideration in this study as the plans have not been implemented yet. In the future, opportunities to use EB in aFRR and FCR markets can also be explored.

3. METHODOLOGY FOR MATHEMATHICAL MODEL

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, replacement of HOB with EB could potentially reduce CO_2 emissions.

To evaluate the proposed hypothesis, a calculation model was created. The calculation principles of EB operation are shown in Fig. 3. Cycle is assumed to be one year. At the start of cycle, the inputs are defined. The inputs to the algorithms include data such as:

- actual heat load data of heat only boilers in CHP-1 and CHP-2 plant per time unit *i* (Q_i^{HOB}). For the relevant season, in the range of 0–546 MW, totalling 5751 hours a year;
- demand and price data for mFRR product per time unit *i* (A_i^{mFRR}, P_i^{mFRR}). In 2021, the demand amounted to 223644 MWh, with an average price of 71 EUR/MWh;
- the price of natural gas per month *m* (P_m^{NG}) was in the range of 0.226–1.237 EUR/m3;
- Nord Pool day-ahead electricity price per time unit *i* (P_i^E). In the range of -1.41 to +1000.07 EUR/MWh. On average, 118 EUR/MWh. Transmission costs and electricity taxes are excluded in calculations;
- the carbon dioxide price per time unit *i* ($P_i^{CO_2}$) ranged from 33.54 to 79.097 EUR/t;
- the average efficiency of the HOB (η_{avg}^{HOB}) was assumed to be 0.995;
- the carbon dioxide emission factor of natural gas (E_{CO_2}) was assumed to be 0.201 t/MWh;
- investments in CAPEX were assumed to be 0.08 million euros per MW, while fixed OPEX standed at 1,100 euros per MW and variable OPEX was 0.5 euros 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 electrode boiler, as well as EB operational costs and potential income together or independently from HOB replacement and mFRR market. Thus, all algorithms ensure evaluation of the formulated hypothesis.

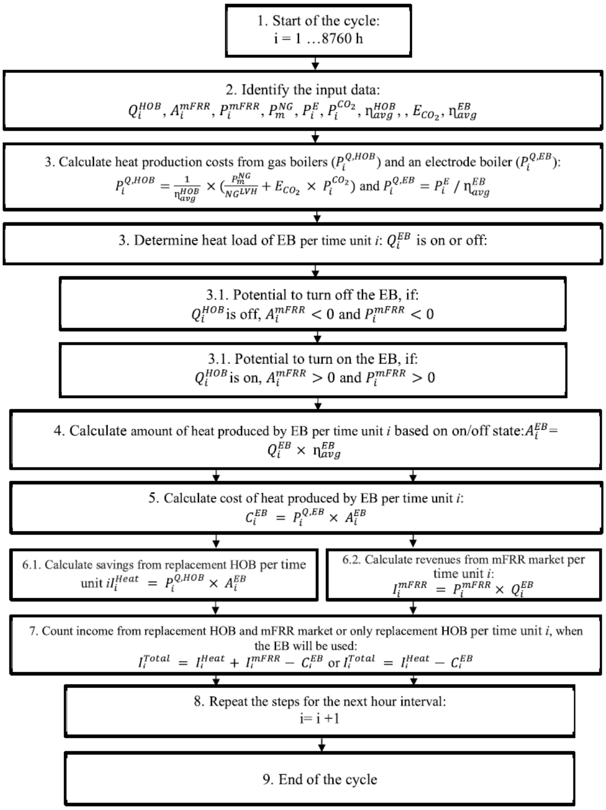
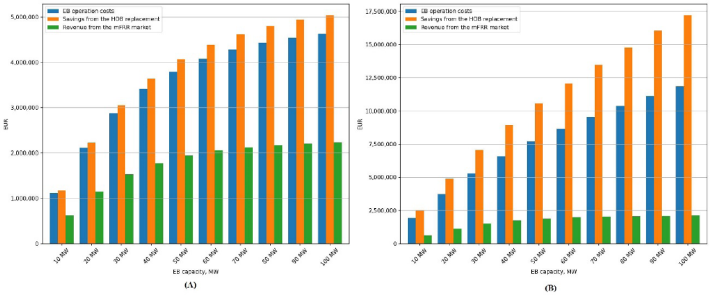


Fig. 3. The calculation principles of EB operation.

4. FEASIBILITY ASSESSMENT RESULTS

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 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 (Fig. 4). Figure 4 (a) represents the scenario where the EB operates and receives savings from HOB replacements and revenues in the mFRR market. Figure 4 (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.



(A) (B)

Fig. 4. Operation of EB in line with the formulated hypothesis.

Figure 4 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, Figure 5 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.

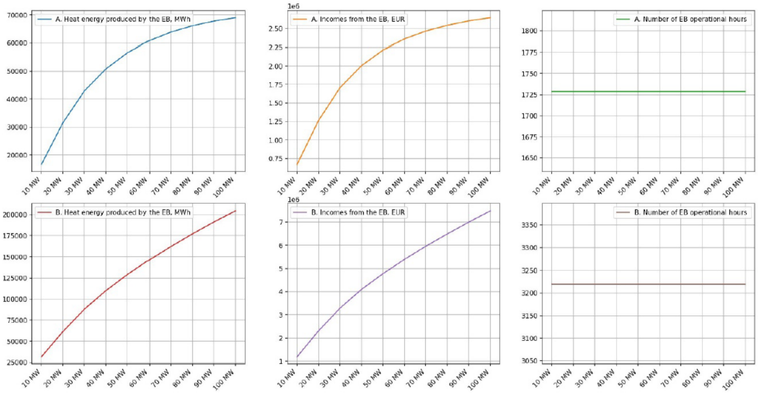


Fig. 5. Operation of EB in two scenarios A and B.

Figure 6 illustrates the broader characteristics for various EB capacity levels. It showcases the project economic indicators, which are expressed as net present value (NPV), internal rate of return (IRR) and the number of years it would take for the project to payback.

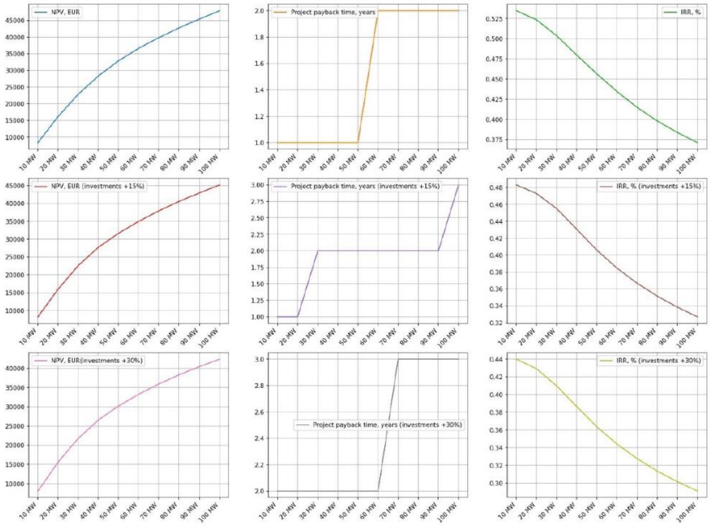


Fig. 6. Characteristics of EBs at different capacity.

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, revenues from mFRR market (Figs. 5 and 6). Even more, the payback indicators of the project increase from such capacity. As a result, the authors suggest that developing an EB of this size (50–60 MW) would be advantageous.

Figure 7 shows the hours of operation for both the HOBs and EB (with 50 MW capacity) throughout the year.

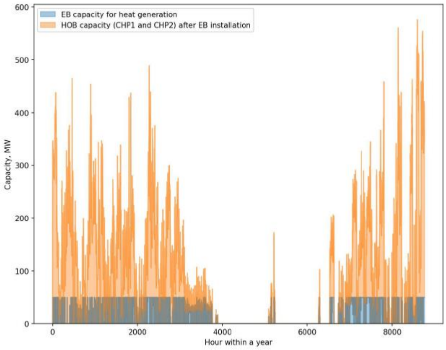


Fig. 7. HOB and EB capacity on an annual basis.

The HOB capacity is denoted in orange, while the EB capacity is shown in blue. Figure 7 demonstrates that the performance of the EB is reliant on the nature of the HOBs. Additionally, it indicates that the utilization of the EB could be even further enhanced if there were possibility to increase EB capacity or it could be profitable to operate under another heat or electricity market conditions.

5. DISCUSSION AND CONCLUSION

EBs have the potential to play an important role in ancillary services and district heating, offering a reliable and efficient solution for meeting energy demands. However, to assess their feasibility, a comprehensive evaluation is necessary, considering various factors such as energy demand, technical feasibility, economic viability, and regulatory market conditions. This paper considered the economic feasibility of EBs in ancillary services and district heating, providing a framework for decision making and helping to ensure that this technology could be deployed effectively.

The formulated hypothesis was proven, i.e., the use of EB can both reduce the heat production costs of CHPs and generate revenues from the Baltic balancing market. The magnitude of the income depends on the chosen EB capacity. In the authors' opinion, the EB with capacity of 50–60 MW can be sufficient, as there are no further significant improvements in economic characteristics. In addition, the use of the EB for balancing the portfolio of JSC Latvenergo, as well as the participation in the FCR and aFRR market, can even more increase the efficiency of EB use, thus also the feasibility. Furthermore, it is crucial to enhance the research by performing a comprehensive evaluation of various cost factors, including but not limited to the expenses associated with network connectivity, the initial and operational cost of the EB itself. Considering these factors, the feasibility can be assessed more precisely.

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