RIGA TECHNICAL UNIVERSITY

Edgars Kudurs

ELECTRICITY STORAGE TOWARDS SUSTAINABILITY

Summary of the Doctoral Thesis

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RIGA TECHNICAL UNIVERSITY
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Summary of the Doctoral Thesis

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DOCTORAL THESIS PROPOSED TO RIGA TECHNICAL UNIVERSITY FOR THE 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 the RTU Promotion Council on April 25, 2024, at 14.00 at the Faculty of Natural Sciences and Technology of Riga Technical University, Āzenes Street 12/1, Room 116.

OFFICIAL REVIEWERS

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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.

Edgars Kudurs ……………………………. (signature)
Date: ………………………

The Doctoral Thesis has been written in Latvian. It consists of an introduction, three chapters, conclusions, 23 figures, and 12 tables; the total number of pages is 167. The Bibliography contains 82 titles.

CONTENTS

INTRODUCTION

Topicality of the Doctoral Thesis

The Green Deal outlined by the European Union is leading its memberstates towards climate neutrality also in the energy sector by setting an increase in the share of renewables. In this case, the leading role will be the use of renewable energy sources of a seasonal nature, such as solar and wind energy. Replacing fossil energy sources would, on the one hand, reduce greenhouse gas emissions into the air and mitigate the impact of climate change, while, on the other hand, it would bring about significant changes in the energy supply system, where some energy sources of electricity and heat would be produced periodically, intermittently.

This means that the management of energy systems must lead to fundamental changes not only on the energy producer's side but also on the energy transmission side, especially on the energy user's side.

In order to ensure that the energy demand varies with the energy user, energy storage becomes an essential element of the energy system. At present, the transition from micro and mini batteries at the level of small electrical appliances to large storage plants is important, which would allow to meet the electricity demand of a small electricity consumer, such as a household and medium and large user – a company or a municipality, involving the use of energy storage also at the regional and national level.

The development of storage systems in the world is taking place at a rapid pace, with innovations developing in different directions not only at the level of individual technological equipment but also in the creation of various storage systems, when electricity is converted into products with high added value, for example, e-fuel, hydrogen, biomethane, etc.

The Doctoral Thesis is devoted to the analysis of the potential of specifically selected types of accumulation and the modelling of their development.

Purpose and tasks of the Doctoral Thesis

The aim of the Doctoral Thesis is to understand the technological possibilities for electricity storage, as well as to find out how and what factors affect the implementation of these technologies, including researching the possibilities of energy accumulation, which would allow the energy system and the economy to move towards energy independence, including various sub-sectors of the economy, companies, municipalities and also household energy consumers, to achieve climate neutrality goals.

To achieve the set goal, the following tasks are performed in the research.

1. Create various databases based on the accumulation indicators found in the scientific literature and the results of practical examples:
   - engineering, economic, environmental and climate characteristics of various technological solutions for accumulation;
   - hydroelectric power activity datasets.
2. Choose criteria for the use of energy storage and determine their importance.

3. Evaluate and prioritize the best innovative technological solutions for energy storage for two energy storage methods separately: (i) storage facilities and (ii) storage systems.
4. Feasibility study of alternative energy storage options.
5. Perform modelling of the operation of the household energy storage system by creating a system dynamics model:
   - a household energy supply system with simple energy storage;
   - a household power supply system with hybrid storage.
6. To carry out an analysis of the possibilities of accumuling watersheds of hydroelectric power plants in order to integrate excess wind electricity.

Thesis hypothesis

The development of innovative energy storage systems depends on changes in the share of renewables in energy supply systems at all levels.

Scientific novelty of the Doctoral Thesis

In order to implement the goals set in the Doctoral Thesis, scientific research has been carried out, which is based on the principle of gradualness: from the simplest to the most complex. The methodologies used in the Doctoral Thesis are illustrated in Fig. 1.

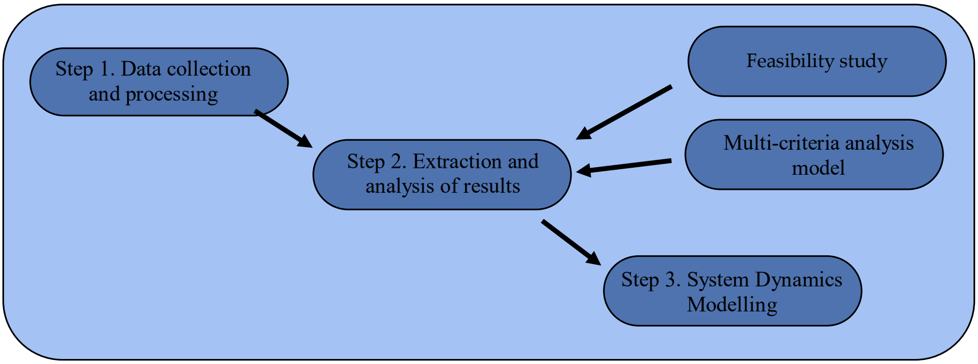

Fig. 1. Methodologies used in the research.

The following methodologies and models were developed and adapted in the course of research for the analysis of energy storage options.

1. Based on the analysis of the scientific literature, engineering, economic, environmental and climate data on various energy storage equipment and systems were collected and a database was created.
2. Data on the performance of different renewable energy sources in different time periods and climatic conditions have been obtained and analysed.
3. Using the multi-criteria analysis model of TOPSIS and AHP, both energy storage equipment and systems have been evaluated and arranged.

4. Based on the data analysis, the baseline scenario methodology for the storage of RES electricity has been prepared, and based on the data analysis the methodology has been copied for the technical economic analysis of different scenarios.
5. A cluster method has been developed for expanding the functions of hydroelectric power plants (HPPs) using reservoirs for the accumulation of excess wind electricity.
6. Two system dynamics models have been developed for integrating energy storage into the household energy supply system.

Practical significance of the Doctoral Thesis

The insights gained during the research process can be applied to various equipment and systems of electricity users, from the household to the regional and national level.

The development of energy storage systems is progressing rapidly, and scientific innovations and their practical application play an important role. For any energy user, the classification of energy storage carried out in the Doctoral Thesis and it's ranking according to the characteristics of the best solutions, using the multi-criteria analysis method, is useful.

1. Electricity and heat storage plays an essential role in a household's energy supply system. The system dynamics models developed in the Doctoral Thesis provide answers to the household energy consumer about the directions of implementation of energy storage (only storage or hybrid storage) and their generosity.

2. The work done in the Doctoral Thesis at the level of enterprises and local governments, with the development of storage development scenarios recommended therein and the analysis of a wide range of storage technological solutions (engineering equipment or storage system), will provide an opportunity for small, medium and large energy users to assess the place of the energy storage system in the energy supply system.

3. For the developers of the national energy policy, the issue of the use of surplus wind electricity at the national level is topical. The cluster proposed in the Doctoral Thesis for balancing wind electricity and hydropower – to store seasonal electricity in hydroelectric reservoirs – outlines an alternative option at the national level.

Approbation of the Doctoral Thesis

In scientific publications

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At scientific conferences

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CONECT 2023: XVI International Scientific Conference of Environmental and Climate Technologies: 2023.

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3. Vamža, I., Valters, K., Dzalbs, A., Kudurs, E., Blumberga, D. Criteria for Choosing Thermal Packaging for Temperature Sensitive Goods Transportation. *Environmental and Climate Technologies,* 2021, Vol. 25, No. 1, pp. 382–391. ISSN 1691-5208. e-ISSN 2255-8837. Available at: doi:10.2478/rtuect-2021-0028
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Structure of the Doctoral Thesis

The research of the Doctoral Thesis is aimed at the settings of problems with the implementation of energy storage systems and their analysis. Six problems are addressed.

1. In the energy supply system, renewable energy sources (RES) are increasingly replacing fossil energy sources, while the share of all resources related to the combustion process is also decreasing. Energy storage will play an important role here.

2. Technological solutions for storage systems are developing rapidly, and the impact of innovation is increasing.

3. All Member States of the European Union have committed to achieving climate neutrality as early as 2050, and it will not be possible to do so without a switch to renewable energy sources and energy storage solutions.

4. A household's energy systems can be part of a large energy system, become a component of an energy community or become a small energy-independent energy system. It all depends on the development and location of the accumulation system.

5. The choice of renewables is increasingly being considered in order to align self-storage options when considering the storage of watersheds in hydroelectric power plants.

6. When switching to renewable energy sources of a seasonal nature (sun and wind), it is important to simultaneously analyse the possibilities of extending the duration of electricity production on a daily, monthly and annual basis, for example, to develop a technological solution with higher-placed wind generators.

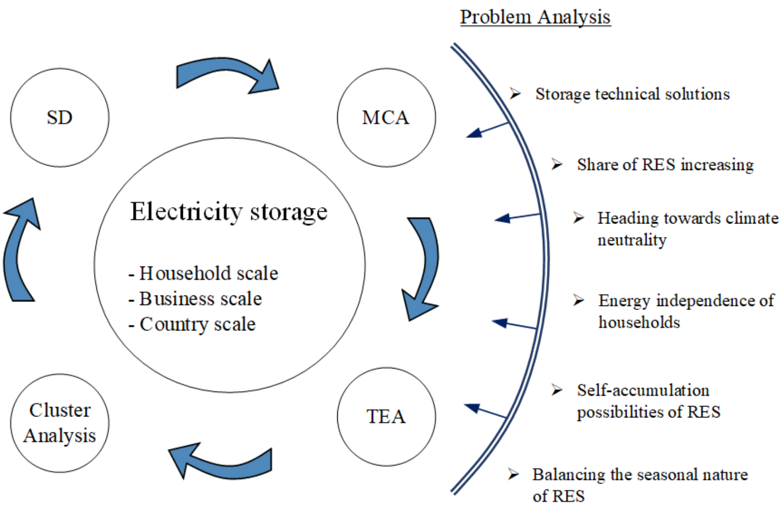

Fig. 2. The structure of the Doctoral Thesis.

The structure of the Thesis is illustrated in Fig. 2.

The Doctoral Thesis explores the storage of energy (more electricity) in various sectors of the national economy: from the national level, municipal and enterprise users to the household sector and individual energy consumer.

Storage system solutions and capabilities are analysed with various methodologies: multi-criteria analysis (MKA), feasibility analysis, data set cluster analysis and system dynamics modelling.

1. METHODOLOGY

1.1. Multi-criteria analysis using TOPSIS method

This study used TOPSIS, Multi-Criteria Analysis (MCDA), to determine the best solution among electricity storage technologies.

Multi-Criteria Decision Analysis (MCDA) is a multi-step process consisting of a set of methods to structure and formalize decision-making processes in a transparent and consistent way. The MCDA methodology can be considered a nonlinear recursive process consisting of four steps:

- structuring the problem of decisions;
- formulation and modelling of preferences;
- compilation of evaluations (preferences) of alternatives;
- making recommendations.

When evaluating MCDA alternatives, it is important to define the criteria that affect the problem. The most popular MCDA are economic, environmental and social criteria.

MCDA is used to make decisions and analyse the relevance of goals from a variety of information and data – qualitative and quantitative, physical and social science data, as well as the data from politics and ethics to evaluate solutions to problems. Various MCDA methods can be used to solve problems and can be sorted by several parameters and the type of their model.

TOPSIS method is the method of selecting orders based on similarities with ideal solutions. This follows from the concept of the shifted ideal point from which the compromise solution has the shortest distance. The main advantages of TOPSIS are the identification of an infinite number of criteria and alternatives by a relatively simple calculation method. In addition, to use this method does not require special software or special programming methods.

TOPSIS results provide an alternative comparison in a useful and easy-to-understand format. For evaluation, alternatives should be selected that are evaluated according to four criteria: technological, economic, environmental and social. The first step using the TOPSIS method is the normalization of the decision matrix, followed by the calculation of the best and worst solutions of the normalized decision matrix. The best solution corresponds to the theoretical variant of the desired level for each criterion, while the worst solution corresponds to the theoretical variant of the least desired level for each criterion. Finally, the distance of each alternative is calculated, which further allows to obtain a proximity factor of the alternatives to ranking. Alternatives rank from the best to the worst. The equations for the TOPSIS method used in this study are as follows:

a) the value of the normalized matrix can be obtained by multiplying the normalized value and weight;
b) the distance for each ideal and non-ideal alternative can be calculated by summing the squares of the values of the weighted criteria;
c) The proximity factor (Ca) shows the distance to the non-ideal solution, which is determined by the equation dividing the distance to the non-ideal solution by the sum of the distances to the non-ideal solution.

For more accurate results, energy storage technologies were compared in two groups. When assessing the scalability and technical characteristics of the technologies, it was determined that lead-acid, lithium-ion, and flow and sodium-sulphur batteries will be compared in one group, and in the other group, storage systems considered in the literature, adiabatic compressed air energy storage systems, diabetic compressed air energy storage systems, hydroelectric power storage, pumping heat electricity storage technologies, hydrogen energy storage green ammonia storage technologies will be compared. Nine comparison criteria were established for batteries, while eight criteria were established for storage systems without assessing capacity density. Technological, economic, environmental, and social aspects were taken into account in the definition of the criteria. The matrices created, the criteria defined, and the assigned values are shown in Tables 1.1 and 1.2.

Table 1.1

Overview of Selected Criteria for Batteries

	Criteria	A1 Lead-acid battery	A2 Lithium-ion battery	A3 Flow battery	A4 Sodium-sulfur battery
C1	Investments, EUR/kWh	150	450	250	375
C2	Power density, W/kg	75	260	130	150
C3	Cycles, count	1750	5000	4500	4500
C4	Duration of operation, years	10	17.5	30	17.5
C5	Response time, s	0.003	0.003	0.003	0.003
C6	Efficiency, %	80	94	72.5	75
C7	Climate impact factor, $kgCO_{2eq}/kWh$	0.2	0.175	0.183	0.67
C8	Technological readiness (1–5)	3	4	2	3
C9	Social factor (1–5)	2	3	1	2

Most of the numerical values in the matrix were obtained after analysing the literature, assuming that the average values are in a given range. Meanwhile, the criteria for technological readiness and social factors were determined on the basis of the information found in the literature analysis, and a survey was also conducted among industry experts. In this case, the criteria were set on a five-point scale, assigning values from the lowest (1) to the highest (5). Accordingly, the social factor of energy storage technologies was assessed on the basis of their impact on sustainable development, taking into account incentive and disincentive factors, as well as a participatory dimension and good practices for integrating energy storage into practice. The more positively the technology was evaluated in terms of its impact on sustainable development and commercialization potential, the higher the assigned value. Meanwhile, technological readiness was assessed based on the technical maturity of the battery or its proximity to wider commercialization. Accordingly, the more developed the technology and the wider its availability on the market, the higher the rating was given. Battery investments were compared as the specific cost of battery investments per kWh. The power density criterion determines the ability of the battery to release energy at a certain moment. Storage solutions with higher power density can power higher electrical load devices. Meanwhile, the number of cycles is related to service life and efficiency, since this parameter describes the number of charge/discharge cycles that the battery can provide before the performance deteriorates. The reaction time parameter characterizes the time required for the system to provide energy at full rated power. Although this parameter is the same for observed batteries, it is more important for comparing energy storage systems. As well as the criterion, a climate impact factor was proposed, which in this case characterizes the intensity of the emissions generated when renewable energy is stored.

Table 1.2

Overview of the Selected Criteria for Accumulation Systems

	Criteria	A5 Adiabatic comp. air	A6 Diabatic comp. air	A7 Pumped hydro	A8 Pumped. heat el.	A9 Hydrogen energy	A10 Green ammonia
C1	Investments, EUR/kWh	1600	800	3400	350	750	2900
C2	Cycles, number	10^6	10^6	10^6	15000	10^6	10^6
C3	Duration of operation, years	30	30	80	25	17.5	30
C4	Response time, s	180	180	0.003	2	60	1
C5	Efficiency, %	70	55	77.5	72.5	30	52.5
C6	Climate impact factor, $kgCO_{2eq}/kWh$	0.15	0.185	0.165	0.175	0.1137	0.003
C7	Technological readiness (1–5)	2	3	4.5	1	2	1
C8	Social factors (1–5)	2	2	3	2	5	5

The energy storage system matrix was also based on the criteria, assumptions, and sources described in the battery matrix. However, the power density criterion was not assessed here. Given the different components of the systems, it is impossible to compare this parameter separately. Likewise, the economic aspect in this matrix was determined as capital expenditure per kW, given that they are mainly perceived as long-term expenses. Using the TOPSIS method, all criteria were assigned the same weights of 0.111 when evaluating the battery criteria, and 0.125 when analysing the criteria of the storage system. This assumption was subjectively made by the author in order to avoid mistakes in the weighing process, since in this case, when analysing storage technologies, it is impossible to distinguish the meaning of the criteria. After the TOPSIS analysis, a sensitivity analysis was performed to assess the change in the results obtained depending on the criteria or the determination of changes in weight from influencing factors. Sensitivity analysis is a research method that determines how different sources of uncertainty in mathematical models contribute to the overall uncertainty of the model. This method is used within certain limits that depend on one or more input variables. Sensitivity analysis is often used in the business world and in the economy. It is usually used by financial analysts and economists.

In order to determine the impact of alternative allocations on the results of the TOPSIS method, the meaning of equal alternatives is determined. Initially, the weights are set to w = 1/n (where n is the number of influencing parameters). The weight subject to change is determined by multiplying the change in weight by a uniform coefficient of variation summing up to 1. The distribution of other weights is changed, according to Equation (1).

$$w_{k21} = w_{k31} = \frac{(1-w_{k11})}{n-1}, \quad (1)$$

where
w_{kxx} – weight, which can vary;
n – number of influential parameters.

The initial weights of the alternatives are replaced by the newly acquired scales in the TOPSIS matrix, and the approach is repeated with the results of all the established criteria. In this research, a sensitivity analysis was carried out for each criterion, varying the weight values from 0.1 to 0.9.

1.2. System dynamics modelling

So far, the integration of storage technologies in households in Latvia is close to zero. There is a lack of aggregated data on energy storage projects implemented. Consequently, it is also necessary to analyse the profitability of the introduction of electricity storage in Latvian households.

The development of a sustainable energy sector requires an understanding of the electricity storage potential, which is an essential component of building an environmentally friendly energy infrastructure. SD models were used to analyse the dynamic behaviour of power storage systems.

SD provides holistic study of complex interconnections of systems in complex systems, allowing for nuanced testing of feedback loops, time delays, and nonlinear relationships. The SD theory is based on the study of the relationship between the behaviour of the system and the underlying structure of the system. This means that by analysing the structure of the system, a deeper understanding of the causes of the behaviour of the system is formed. According to the author, this is best done with SD. For decades, system dynamics modelling has been used in energy systems research. Models of system dynamics can take into account four main factors that are often ignored by other modelling methods: material and information delays, nonlinear relationships, causality rather than correlation, and feedback in the system. The research reflects the two developed separate SD models. One has been used as a base model to predict the prevalence of electricity storage solutions in households by studying factors influencing decision-making. The second, as a case study, which explored the economic rationale for the use of storage in households, is shedding light on financial considerations and impacts in integrating energy storage solutions into households. This section of the methodology aims to make a significant contribution to the ongoing discourse on creating a sustainable energy environment through the synthesis of theoretical bases and practical applications.

System dynamics model for forecasting electricity storage in households

In order to predict the practice of electricity storage in Latvia in the coming decades, the SD modelling method was used. The modelling was carried out using Stella Architect software.

Contextualisation of the model

As defined by Sterman, there is no single best approach to successful modelling. Nevertheless his Five-step Guidelines, including (1) problem formulation, (2) dynamic hypothesis building, (3) model formulation simulation, (4) model testing, and (5) policy making and testing, are widely used in the creation of the SD model, as well as being observed in current research.

The problem analysed, identified in the introduction, is the need to increase the share of renewable electricity, especially from carbon-neutral sources as photovoltaic solar panels (PV). As PV technologies are suitable for decentralised use, households' benefit. Although the recent increase in the number of PV equipment is due to the decrease in equipment prices and subsidy policy, the installation of combined PV and energy storage system (ESS) is still not widespread. The selected modelling time frame is up to 2050, which is in line with the EU's vision for climate neutrality.

The dynamic hypothesis of the study is shown in Fig. 1.1 in the form of a causal loop diagram.

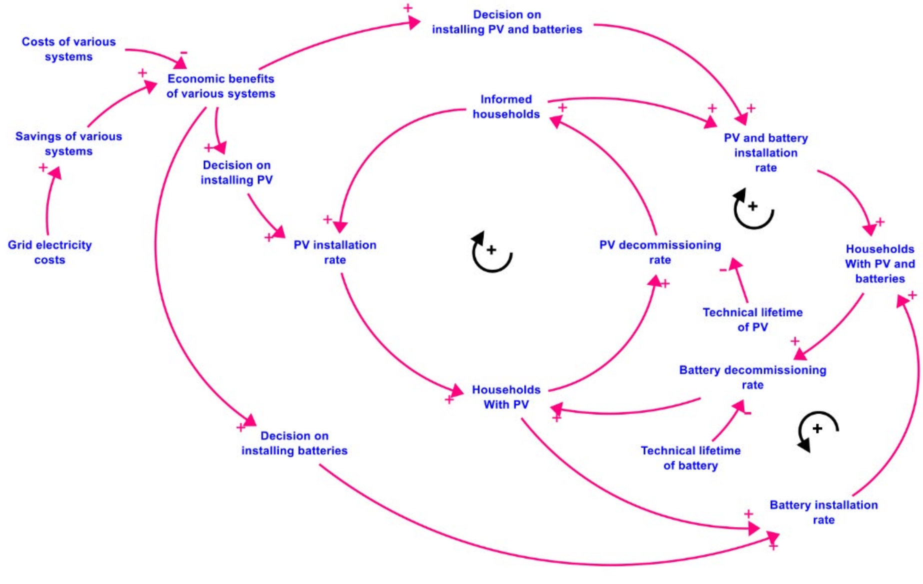

Fig. 1.1. PV and battery storage diffusion causal loops.

The causal loop diagram illustrates the process of diffusion of PV and batteries in the household sector. The centrepiece is informed households who have considered the possibility of installing PV or batteries but have not yet made a final decision. This is the origin of the spread of specific technologies. Households that are not informed cannot make a decision, and only informed households can do so. The causal loop diagram shows several development paths, including the possibility of installing only PV panels or a combined PV and battery storage system. The decision is made by comparing the economic benefits, including the benefits of choosing each system. The decision to install the battery can be made by both informed households and those in which PV panels are already installed. Due to the limitations of the technology's service life, decommissioning costs are included in the modelling of the diffusion process. Each technology has its own service life. After decommissioning, households can choose the next solution.

The structure of the system dynamics model was created on the basis of the basic principles shown in the causal loop diagram, which is shown in Fig. 1.1.

Structure of the model

As a result of the dynamic hypothesis, a system dynamics model was created for the Latvian case study, which provides for the introduction of battery storage in private households. All input parameters, such as solar radiation, electricity price, number of households and other parameters used, were specific to the case of Latvia.

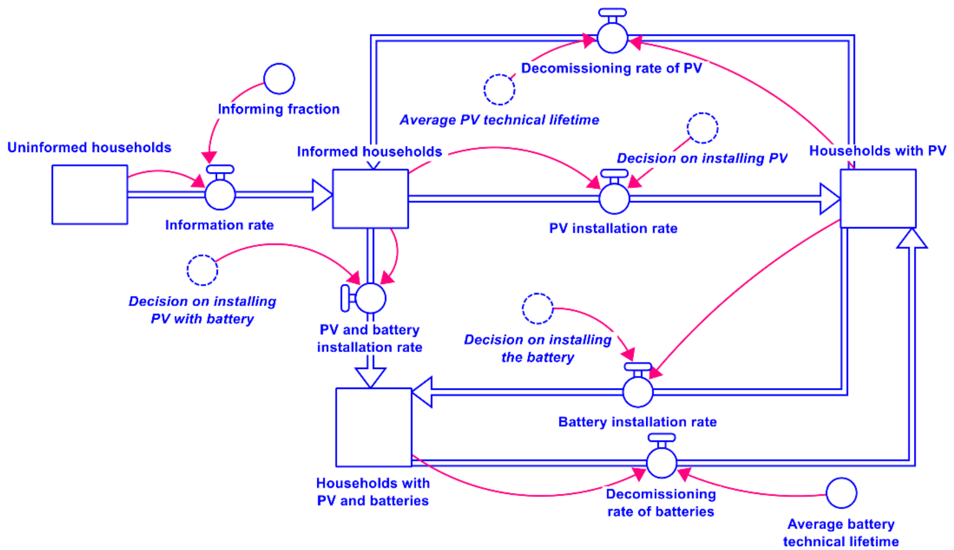

Fig. 1.2. PV and battery storage diffusion submodel.

The numerical values of the model parameters are based on assumptions obtained by analysing statistical databases, analysing electricity market data, as well as other sources. The central part of the model structure is shown in Fig. 1.2. This part of the structure reflects the dynamics of the installation of the main PV and battery system. An important parameter in the development of this model is the total number of private households (single-family buildings) in Latvia. In this study, the installation of a solar PV and battery storage system is evaluated and predicted for single-family buildings with PV and battery systems. Based on the statistical database, there are about 200 000 households of private houses in Latvia. The inventory "Uninformed households" describes the share of households that have yet to be informed about alternatives to self-generation and storage of electricity. When a household receives sufficient information, it moves from an "uninformed household" to an "informed household" stock and is ready to make a decision on microgeneration and storage. These stocks are influenced by the speed of information, which depends on the informing fraction, and the model assumes that it is 0.1. The uninformed household information indicator is obtained by multiplying the number of uninformed households by the information fraction describing the speed at which uninformed households are informed about these technologies.

Accordingly, households that obtain information and begin to evaluate the installation of PV or batteries make a decision to install one of the options (PV, batteries or both) or to maintain the current grid connection without additional technologies. Outflows characterize the total number of informed households and the decision taken accordingly. The flow "PV installation speed" in the model is obtained by multiplying the number of informed households by the investment decision in a particular solution. The outgoing flow "PV and battery installation speed" is also determined according to the same principle. The model also includes the flow "Battery installation speed", which describes the number of households who decide to install the battery when the PV has already been installed in advance, or to reinstall the battery, since the battery life is shorter than the duration of the PV system.

The stock "Households with PV" describes the number of households that have installed only PV panels. On the other hand, the stock "Households with PV and batteries" describes the number of households who have not only installed PV but also connected the battery. This figure is currently not counted and analysed in publicly available data. It was assumed that this figure is minimal, with five households as the initial value. Both of these stocks are also affected by outflows, which characterize the depreciation time of the technology, which is affected by the average life of the technology. This means that after the end of the technical service life of the technology, the household returns to its previous stock. Since the technical life of batteries is shorter than that of PV, households with PV and accumulators are switching to the stock "Households with PV" after the end of the technical life of the batteries, since they still have working PV left. After that, they can again make a decision to install batteries. "Households with PV" after the end of the technical life of the PV return to the stock "Informed households" and again can make a decision to install PV or PV and batteries. The flow "PV decommissioning rate" is determined by dividing the number of households that have specific technological solutions by the technical service life of a particular technology (PV or battery), in years. The flow "Battery decommissioning rate" is determined according to same principle.

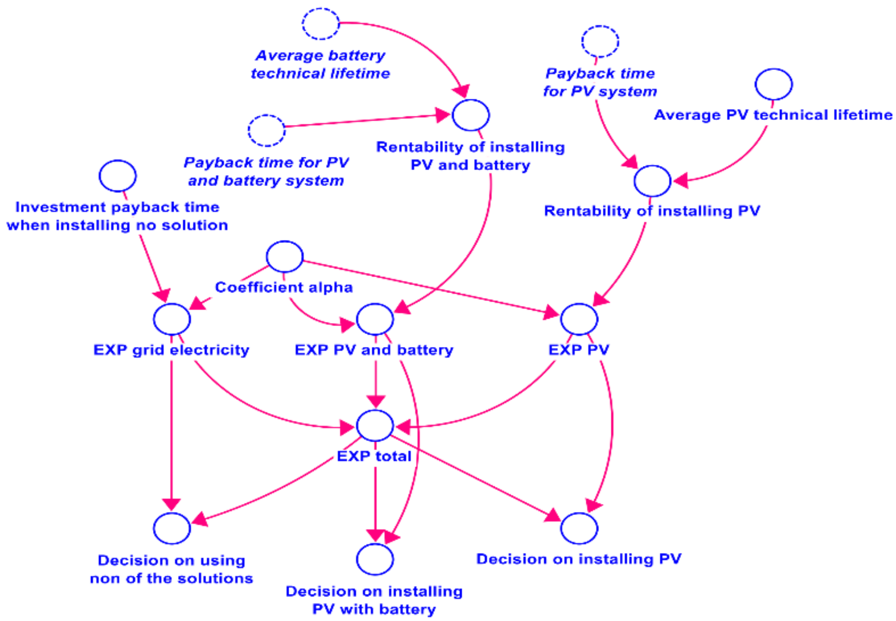

Fig. 1.3. Decision-making submodel.

The decision to install a PV or battery system in the model is made on the basis of the payback of each system. Figure 1.3 shows the structure of the model responsible for decision-making. In order for the system to be attractive, the payback period must be less than the service life of a particular technology. Otherwise, the choice in favour of installing a particular technology will be made only by those for whom the financial aspect is not decisive. The decision on the choice of technology is calculated using the "logistic" function in which the payback of all solutions is compared, including the situation when nothing is installed.

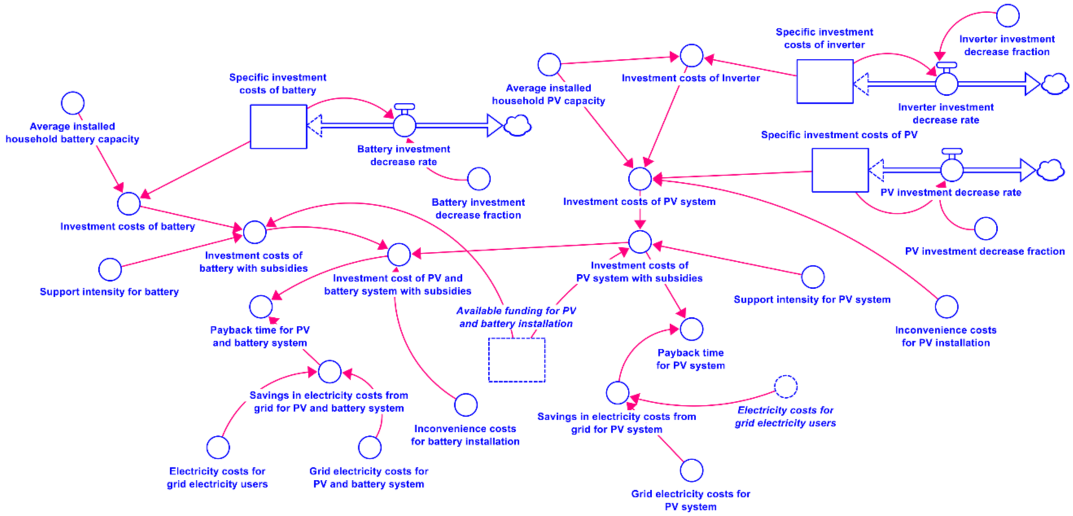

Fig. 1.4. Submodel for calculating the payback time.

Decisions on the installation of PV and battery systems are greatly influenced by the amount of investment required and the payback period of installation of technology. The cost of investment depends on the installed capacity of the technology. The payback period is also affected by the subsidies granted and the aid intensity. On the other hand, the payback period is affected by the necessary investments for the installation of technology, as well as the savings in electricity costs. A submodel of these influencing parameters is shown in Fig. 1.4. The payback period, if PVs are installed for a household, is determined by the investment costs of PV panels and the savings in electricity costs, which, respectively, is determined by comparing the annual cost of electricity with the grid connection and the cost of electricity with the installed PVs. The cost of electricity for grid electricity users, the cost of grid electricity for the PV system, and the cost of grid electricity for the PV and battery system were calculated using a previously developed model. This study assumed that the price of electricity is constant throughout the simulation period, so it was assumed that the cost of grid electricity for all three systems is also constant for the entire simulation. Similarly, the payback period of a system with storage is affected by savings in electricity costs and investment costs and is determined according to the same principle, where the gross payback time is calculated by dividing the final costs (includes subsidies, if any) by savings achieved through the use of a specific technology. The above collection "Available funding for the installation of PV and batteries" comes from a submodel with related flows and parameters. The amount of support available in the stock is also influenced by the allocation of the incoming funding flow, which characterizes the planned additional funding. According to the Ministry of Economics, support is planned in the amount of 20 million euros, however, separate funding is also available from the Ministry of Climate and Energy and the Ministry of Environmental Protection and Regional Development. In turn, the amount in stock is reduced by the outflow "Coefficient of use of funds", which characterizes the aid granted within the framework of implemented energy efficiency projects.

Input data and assumptions

This section describes the key input data and assumptions used in the system dynamics model. The relevant data on technology is taken from technology catalogues. Information on the average capacities of technologies is taken from statistical and scientific literature. Information on households is taken from statistical databases. The most relevant information used in the system dynamics model is shown in Table 1.3. These data reflect the current system situation and are used as initial values in the scenario modelling model.

Table 1.3

Model Input Parameters

Parameter	Value	Unit
PV investment costs (with installation)	1100	EUR/kW
Inverter investment cost	100	EUR/kW
Battery investment cost	800	EUR/kWh
Average installed household PV capacity	8	kWp
Average installed capacity of a household battery	5	kWh
Average PV technical service life	35	Years
Average technical life of the battery	20	Years
Number of single-family households	198 541	number
Number of households with PV	11 764	number

Historical electricity moment price data were taken from the NordPool database for 2013–2022 to assess changes in the immediate price of electricity and decide on the best value to use for simulation of battery diffusion forecasts. The annual average values were compared. Historical data show (see Table 1.4) that from 2013 to 2020 there are fluctuations in electricity prices, however, the price remains at 34–50 EUR per megawatt hour. It also depends on the price of imported electricity. 2021 and 2022 came with several shocks to the system. Since Latvia historically imported most of its natural gas from Russia, the rise in natural gas prices after the conflict between Ukraine and Russia had a devastating impact on the energy sector, and the average annual electricity price reached an unprecedented level – EUR 227 per megawatt hour. The author believes that given the many wind and solar projects at different stages of development, combined with the diversification of natural gas importers in the region, electricity prices will decrease. For the purposes of this study, it is assumed that the base price of electricity in the long term will be at the level of 2013–2020, and not at the level of 2021 or 2022.

Table 1.4

NordPool Average Annual Electricity Price for Latvia

	2013	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**
Average electricity price, EUR/MWh	48.40	50.12	41.85	36.10	34.68	49.90	46.28	34.07	88.77	226.92

There is no information about how many households have installed battery systems so far, so it is assumed that they are 5 and the average price of electricity will be constant for the entire simulation. The purpose of the current study is to test the structure of the model, and not to predict changes in electricity prices, so the price was determined as constant for the entire simulation. As regards subsidies, it was assumed that EUR 20 million would be allocated to all subsidy scenarios at the start of the simulation (based on national plans) and new finances of EUR 20 million will be allocated every 5 years.

Model validation

In order to build confidence in the model, it is necessary to conduct a number of model validation tests. No model exactly matches the real object or system being modelled, so absolutely reliable models do not exist. Models are considered reliable and valid if they can be used with confidence, but first you need to clearly define the purpose of the model.

The purpose of testing or approving a model of system dynamics is to determine the validity of the model structure. The accuracy of the reproduction of the real behaviour of the model is also appreciated, but this is only meaningful if we already have sufficient confidence in the structure of the model. Thus, the general logical sequence of validation is to first check the validity of the structure, and after the structure of the model is perceived as adequate, to begin to check the accuracy of the behaviour. This sequence was also used in this study. Verification of the structure and parameters was carried out in consultation with energy experts and by analysing the scientific literature in order to make sure that the structure of the created model complies with generally accepted principles and all parameters in the real system have an appropriate element. Since system dynamics are rooted in engineering theory, system dynamics models need to ensure consistency in size. The dimensional consistency test provided a dimensional analysis of the parameters used in the model equations. This test made it possible to make sure that no random error got into any of the equations. A test of extreme conditions was conducted to make sure that the model would work in the appropriate way even if the values fell out of the overall range. Behavioural validation tests were also conducted to assess whether the model could represent the behaviour of the real-life system. In order to assess sufficiency, the results of the model were compared with historical data on the integration of PV in Latvian households. The model describes the historical development of PV integration very well, as can be seen in Fig. 1.5. Although the simulated results do not exactly correspond to historical developments, the overall trend is very similar, and this builds confidence in the model.

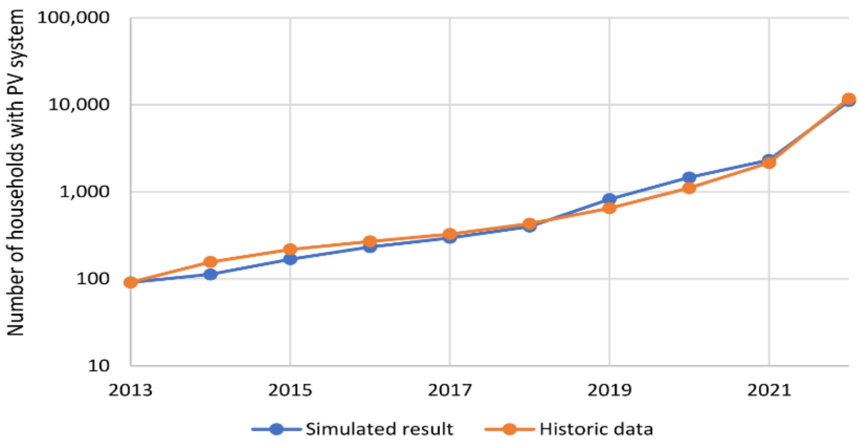

Fig. 1.5. Model validation with historical data for PV installation.

The historical development trend of the introduction of batteries cannot be compared, because so far, the installation of batteries in households in Latvia has hardly taken place and there is nothing to compare with. Based on the historical prices of batteries, technology parameters and electricity prices, the results of the model showed that in the period from 2013 to 2022, battery systems were practically not installed, since for the most part the payback time was much higher than the life of the battery. This also explains why there were almost no battery systems installed in Latvia during this period.

Definition of scenarios

This section describes the scenarios that were selected and modelled in this study. It describes which policy measure was chosen for testing and which sensitivity parameters were chosen.

The main goal of the study was to create and validate a system dynamics model that allows predicting the future implementation of PV and battery systems. To test the approved model, it was supplemented by one policy measure – subsidies. Since the main objective of the study was to establish and validate the basic structure of the system dynamics model, rather than to analyse and evaluate the optimal way to promote diffusion of battery storage in the household sector, only one policy measure was examined. In the future, the research model may be complemented by additional policy instruments to test their impact on the integration of battery systems in households. In this study, four separate scenarios were developed. The baseline describes a system that does not implement any additional policies other than those already in place in the current energy system. This is mainly due to net metering for households that have installed PV systems. This basically means that the distribution grid acts as a storage facility. The advantage is a lower price of electricity when recovering excess solar energy. When the accumulated excess solar energy is removed back from the grid, only the tariff of the distribution system operator should be paid instead of the full electricity tariff. This is taken into account when calculating the cost of each system (only grid electricity, PV, battery, PV and battery).

There are 3 separate subsidy scenarios (see Table 1.5). Each of them includes the already existing policy, which was mentioned before, and additionally provides subsidies for the introduction of specific technologies. The main difference between the scenarios is the technology receiving the grants and the amount of financial support available. For scenarios where only 1 technology receives subsidies, the amount of funding is EUR 20 million every five years, however, when both technologies receive subsidies, EUR 20 million is allocated separately for each technology deployment.

Table 1.5

Description of the Scenario, Technology Receiving Subsidies

Scenario	PV	Batteries	Funding, MEUR	Aid intensity, %
Scenario 1			0	0
Scenario 2	X		20	50
Scenario 3		X	20	50
Scenario 4	X	X	2 × 20	50

Sensitivity analysis

To check the sensitivity of the model to changes in various parameters, a sensitivity analysis was performed. The electricity tariff, the technical life of the battery, the initial investment of the battery, and the share of the reduction in the battery investment were selected as the four parameters that most affect the results of the model. Table 1.6 shows the intervals tested for sensitivity analysis. The results of the sensitivity analysis are presented in the results section. Sensitivity analysis was performed separately for each parameter. For the parameters shown in Table 1.4, the specific interval was checked, while for other parameters the values in Table 1.3 were used.

Table 1.6

Parameters of Sensitivity Analysis

Parameter	Unit of measurement	Lowest value	The greatest value
Electricity tariff	EUR/MWh	30	150
Technical life of the battery	Years	10	30
Initial investment of the battery	EUR/kWh	600	1000
Battery investment reduction fraction	%/year	0.5	3

Simulation of the system dynamics model for a hybrid energy system in the household

Structure of the study model

Household electricity consumption is a dynamic problem. Therefore, in order to assess the profitability of installing energy storage systems in private households in Latvia, the system dynamics (SD) modelling method was used. As mentioned in the previous subsection, in general, the process of developing a system dynamics model consists of several consecutive steps. These steps include the formulation of the problem, which is the identification of dynamic hypotheses that explain the causes of the problem, the formulation and simulation of the model, which implies testing the model to assess its relevance to the real situation, as well as formulating a policy and drawing conclusions.

In this study, an hourly consumption model was developed to analyse the cost of electricity (1) for a standard connected system, (2) for a PV system with net metering, (3) for a grid system with an installed battery, and (4) for a grid system with a combined PV and battery storage system. The modelling was carried out using Stella Architect software.

The purpose of the model is to determine the profitability of installing a battery storage system, taking into account the overall electricity consumption profile of the household. The algorithm of the PV system with net metering for a household works on the principle that when PVs generate more energy than household appliances can immediately consume, excess electricity is automatically fed into the shared grid. The amount of electricity fed into the grid may be credited and used to compensate for consumption later in the accounting year. However, at the end of the net metering reporting period, the accumulated excess electricity is reset, and a new accounting balance is started. In turn, by connecting the battery to the storage of the generated energy to the above system, it is possible to ensure greater independence from the grid connection, as well as to obtain economic benefits by effectively using the capabilities of the battery. When more energy is produced than a household can consume at any time, excess electricity is mainly stored in the battery, which happens automatically in the system. In this case, the purchase of electricity from the grid is necessary only at moments when there is insufficient power generation from the PV system and insufficient battery supply to cover the load. Also, the model includes the fact that the battery for more cost-effective use can be charged from the grid when it is economically justified.

Components and characteristics of the model

The main factors affecting electricity costs and household consumption profiles for different systems are represented in the SD model as various elements: stocks, flows and feedback loops. The values of these elements are defined using mathematical equations and constants. The hourly model of the dynamic system assumes that the consumption profile of households is based on input data obtained from the system dynamics model developed in 2021 in order to study the potential of aggregators to reduce the surplus of renewable energy in Latvia. The model predicts hourly electricity prices based on historical indicators from the 2021 NordPool electricity market, seeing them as an indication of electricity price trends over the next decade. Although electricity and gas prices have now fallen compared to 2022, these assumptions are always so relevant, as changes in distribution system service tariffs are expected: inflation will lead to an increase in tariff charges for customers, an increase in the transmission tariff, as well as taking into account geopolitical circumstances and long-term future forecasts. In addition, to determine the sensitivity of the model results from the input data, the development process includes a comparison with hourly electricity price data from 2019 and 2022.

In the model, separate system dynamics are created for all analysed variants of the household electricity system: (1) for a standard connected system, (2) for a PV system with net metering, (3) for a grid system with integrated storage of battery power, and (4) for a system connected to the grid with PV and integrated storage of battery power. Since these variants are based on similar basic structures, only the fourth system is considered in detail in the methodology section (as the most comprehensive, in which all possible subsystems are considered).

To determine the electricity costs incurred in a particular household profile, NordPool's hourly price tariff for 2021 is used for electricity purchased via grid connection. The fixed electricity connection fee is also taken into account, which according to the data of the distribution operator is 3.87 EUR/month for the respective household profile. The model also includes an electricity sales fee (2.68 EUR/MWh), an electricity transmission fee (40.76 EUR/MWh) and VAT on electricity (21 %). These values are accepted on the basis of the costs of equivalent household profiles in Latvia during the given period in accordance with the market offers of electricity merchants such as Elektrum, Enefit, etc.

Battery size is an essential parameter of the system. As Zhang Z. and others emphasize, too frequent discharge at a low level or, on the contrary, too rare full charging in both cases leads to a shortening of the life of the system. To determine the battery capacity, additional model optimization is carried out. After evaluating the amount and power of the installed PV panels according to the obtained optimization results, it is concluded that the optimal for a particular household is to install a battery with a power capacity of 5 kWh of electricity to cover the night load. The amount of electricity transferred to the grid per day is also taken into account. Based on previous research developed by the author, which compared different storage alternatives, the model includes a lithium-ion battery as the best solution for storing electricity in households. The model includes technological parameters of this type of battery, such as charge/discharge efficiency, average service life and energy storage duration. In the structure of the SD model, the total cost of electricity for a household PV and lithium-ion battery system is described by stock: the cost of electricity with PVs and a battery (see Fig. 1.6). These costs are affected by inbound flow, i.e. hourly costs of photovoltaic and battery electricity, which depend on the electricity tariff, fixed electricity connection charges, the cost of supplying (transmission) solar energy taken back from the grid, and the amount of electricity used from the grid to charge the battery and cover consumption.

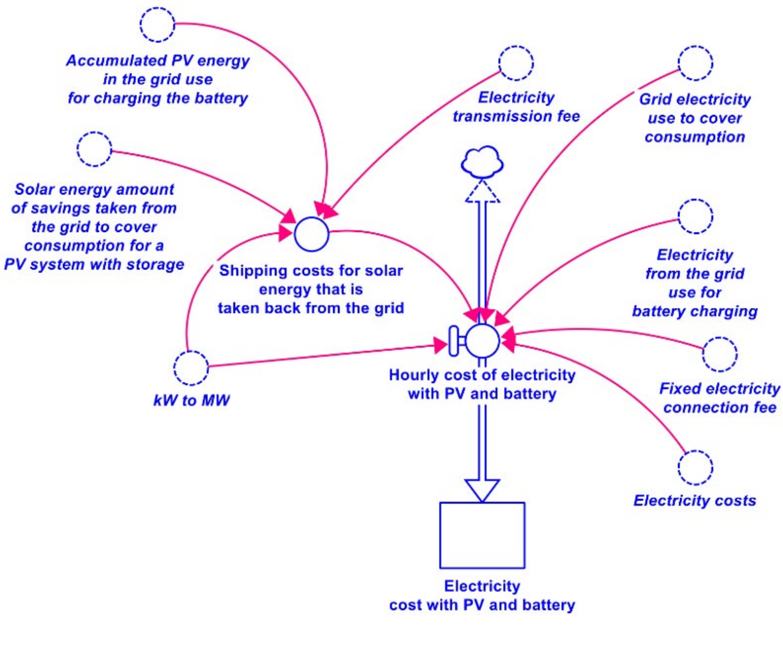

Fig. 1.6. A submodel of the cost of electricity for a system with PVs and a battery.

The hourly cost of electricity for a system with PV and battery is determined by Equation (2).

$$EC_h = C_{connect.} + (EA_{cons.} + EA_{accum.}) \cdot \frac{C_{electr.}}{Coef_{transf.}} + C_{deliv.}, \quad (2)$$

where

EC_h– hourly electricity costs with PV and battery, EUR/h;
$C_{connect.}$– fixed electricity connection fee, EUR/h;
$EA_{cons.}$– use of grid electricity to cover consumption, kW;
$EA_{accum.}$– using electricity from the grid to charge the battery, kW;
$C_{electr.}$– electricity tariff, EUR/MWh;
$Coef_{transf.}$–transformation factor from kW to MW, kW/MW;
$C_{deliv.}$– solar energy supply costs recovered from the grid, EUR/h.

The amount of electricity used from the grid to cover the battery charge at more favourable prices is determined by Equation (3). As mentioned before, the battery is charged from the grid if the condition of the lowest price is not met within five hours, also taking into account the available battery charging capacity, and the accumulated solar energy is enough to charge the battery.

$$EA_{accum.} = IF\ (N_{lowest\ price} = 0)\ THEN\ 0\ ELSE\ (J_{network} \cdot N_{PV}), \tag{3}$$

where
$EA_{accum.}$– using electricity from the grid to charge the battery, kW;
$N_{lowest\ price}$– the lowest price condition for charging the battery from the grid;
$J_{network}$– available battery charging capacity using electricity taken from the grid for charging, kW;
N_{PV}– PV power adequacy condition for charging the battery from the grid.

The cost of supplying solar energy recovered from the grid (from storage) is influenced by the amount of electricity recovered for household immediate consumption, the amount of stored electricity used to charge the battery, and the electricity transmission charge (as mentioned before, 40.76 EUR/MWh). The total cost of supplying stored solar energy from the grid is shown in Equation (4).

$$C_{deliv.} = (U_{network} + EA_{PV\ accum.}) \cdot \frac{C_{transm.}}{Coef_{transf.}}, \tag{4}$$

where
$C_{deliv.}$– supply (solar energy transmission costs recovered from the grid, EUR/h);
$U_{network}$– amount of stored solar energy consumed from the grid, kW;
$EA_{PV\ accum.}$– using the PV electricity stored in the grid to charge the battery, kW;
$C_{transm.}$– electricity transmission charge, EUR/MWh;
$Coef_{transf.}$– transformation factor from kW to MW, kW/MW.

Next, the amount of energy stored for each hour of the year was determined, as shown in the submodel: the amount of energy stored in the battery (see Fig. 1.7). In addition, taking into account the amount of solar energy stored in the grid, the model includes the fact that the available battery charging capacity is influenced by the efficiency of battery charging, which, based on the data found in the literature, was assumed to be 0.98.

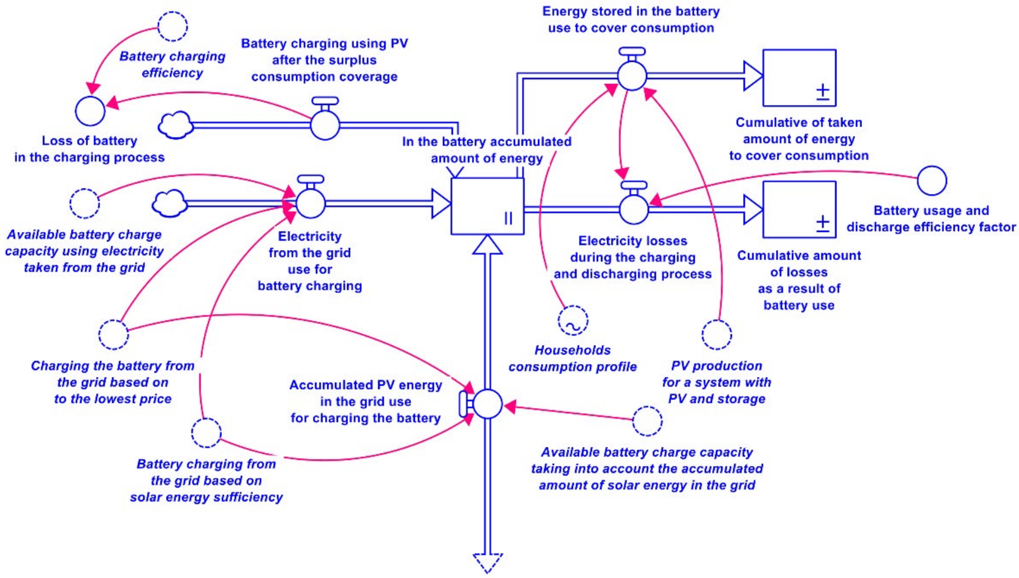

Fig. 1.7. Part of the submodel: The amount of energy stored in the battery.

Stocks that reflect the amount of energy stored in the battery are affected by the flow that characterizes the charge fraction of the battery, using the excess energy of PVs after covering household consumption. This flow depends on the available battery charging capacity, taking into account the availability of excess energy from PVs after consumption coverage. In addition, stocks are affected by the incoming flow, which describes the amount of electricity that is used to charge the battery from the grid. Thus, the battery is mainly charged based on the adequacy of solar energy and the available battery charging capacity. After that, it is charged, extracting the accumulated energy from the grid, and finally, when it is economically justified, the battery is charged from the grid.

The accumulated energy of PVs stored in the grid and used to charge the battery is also an incoming flow, and its impact can be described in a similar way to previous flows. However, in this case, the amount of energy stored instead of available grid electricity depends on the amount of solar energy stored in the grid.

Also, the amount of energy stored in the battery is affected by the outgoing flows. The amount of stored energy in the battery decreases if the consumption is covered using the energy stored in the battery.

Electricity losses also affect the amount of stored and transferred energy, which was described in the model as the outflow from the amount of energy stored in the battery.

The general submodel, which describes the PV and energy storage system, also affects the energy fraction of PVs fed into and stored in the grid. This part of the model is illustrated in Fig. 1.8.

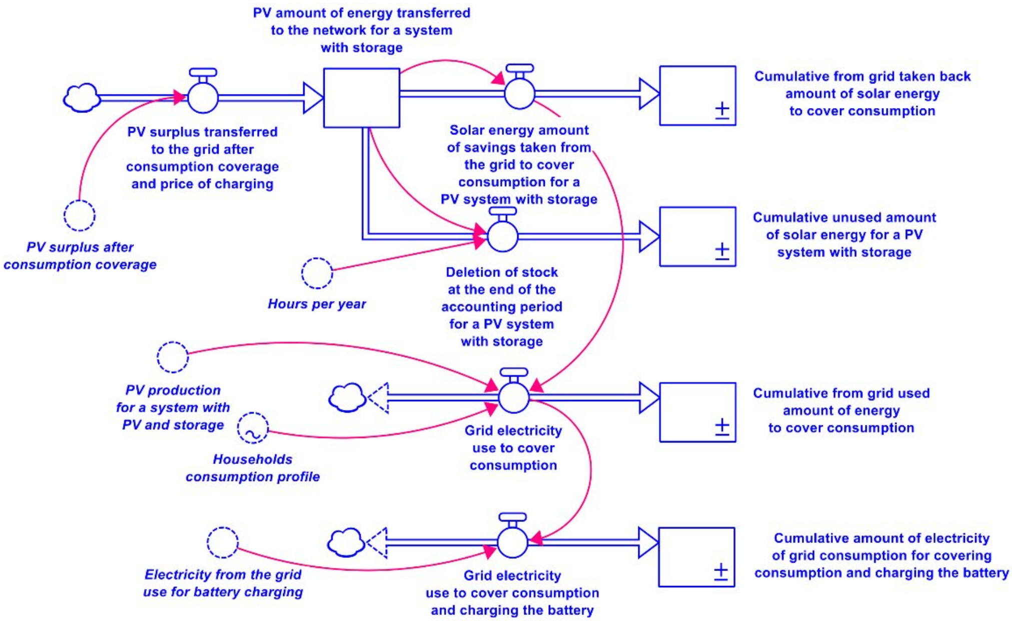

Fig. 1.8. Submodel of the accumulation of excess solar panels in the grid and its further use.

Stocks, i.e. the energy of PVs transmitted into the grid by the storage system, are affected by the flow described before, i.e. the stored PV energy stored in the grid and used to charge the battery, as well as the incoming flow, which forms excess energy transmitted to the grid after consumption and charging the battery, also taking into account electricity losses.

Also, the amount of energy stored in the grid is affected by outflows. In this submodel, the energy stored in the grid is used to meet household consumption, which is reflected in the flow, i.e. the amount of solar energy taken from the grid for consumption in a PV system with storage.

The submodel of PVs and electricity storage system also takes into account the storage degradation coefficient at the end of the accounting period, which characterizes the amount of energy lost. In this submodel, this aspect is characterized by flow, i.e. storage degradation at the end of the accounting period for a PV system with storage, which is affected by the parameter of the number of hours per year, as well as the amount of PV energy transmitted to the grid.

1.3. Algorithm for data aggregation and critical analysis, calculation and forecasting

Scientific literature, reports, policy plans, development trends, and future forecasts were critically reviewed and analysed in order to characterize the current energy supply system in Latvia. Analytical methods were used to investigate the relationship between weather conditions and electricity production intensity by collecting and interpreting data obtained from official databases. Cluster analysis methods and descriptive analysis methods such as the arithmetic mean approach and percentage distribution were also used.

The country's energy supply system was characterized by the available local electricity production capacity, the total state electricity consumption and available energy resources (fossil fuels and renewable energy sources). In order to assess the accumulation of electricity produced from renewable energy sources (solar, water, wind), it was necessary to assess the current total installed generation capacity, the total electricity produced and its distribution by source. The balance of electricity produced against consumption was calculated to determine the excess electricity. The electricity balance was evaluated at different time intervals in order to determine the potential for electricity storage in Latvia.

In order to characterize the Latvian energy supply system, input data were used from the following data sources: Central Statistical Bureau, Latvenergo AS, Augstsprieguma tīkls AS (electricity market reports), weather observations and studies of the Latvian Environment, Geology and Meteorology Centre (LVĢMC).

When carrying out the assessment, analysis and calculations, the following input data were used:

- Latvian electricity production capacity by energy sources (per year): Information on installed capacities of different types of electricity production sources in Latvia. These data provide an overview of the country's electricity generation potential from each energy source.
- Total electricity produced in Latvia: data on the total electricity produced in Latvia, measured at different time intervals, including annual, monthly, daily and hourly levels.
- Total electricity consumption in Latvia: statistical data on the total electricity consumption in Latvia, which are measured in different time intervals, including annual, monthly, daily and hourly levels. These data reflect the demand for electricity in the country for certain periods of time.
- Share of electricity produced from renewable energy sources in the electricity produced.
- Daugava flow rate (m^3/s): data on the flow rate of the Daugava River, which is important for the production of hydroelectric energy.
- Wind speed (m/s): data on the average wind speed in Latvia to estimate energy production.

The evaluation of the Latvian electricity production profile began with an assessment of the existing production capacity, looking at the main sources of electricity production and their potential in Latvia. Taking into account the climate neutrality objectives of both the EU and Latvia, it was necessary to carry out an assessment of energy supply from the perspective of the use of renewable energy resources, evaluating the share of renewables in the total electricity consumption of Latvia and its potential increase in the future. Taking into account that renewables are periodic in nature, it was also important to evaluate the possibilities of electricity storage during periods of overproduction in order to satisfy the electricity consumption of Latvia. The assessment of Latvia's energy supply was carried out according to the following methodology (see data analysis algorithm in Fig. 1.9):

1. Assessment of Latvia's existing RES capacity and production based on climatic conditions.
2. Share of renewables (%) in electricity production.

3. Trends of electricity production and consumption in Latvia by seasons, working days and weekends, as well as hourly fluctuations.
4. Possibilities of storing excess electricity produced from RES.
5. Future opportunities and forecasts for increasing renewables capacity and electricity production, as well as future electricity storage potential in the territory of Latvia.

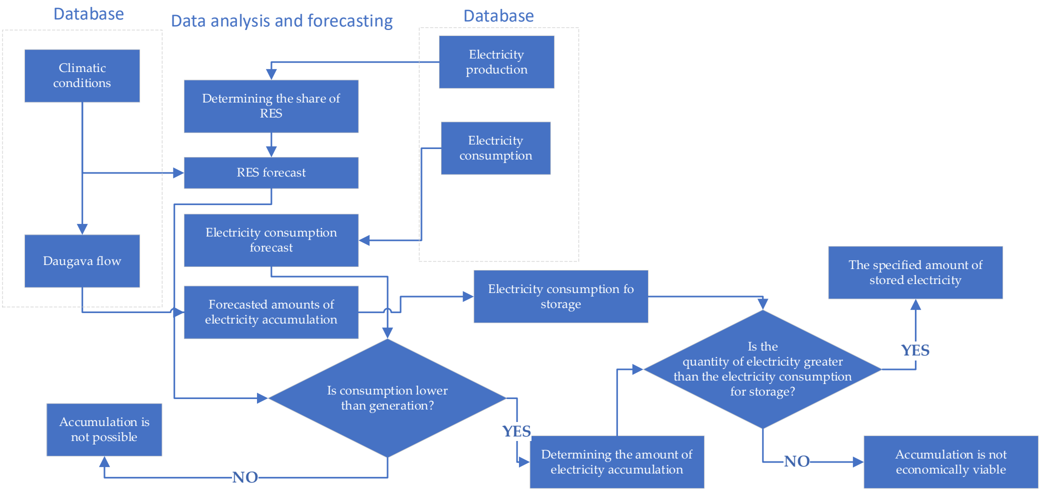

Fig. 1.9. Electricity production and consumption, climatic conditions, and Daugava flow data analysis algorithm to assess the potential of excess electricity in Latvia.

1.4. Feasibility analysis of electricity storage solutions for companies

Data and assumptions. Description of the situation

The installation of electricity storage systems in enterprises is most often evaluated from the point of view of economics, safety and sustainable business. This study analyses and evaluates how to recover from the prism of an investment project. The question of whether the gross return period for such projects is within ten years with and without aid is raised. Such a deadline has been adopted on the basis of business plans for similar technological investment projects, such as solar power plants. An important factor for the accepted period is also the fact that ESS technologies are developing rapidly, which in a dynamic business environment does not allow investing in projects with a longer payback period. To conduct such an analysis, it is necessary to take into account a set of characteristics that would give a result with a high degree of accuracy. The study uses both technological and capital investment parameters as well as electricity public grid and business settings. The technology has been selected based on the results of a previously developed multi-criteria analysis model – Lithium-ion batteries as the basis for electricity storage systems. This study is related to electricity market conditions in the territory of Latvia, but when the parametric values change, it is also applicable in other countries. The study does not take into account profit scenarios from the balancing services of

JSC "AST". In the case of hybrid systems, mechanisms for the sale of green certificates of origin are also not taken into account.

The calculation model of the payback period for the use of electricity storage solutions uses the necessary parameters. These characteristics are divided into two groups, see Fig. 1.10.

1. Parameters that are constant in the business model and change infrequently

1.1. Inverter conversion and system losses and/or efficiency factors of electricity produced by solar panels.
1.2. Lithium ESS DC conversion and system losses and/or efficiency factors.
1.3. 0.4 kV low voltage (hp) – 20 kV medium voltage (VS) conversion utility with cable losses.
1.4. Period – number of weeks in a year.
1.5. Electricity trader's commission for both purchased and sold electricity.
1.6. Tariff of electricity producers of JSC "Sadales tīkls" (for exported capacity).
1.7. Maintenance of the line capacity of JSC "Sadales tīkls".
1.8. JSC "Sadales tīkls" line transmission tariffs.

2. Variable parameters

2.1. Number of working days per year.
2.2. The number of peak hours (expensive) per day.
2.3. The number of daily (base) hours per day.
2.4. The basic price of electricity is accepted (day).
2.5. Lithium ESS costs (DC part, assembly, natural resources tax).
2.6. Lithium ESS costs large scale > 2.5 MWh (20/40 ft containers).
2.7. Lithium ESS DC – 0.4 kV Low Voltage Conversion Node Cost
2.8. Lithium LFP class "B" cell ESS resource 0–100 % DoD.
2.9. The cost of new connections of ST 20 kV (assumption from experience).
2.10. 0.4 kV hp – construction costs of 20 kV nodes (substations + cables).
2.11. Funding grant.
2.12. Funding participation.
2.13. Financing loan interest rate.
2.14. Number of night (cheap) hours per day.
2.15. Number of holidays and public holidays per year.
2.16. Price of electricity during peak hours.
2.17. Price of electricity at night.
2.18. The nominal required by the input protection device.
2.19. Price of electricity on weekends and public holidays (except Sunday evenings).
2.20. Financing credit.
2.21. Factor C, used to express the rate of charge and discharge of batteries, 0.125–0.5 C
2.22. Lithium LFP "B" class ESS cycle 0–20 to 80–100 %

Fig. 1.10. Parameters of feasibility study.

Alternatives to solutions. During the study, it was found that there is no single universal alternative, so four assumptions characterizing the alternative were put forward that would reflect the result of the mounted question:

1. The size of the electricity consumer.
2. Electricity consumers with and without a solar power plant.
3. Accumulated electricity is used for self-consumption, hybrids or only for-profit purposes.
4. Number of discharge cycles per day for electricity batteries.

According to the assumptions made above, 8 alternatives with several sub-scenarios were developed in order to study the issue as widely as possible. In total, 8 alternatives with 22 scenarios were used in the calculations:

Alternatives 1 and 2: Small and medium-sized electricity consumers with connection capacity 11 – 500 kW, 9 working hours 5 days a week, large electricity consumers with capacity over 500 kW mid voltage connection, 9 working hours 5 days a week.

1.1. Compensation of maximum hours.
1.2. Compensation of peak hours and peaks of electricity consumer.
1.3. Compensation of daily hours.
1.4. Compensation of daily hours and peaks.

Alternatives 3 and 4: Small and medium-sized electricity consumers with connection capacity 11–500 kW, 9 working hours 5 days a week with installed type B solar panels without export capacity and large electricity consumers with capacity over 500 kW medium voltage connection, 9 working hours 5 days a week with installed type C solar panels without export capacity.

3.1. Maximum hour compensation.
3.2. Compensation of peak hours and peaks of electricity consumer.

Alternatives 5 and 6: Small and medium-sized electricity consumers with connection capacity 11–500 kW, 9 working hours 5 days a week with installed type B solar panels with full export capacity as a balancing hybrid and large electricity consumers with capacity over 500 kW medium voltage connection, 9 working hours 5 days a week with installed type C solar panels with full export capacity as a balancing hybrid.

6.1. Compensation of maximum hours and sale of electricity.
6.2. Compensation of peak hours, electricity consumer peaks and sale of electricity.
6.3. Compensation of maximum hours and sale of electricity for all hours.
6.4. Compensation of peak hours, peaks of electricity consumer and sale of all h electricity.

Alternatives 7 and 8: Large balancing solar power plant with connection capacity over 500 kW with existing built-in connection (calculations made outside the solar project's profit from the energy produced) and large ESSs with a capacity of more than 500 kW separately standing with a new electricity connection.

7.1. The sale of electricity during peak hours.
7.2. The sale of electricity with a more technology-friendly use profile during peak hours.

The listed eight alternatives differ in a number of parameters that significantly affect the overall project goal and gross return period. The size of the electricity consumer makes a big difference. In this study, the dividing line has been used at 500 kW of electricity connection capacity. Those that are below, are small and medium-sized consumers, those over 500kW are large consumers. The division was made for the purpose of distinguishing which ones most often have larger or smaller electricity storage systems, since they have a direct impact on capital investment. Also, separate alternatives were distinguished to show in which cases the company gets savings from the installed accumulation system, in which cases savings and partly also revenues from the sold electricity, and in which cases it gets revenues from economic activity by accumulating cheap exchange hours and trading the more expensive ones, thus earning from arbitrage. Then, after possible alternatives have been broken down by consumer size, the project's goal of earning or saving or operating hybrids, different scenarios also need to be evaluated for each alternative, so a total of twenty-two scenarios were considered. The total number of scenarios is higher, but the gross return period not mentioned in this study may even exceed 50 years. The scenarios were evaluated according to the peculiarities of the existing national electricity consumption; for example, in the mornings and evenings for 4 hours electricity is consumed much more than in the middle of the day, therefore, during these hours the price for it can also exceed 100 % from the daily price and more, while during the night the consumption of electricity is the lowest and often the price of electricity is even negative. Another aspect for alternatives, where the payback is made up of savings made to the consumer, is the reduction of the nominal required by the input protection device.

Mathematical equations

Calculations are carried out using equations that include engineering and economic parameters.

1. The capital investment of the electricity storage system is determined by an equation in which the required battery capacity is multiplied by the reference of the base capital investment from the set parameters. Capital investment of the selected electricity storage system = number of selected hours per day X connection capacity X connection utilization intensity X (capital investments of the electricity storage system per 1 MWh + capital investments of the electricity storage system conversion unit to 1 MWh / C ratio: charge and discharge rate) + connection costs.
2. The annual financial savings or revenues generated by the electricity storage system shall be determined by an equation in which all the savings and/or revenue targets set by the project are added together. They can be both at peak hours and maximum hours, and at the reduction of the nominal required by the input protection device, both at the hours of the day and at all hours. In this study, for alternatives that are with the company's self-consumption, the cost share of the AS "Sadales tīkls" (ST) distribution tariff and transmission tariff as well as the energy trader's commission are included in the equation next to the revenue, since ST automatically calculates these costs. Values are obtained depending on the purpose but with a universal equation.
3. The costs related to the connection of the electricity storage system to the electricity public grid shall be determined by adding together the connection capacity maintenance, the ST electricity producers' tariff, the ST transmission tariff and the energy trader's commission. Values shall be obtained depending on the objective of the project, each of those parameters multiplied by the connection capacity and used, if applicable, in the project in question.

4. The gross repayment period is determined by dividing the capital investment of the electricity storage system by revenues and/or savings and subtract costs.

2. RESULTS

2.1. Multi-criteria analysis using the TOPSIS method

The results obtained for alternative batteries after a multi-criteria analysis using the TOPSIS method and determining the same weighted weight of 0.111 are shown in Fig. 2.1.

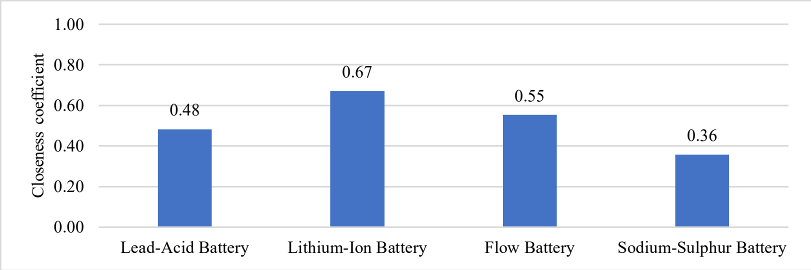

Fig. 2.1. Results of analysis of the TOPSIS MCDA battery.

Among the four types of batteries analysed, lithium-ion batteries were determined to be the closest to the ideal option with a proximity factor of 0.67. Although investments in a lithium-ion battery (EUR/kWh) are the highest among the batteries compared, this parameter is outweighed by its high-power density, which is approximately twice as high as other alternatives, as well as the significantly high efficiency and number of charge/discharge cycles, which are considered the primary aspects of achieving such results. It is important to note that the social factor and technological readiness of lithium-ion batteries are also rated the highest. Therefore, lithium-ion batteries are considered the most potential solution for energy storage at the moment. Then, with a proximity factor of 0.55 in the ideal scenario, flow batteries are ranked. The main advantages of these batteries are their long service life and the large number of charge/discharge cycles, which ensures high power density while maintaining relatively low investment costs. Accordingly, lead-acid (0.48) and sodium sulphur (0.36) batteries have received a lower rating. Such results are mainly influenced by their relatively low power density and service life. In addition, the impact of these batteries on climate change (kgCO_2eq/kg) is higher than that of the other two batteries. However, even types of batteries with lower ratings are not considered uncompetitive in the market of energy storage technologies. According to specific parameters, which may vary mainly depending on technological needs and individual beliefs, flow batteries, lead-acid batteries and sodium-sulphur batteries, while continuing to develop their innovation potential, can provide efficient energy storage, facilitating a global transition to the use of renewable resources.

Similarly, when analysing multi-criteria decisions using the TOPSIS method and determining the same weighted value of 0.125, the results of energy storage systems are shown in Fig. 2.2.

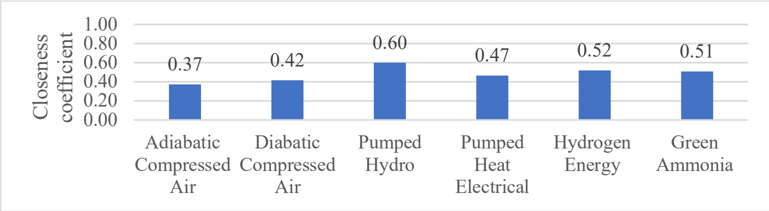

Fig. 2.2. Results of analysis of the TOPSIS MCDA storage system.

Among the six energy storage systems compared, it was found that the hydroelectric power station is the closest solution to the ideal renewable energy storage technology, reaching a proximity coefficient of 0.60. This result was obtained mainly due to the fact that it is the most developed storage system among those considered, since the storage of electricity is also possible in hydroelectric power plants, so large capital expenditures are not required. The service life is also significantly longer, reaching up to 80 years, and the efficiency is the highest – 77.5 %. Hydrogen energy (0.54) and green ammonia (0.51) storage technologies are ranked lower. According to the literature analysis, these two energy storage technologies were also rated as the most promising and have higher added value outside the energy sector. However, capital expenditures for these storage systems are significantly higher, and technological solutions are still in the process of developing innovations. With a proximity factor of 0.47, heat electricity storage technology is ranked lower, because, although capital expenditure in EUR/kWh is the lowest among the compared storage systems, technological readiness is still at the demonstration level, thus the social factor is rated the lowest. The farthest from the ideal solution is the diabatic compressed air energy storage system (0.42) and the adiabatic compressed air energy storage system (0.37), taking into account the technological limitations of operation, geographical limitations and the fact that the infrastructure of the compressed air energy storage system is suitable for mountainous areas where underground craters are also found. The response time for both technologies is also significantly longer. However, among the compared alternative storage system options, each of them is considered a competitive storage technology in the near or distant future, ensuring efficient energy storage. In addition, different concepts of storage technologies can be adapted to specific geographical regions and infrastructure problems.

To verify the results, a sensitivity analysis of battery alternatives was carried out using all of the above criteria. For accumulation systems, no sensitivity analysis was performed due to overlapping criteria and a broader analysis would reduce the transparency of the results.

Taking into account the results of the sensitivity analysis, it is possible to determine the specific impact of each criterion on the selected technological solutions for storing renewable electricity, allowing to identify the most important factors that change the results of the TOPSIS analysis. The main conclusions arising from the analysis of batteries are as follows: lithium-ion batteries are negatively affected by the amount of investment required; also, according to the input data, it can be concluded that the investment in EUR/kWh at this point in time of development is about two times higher than for other types of accumulation in this group and also in terms of the life of the technology. However, this is outweighed by the fact that in practically all other criteria, lithium-ion batteries show the best indicators, accordingly, justifying its appearance at the head of other batteries. It should be noted that lead-acid and sodium-sulphur batteries are almost not affected by technological ripeness, since their innovative progress is average, like the social factor, direct benefit to society, while the response time does not particularly affect all types of batteries, since it is almost identical for all types. And the last visible influencing factor is the environmental impact factor of sodium-sulphur batteries, which is also significantly higher in the collected data.

2.2. System dynamics modelling

This section provides the main preliminary results characterising the prevalence of PV systems and electricity storage system in households in Latvia until 2050, based on various parameters. The sensitivity of the most important parameters is assessed using the system dynamics model.

Results of the system dynamics model for forecasting electricity storage practices in households

This is in some ways an intuitive conclusion, however, it turned out that the price of electricity plays an important role in the transition from grid electricity to the use of PV and batteries. Figure 2.3 shows a comparison of PV and PV with the diffusion level of the battery system at different electricity tariffs. Figure 2.3(a) shows that if the price of electricity for the entire simulation period were 35 EUR per megawatt hour, which is approximately the lowest electricity price achieved in the last 10 years, interest in installing both PV and PV with batteries would be very low. Interest in batteries would only begin after 2040, when the investment costs would be sufficiently reduced to reduce the payback period than the technical lifetime of batteries. It is logical that with low electricity prices, the payback period of PV and batteries is too long to make it a desirable option. The results of the model show that at this level of electricity prices in 2050, only 25.4 % of all households would have installed only PV systems and 3.5 % would have installed PV systems supplemented by battery storage. The rest would still be entirely dependent on grid electricity.

Figure 2.3(b) shows that if the price of electricity for the entire simulation period were 50 EUR per megawatt hour, which was the highest electricity price between 2013 and 2020, interest in PV and batteries would increase significantly. The introduction of PV technology is gaining traction instantly, while the installation of PV and batteries begins to increase already before 2030. The results of the model show that at this level of electricity prices in 2050, 48.6 % of all households would have installed only PV systems and 10.8 % would have installed PV systems supplemented by accumulating batteries.

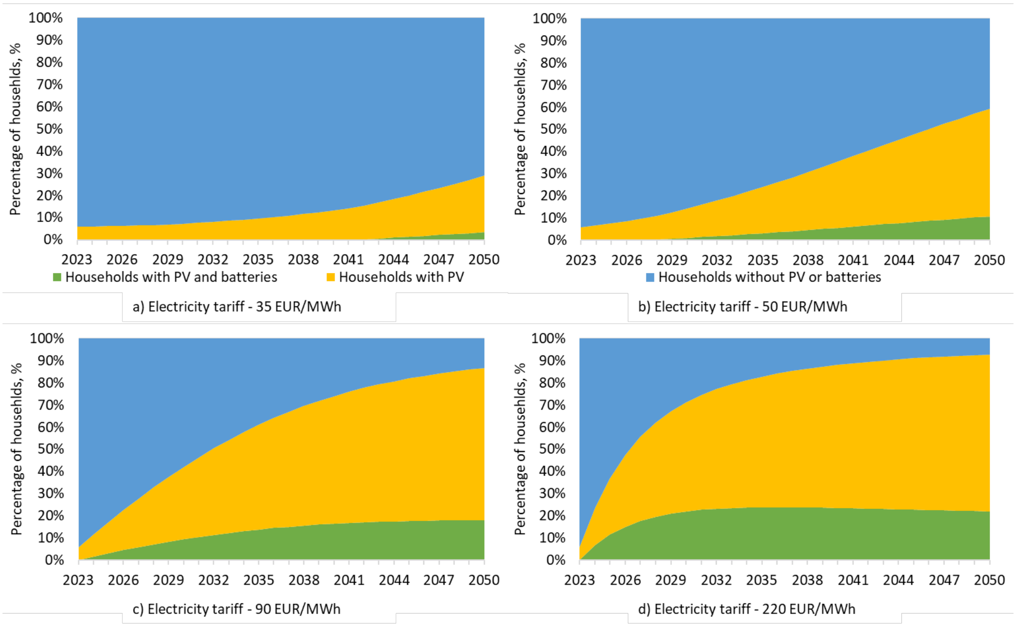

Fig. 2.3. Diffusion of PV and battery system based on electricity tariff.

Figure 2.3(c) shows that if the electricity price for the entire simulation period were 90 EUR per megawatt hour, which was approximately the price of electricity in 2021 and also in 2023, interest in PV and batteries would increase significantly. The results of the model show that at this level of electricity prices in 2050, 68.6 % of all households would have installed only PV systems and 18.0 % would have installed PV systems supplemented by battery storage.

Figure 2.3(d) shows that if the price of electricity for the entire simulation period were 220 EUR per megawatt hour, which was approximately the price of electricity in 2022, the PV and battery installation speed would explode. Grid electricity is so expensive that even battery technologies, which are still expensive at this point, seem more profitable than just using grid electricity. PV-only systems still have a higher proportion than PV with batteries, as the total investment payback time for PV will always be less than for a PV system supplemented with batteries. The results of the model show that at this level of electricity prices in 2050, 70.8 % of all households would have installed only PV systems and 22.0 % would have installed PV systems supplemented by accumulating batteries. The end results are similar to where the price of electricity is 90 EUR per megawatt hour; however, the initial level of investment is significantly higher.

It is important to mention that the results show a situation where net metering systems operate for full simulation in all electricity price scenarios and all households can use the system, yet in reality the distribution system operator would most likely not be able to store all the excess solar electricity shown in scenarios (c) and (d) in the grid, and net metering would be eliminated in order to maintain grid stability. This, in turn, would affect the speed of integration of the PV and battery system, since without net metering, the payback period increases and grid connections look more attractive. However, this study does not analyse the impact of the speed of PV integration on the power grid and net metering system. The model needs to be expanded to analyse this effect. This is the purpose of further research.

The results show that the implementation of subsidy policies is changing the PV system by integrating the battery system into households. If subsidies are given only for the installation of PV, but not for the storage of batteries, the initial increase in the installation of systems with PV and batteries is greater than in the case of the baseline scenario, however, the end result is only slightly higher. The initial increase is due to the fact that subsidizing the installation of PV also reduces the total cost of the system with PV and batteries, so it is more attractive than in the baseline scenario, however, in the long run, only PV systems are still more attractive than a combined system. If only batteries are subsidised, the initial increase for the installation of the PV and accumulator system is similar to that for the PV subsidy and higher than in the baseline scenario, but the end result is better than the baseline scenario and the subsidies for the PV scenario only. If both technologies are subsidised, the initial growth is expected to be higher than in previous scenarios. This increase occurs not only at the expense of PV systems, but because both PV and combined PV and battery systems become competitive with the grid electricity tariff, and the increase in installation occurs in both categories. However, the end result is similar to the scenario with subsidies only for batteries, and since both technologies receive subsidies, the difference in investment and savings between solutions is still in favour of the PV system. In the baseline scenario, 21,422 households have a combined PV and battery system installed, while in the scenario with subsidies for both technologies, 25,118 households have the system installed.

Results of sensitivity analysis

A sensitivity analysis was performed to assess how changes in key parameters could affect the implementation of combined PV and battery systems. Sensitivity analysis was carried out for a non-subsidy system with four parameters: electricity price interval 30–150 EUR per MWh; technical working life evaluated in the interval from 10–30 years; initial investment interval 600–1000 EUR per kWh; and battery contribution reduction fraction interval 0.5–3 % per year.

From the sensitivity analysis, the author concludes that all 4 parameters – the price of electricity, the technical life of battery storage, initial investments in battery storage and investments to reduce the battery storage share have a huge impact on the battery storage unit, therefore it is very important to carefully consider the values of these parameters when making a future forecast of the development of battery storage.

Results of simulation of the system dynamics model for a hybrid power system in the household

This section provides the results characterizing the cost-effectiveness of installing an energy storage system in households in Latvia, taking into account the total electricity consumption profile of the household.

Simulating the operation of the systems at NordPool's hourly electricity prices for 2021, it was found that the total electricity cost for a household with a total annual consumption of 7800 kWh/year and consuming only energy from the grid is 2663.55 EUR/year. On the other hand, if a household of the same profile installs PVs, uses the generated electricity for self-consumption and the grid as a surplus, then the total cost of electricity is 715.82 EUR/year, thus a significant improvement can be seen. If a lithium-ion battery is also connected to the PV and the system is used efficiently, then the cost of household electricity is 639.41 EUR/year. The cost differences from system dynamics simulations in three different years are summarized in Table 2.1.

Table 2.1

Comparison of Electricity Costs

NordPool data	Grid connection, EUR/year	Added PV panels, EUR/year	With added accumulation system EUR/year
2019	1779.78	710.14	642.18
2020	1554.06	646.98	571.34
2021	2663.55	715.82	639.41
2022	4851.32	968.97	858.02

Table 2.1 shows a significant difference in the total annual electricity costs, depending on which year the data (NordPool electricity exchange price) were selected as the forecasted electricity prices in the simulation. According to the results compiled in the model, the Latvian case study examined the profitability of installing electricity storage with the existing solar potential and annual radiation intensity, taking into account the electricity costs, which affect the principles of operation of the storage system. The results obtained for the household with PV installed and battery for one day (24 h base) for the average electricity load during the summer month described before are shown in Fig. 2.4.

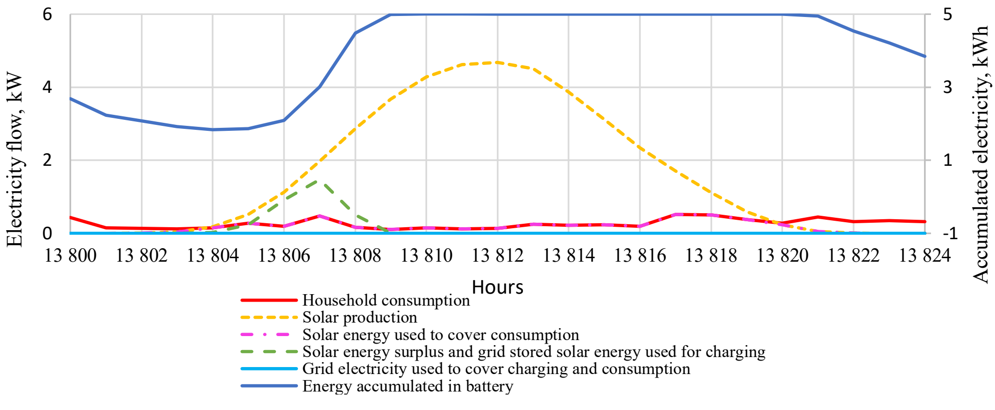

Fig. 2.4. Energy flow profile for a system with solar panels and a battery on a summer day.

In summer, household electricity consumption is relatively low (see the red curve in Fig. 2.4); therefore, the amount of energy stored in the battery is enough to cover the consumption during the night hours (represented by the dark blue line), while during the day the amount of energy produced by the PV system becomes large enough to not only cover household consumption but also to fully charge the battery. To examine the impact of seasonality, data on the daily electricity profile for one selected day in the winter month were analysed. The results are shown in Fig. 2.5.

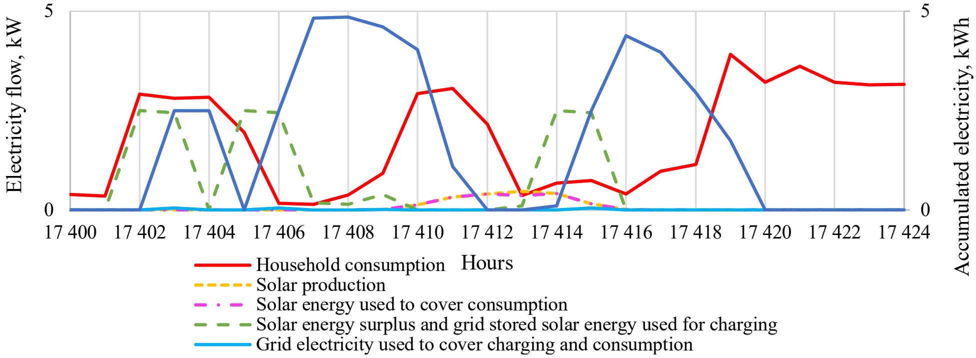

Fig. 2.5. Daily energy flow profile for a system with PV and battery on a winter day.

As can be seen from the resulting graph, household electricity consumption in winter is relatively higher. On a winter day, energy demand is partially covered by the amount of energy stored in the battery (see the dark blue line in Fig. 2.5), while electricity consumption from the grid, given the current tariff, is very low on that day. During the winter months, the excess solar energy and the accumulated solar energy of the grid are used to charge the battery, which is described in the graph by the green discontinuous curve. However, on a winter day, in Latvian conditions, after covering the consumption and charging the battery, there is no more solar energy to transfer to the grid, as it is fully consumed. In general, it is possible to observe the profitability of installing an electricity accumulation system in a household in Latvia also in the winter period.

The results obtained in the system dynamics model (using data from 2021) were compiled. Figure 2.6 shows the profile of energy flows by month of year if a PV system is installed in the household, while Fig. 2.7 shows a system with PVs and a battery.

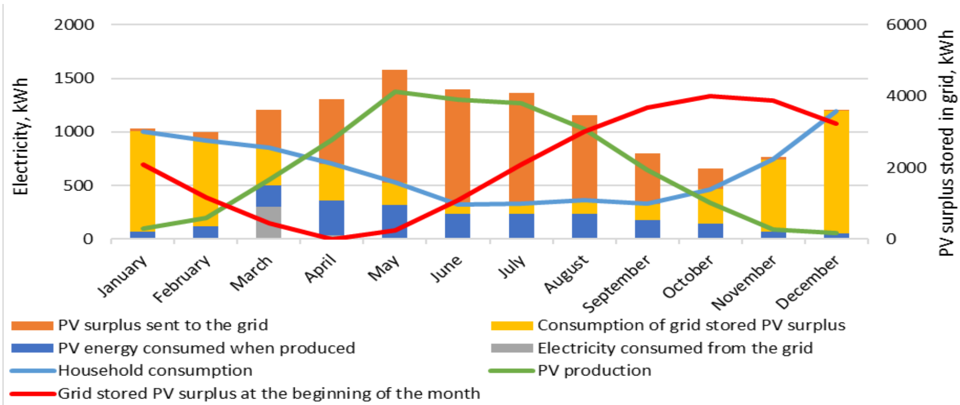

Fig. 2.6. Monthly energy profile for the PV system.

The results obtained show that the highest production of electricity from PVs takes place between May and August, which is represented by the green curve in Fig. 2.7. Also, the lowest electricity consumption is observed in the summer months (denoted by the blue curve). The red curve indicates the amount of energy of PVs stored in the grid at the beginning of each month. It can be observed that starting from May (the beginning of a new balance sheet year), this volume is growing, and the highest savings (~ 4000 kWh) are reached in October, which allows this energy to be used until the next April. The graph shows the distribution of sources for each month to cover consumption. During the winter months, from November to January, the amount of electricity stored in the grid is mostly used to cover consumption. During the summer period, already from May to August, the energy produced by PVs is mostly consumed immediately. The results obtained are shown in Fig. 2.7.

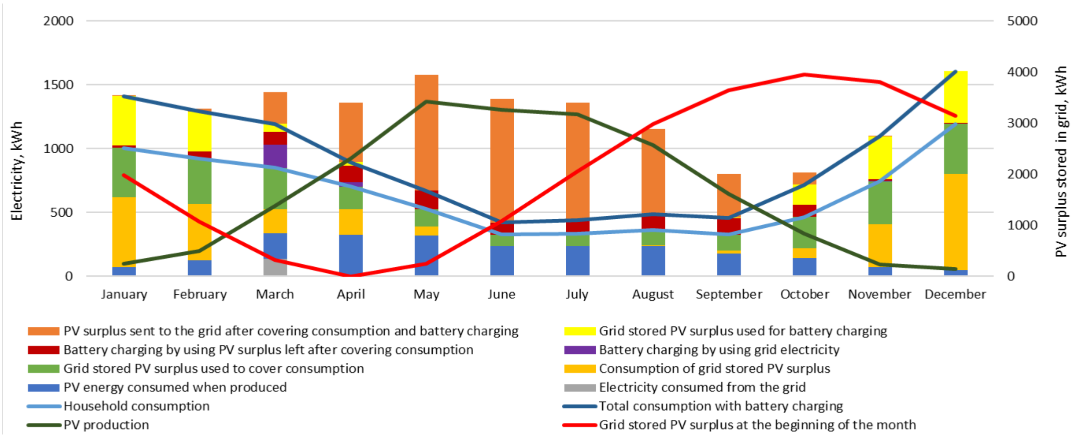

Fig. 2.7. Monthly energy profile for a solar panel system with a battery.

In order to summarize the results obtained, a comparison of all four analysed systems is carried out, determining the annual cost of electricity from the grid, the annual savings and payback of each system, and the amount of electricity consumed from the grid during the year according to the analysed electricity prices from 2019 to 2022. A summary of the results can be found in Tables 2.2–2.5.

Table 2.2

Comparison of Different Systems with the Price of Electricity at the Level of 2019

2019	**Annual cost of grid electricity**	**Annual savings**	**Payback time**	**Consumed grid electricity**
	EUR/year	**EUR/year**	**Years**	**kWh/year**
Grid electricity	889	-	-	7755.55
PV system	293	596	16.8	331.32
Battery	858	31	448.3	7862.27
PV + battery system	260	629	22.3	372.39

At electricity prices in 2019, it is possible to observe that at times when the energy costs of the grid are relatively low, it is still possible to save by installing a PV system or a PV and battery system (see Table 2.2). However, due to the installation costs, the payback period would be significantly long, with the PV system reaching almost 17 years and the system with a connected battery 22.3 years, thus reducing the economic justification for the introduction of the system in Latvian households. On the other hand, when installing only batteries, the annual savings on low electricity prices are insignificant, and taking into account the payback period, which reaches 448.3 years, it is possible to say that installing batteries alone in the given conditions is unprofitable.

Table 2.3

Comparison of Different Systems with the Price of Electricity at the Level of 2020

2020	Annual cost of grid electricity	Annual savings	Payback time	Consumed grid electricity
	EUR/year	EUR/year	Years	kWh/year
Grid electricity	776	-	-	7755.55
PV system	285	491	20.35	331.32
Battery	724	52	266.9	7857.75
PV + battery system	250	526	26.6	368.78

In the case of even lower electricity costs, i.e. at 2020 electricity prices, when the total annual cost of grid electricity in each of the system solutions analysed decreases, it is possible to determine that the annual savings in PV and PV with storage systems will decrease, with a corresponding increase in the payback period for both systems (see Table 2.3). Meanwhile, in a situation where there is only a battery, the annual savings increase and the payback time decreases, the payback time is still unrealistic, and the scenario is defined as unprofitable.

Table 2.4

Comparison of Different Systems with the Price of Electricity at the Level of 2021

2021	Annual cost of grid electricity	Annual savings	Payback time	Consumed grid electricity
	EUR/year	EUR/year	Years	kWh/year
Grid electricity	1331	-	-	7755.55
PV system	293	1038	9.6	331.32
Battery	1223	108	129.2	7862.81
PV + battery system	259	1072	13.1	370.68

In cases where electricity costs are higher, for example, as in the case of electricity prices in 2021, it is possible to achieve much higher annual savings and a more acceptable payback period only for the PV panel system and the PV and battery system, achieving savings of 1072 EUR/year and in the latter case reducing the payback period to 13.1 years (see Table 2.4). This justifies the profitability of installing energy-efficient solutions in households in Latvia. However, even at 2021 prices, only the battery system does not pay off in a reasonable period of time.

Table 2.5

Comparison of Different Systems with the Price of Electricity at the Level of 2022

2022	Annual cost of grid electricity	Annual savings	Payback time	Consumed grid electricity
	EUR/year	EUR/year	Years	kWh/year
Grid electricity	2425	-	-	7755.55
PV system	350	2075	4.8	331.32
Battery	2164	261	53.7	7860.62
PV + battery system	307	2118	6.6	367.85

The four preceding tables point to another peculiarity: consumption is higher only in the battery system than in the grid electricity scenario. This is due to the process of charging/discharging the battery, in which inevitable losses occur (including those in standby mode). To cover the same load of household consumption, using a system designed exclusively for batteries, more electricity is needed. The same effect is observed in PV and battery systems compared to systems designed exclusively for PVs. The greatest benefits can be found if the cost of electricity is at the price level of 2022. In this case, the annual savings for the installation of the PV system amount to 2075 EUR/year and the payback period decreases to 4.8 years (see Table 2.5). At electricity prices in 2022, also for PV and battery systems, the annual savings would reach 2118 EUR/year, but the payback period would decrease to 6.6 years, thus indicating the profitability of system installation in households in Latvia in case electricity prices would not decrease significantly from the level of 2022 or, in the long term, if prices increase due to other global economic and environmental problems (for example, climate change). A system designed exclusively for batteries remains a difficult option; although the payback period is decreasing, it still reaches 53.7 years, which is not profitable.

2.3. Algorithm for data collection and critical analysis, calculations and forecasting

The share of renewables in the total electricity produced in Latvia is shown in Fig. 2.8. On average, depending on the season, which significantly affects the production of electricity from RES, Latvia produces about 40–50 % of the total electricity required from RES. Three cascades of hydroelectric power plants of the Daugava River provide most of the total electricity produced, ensuring the electricity base capacity of Latvia. By 2021, wind power generation capacity was only 77–78 MW, but in 2022, it increased to 136 MW due to the creation of a new wind farm. In 2022, solar power capacity also increased significantly. As the geopolitical situation in Europe intensifies, citizens are increasingly considering individual energy independence. In addition, the Latvian government has offered support for the installation of PVs in households, as a result of which the total installed solar capacity increases significantly. Currently, the solar energy production capacity in the country is almost 150 MW, over the past three years it has increased about nine times.

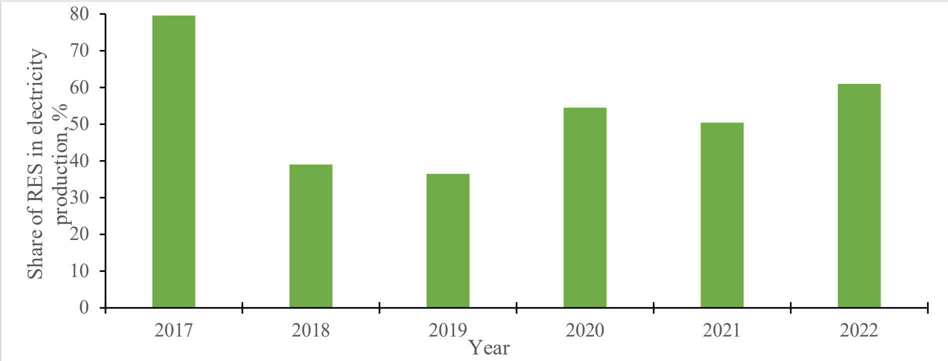

Fig. 2.8. Share of renewable energy resources (%) in the total electricity produced in Latvia in 2017–2022 (Data: Latvenergo AS).

The amount of electricity produced from RES varies greatly depending on the season and weather conditions. This applies not only to wind and solar energy but also to hydropower. The operation and capacity of the three HPPs depend on the harshness of winter and the flow of the Daugava River (Fig. 2.9). If the water level is low, there are fewer resources from which to generate electricity, which means that electricity production in dry summers in Latvia is several times less. In turn, during the spring thaw period, locally produced electricity fully satisfies the demand in Latvia.

In the production of hydropower there are not only seasonal but also annual differences. In April 2023, three hydroelectric power plants of the Daugava River produced 893 GWh or approximately 90 % of the total electricity produced in Latvia. This month, due to the large water supply in the Daugava River, the largest amount of electricity was produced in Latvia since April 2011. In January 2023, the Daugava HPP produced 638 GWh (69 % of the total amount of electricity produced in the country). In January 2022, the share of the Daugava HPP in the total electricity produced was only 43 %.

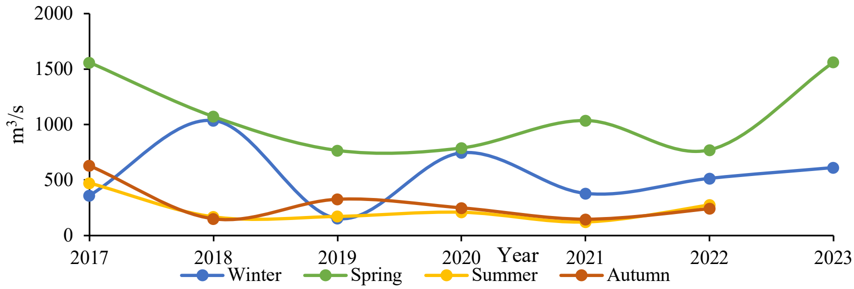

Fig. 2.9. The Daugava River flow in Jekabpils (m^3/s) by seasons in 2017–2023. Data compiled from the Latvian Environment, Geology and Meteorology Centre (LVĢMC).

When calculating the annual electricity balance of Latvia, which is the difference between the electricity produced and consumed, the results show that the volume of electricity production in Latvia is uneven and insufficient to meet the local electricity demand (Table 2.6). The annual electricity balance is mainly negative, as a result of which it depends on electricity imports.

When summing up the amount of electricity produced and consumed by month and calculating the balance sheet, a trend was observed, where a positive balance is mostly achieved in the spring months. The largest share of electricity production in Latvia comes from three Daugava hydroelectric power plants.

Table 2.6

Latvian Electricity Balance (GWh) by Month in 2017–2022 (Positive Balance and the Total Values for the Year are Highlighted in Bold. Data: Compiled from Latvenergo AS)

Month	2017	2018	2019	2020	2021	2022
January	**43.7**	**184.1**	–107.8	–31.8	–65.7	–156.3
February	–25.8	**69.7**	–146.2	–16.5	–40.7	–151.8
March	**302.9**	**4.7**	**34.6**	**44.9**	**56.5**	–192.9
April	**161.5**	**238.8**	–80.9	–177.5	**73.8**	**75.0**
May	**12.7**	–138.6	–160.7	–110.1	–46.6	–168.6
June	–164.8	–244.1	–144.7	–52.3	–200.4	–259.2
July	–177.8	–196.8	–198.5	–293.1	–91.3	–336.1
August	–178.3	–141.4	–54.0	–173.0	–419.6	–310.9
September	–39.6	–180.2	–17.5	–225.0	–265.9	–330.2
October	–14.6	–239.3	–107.8	–285.0	–335.1	–352.4
November	**85.0**	–151.3	–42.0	–154.8	–200.1	–104.7
December	**59.2**	–157.1	–92.5	–151.5	–37.4	–23.5
TOTAL	**64.2**	**–951.5**	**–1118.1**	**–1625.7**	**–1772.5**	**–2311.5**

In order to assess the electricity storage potential, the clustering method was used, grouping the volumes produced and consumed by season and by day – on weekdays and weekends, while assessing the intensity of electricity production and consumption.

From the analysed data, the results show that currently electricity consumption exceeds the production from RES, although the Daugava hydroelectric power plants were able to achieve a positive electricity balance in certain periods in April 2022 (data are not presented). Looking at the total electricity balance, there are a few months when the electricity balance in Latvia has been positive (see Table 2.6). The positive balance allows to store excess energy in water reservoirs with PHES technology. This stored energy could be used at a time when the demand for electricity is high. In addition, RES capacity is expected to increase in the future, and wind and solar energy will be needed to store during peak production hours. If hydroelectric power reaches its maximum potential in spring, then the potential of wind energy is reached in the winter months, when the highest average wind speed is observed in the entire territory of Latvia.

In 2022, the total installed wind energy capacity in Latvia reached 136 MW. If the total installed capacity reached 1000 MW, the electricity produced would increase 7 times. If the total installed wind energy capacity in 2022 was 1000 MW, wind energy could provide about

25–30% of Latvia's electricity in the winter period, while in the autumn it could reach 50 % and more.

Latvia's offshore wind energy potential is estimated at around 15 GW. At the moment, this potential is untapped. The potential of offshore wind energy, if fully exploited, would cover Latvia's electricity consumption many times in surplus. It is planned to increase the production of wind energy in Latvia by 2030. The development of wind energy will require energy storage facilities. A potential solution is to rebuild the existing hydroelectric power plants of the Daugava River so that hydroelectric energy storage can be located in them. Due to the high cost of capital and environmental reasons, it is desirable not to build a hydroelectric storage system from scratch but to adapt the already existing cascades of hydroelectric power plants. The efficiency of hydroelectric energy storage varies from 75 % to 85 %. PHES is the most efficient storage method for large amounts of electricity. Energy can be stored for a long time, and the system has a fast reaction rate. PHES is useful for integrating and balancing RES into the power grid.

The Daugava HPP is the largest hydroelectric power plant in the country, which provides a large share of renewable energy to the electricity grid. In 2022, 2.7 TWh of electricity was produced at the Daugava HPP. The installed electrical capacities are: 908 MW (Pļaviņas HPP), 402 MW (Riga HPP) and 248 MW (Ķegums HPP). Places on the Daugava River from the farthest up to the lower reaches are Pļaviņas, Ķegums and Riga. In terms of installed capacity, the Pļaviņas HPP is the largest hydroelectric power plant in the Baltic States and one of the largest in the European Union. Three Daugava HPPs store water in reservoirs behind dams and produce electricity during peak hours. The exception is when in the spring there is flooding in the river and a greater flow of water. Then hydroelectric power plants are operated at maximum power. If the water level is too high, it is passed through the leaking gate for safety and environmental reasons. Thus, the possibilities of balancing the electricity of the HPP in the spring are limited. The amount of energy that can be stored by PHES technology depends on the height difference between the reservoirs and the amount of water that can be transported between the reservoirs. The height/fall of Pļaviņas, Ķegums and Riga HPPs is 40, 14 and 18 m, and the volumes of water reservoirs are 0.509, 0.157 and 0.339 km^3, respectively. A more detailed analysis of technical aspects as well as investment costs for the potential adaptation of the Daugava HPP for the storage of hydroelectric power from pumps is outside the scope of this study.

The results of the algorithms indicate that there is a great potential for the development of wind energy in Latvia. This potential can be exploited in electricity generation in months when hydroelectric power generation is reduced due to low water levels. This would strengthen Latvia's electricity supply by reducing dependence on imported energy and contribute to the achievement of climate objectives. Integration of hydroelectric energy storage in the existing hydroelectric power plants of the Daugava River would promote the use of renewable energy. Such diversification in energy production and storage will ensure both safety and sustainability in the electricity supply.

2.4. Feasibility study for companies

Figure 2.10 shows the overall results for all 22 scenarios out of the eight selected alternatives analysed in this study.

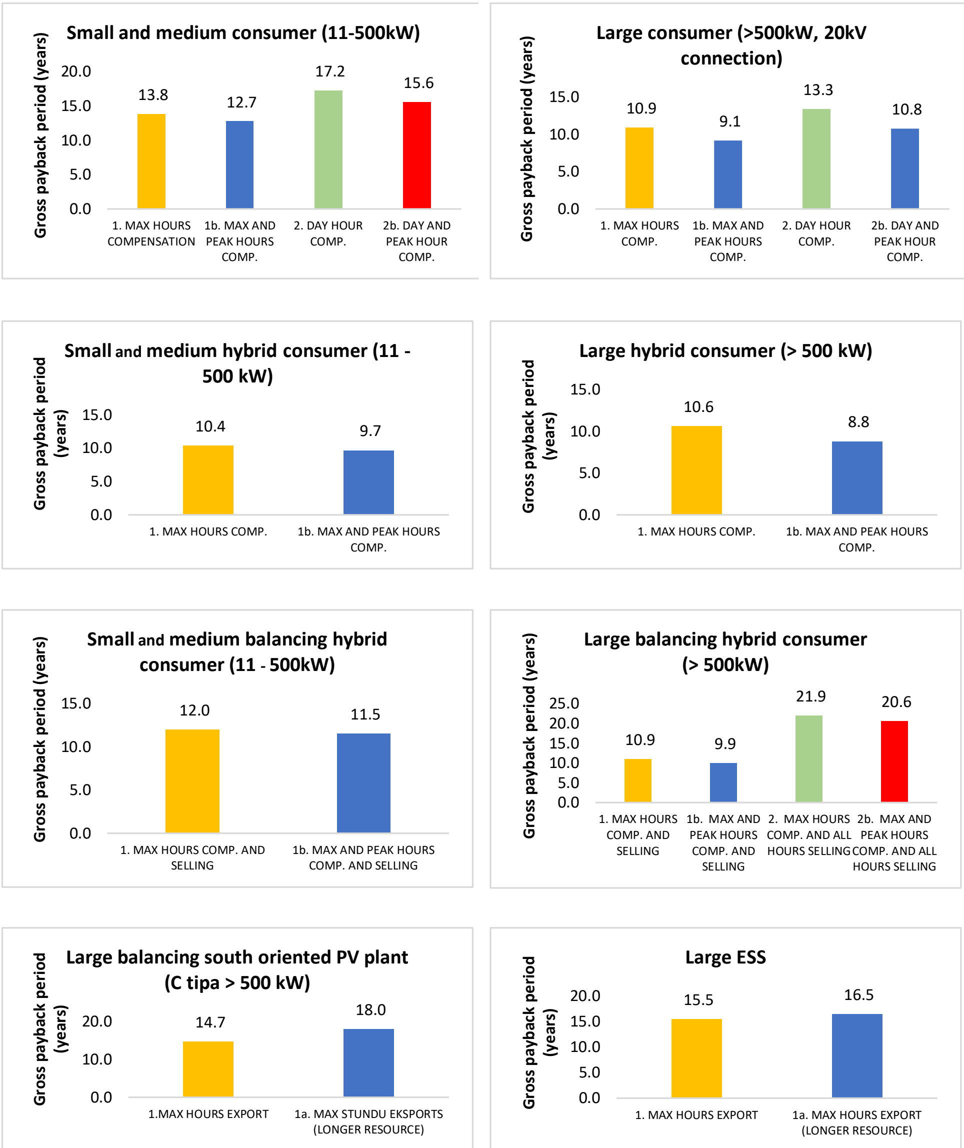

Fig. 2.10. Gross payback period for all alternatives and all scenarios.

The author believes that the results of this feasibility study might surprise many experts in the field, because it is currently believed that at an average investment of less than 400 EUR/MWh, the accumulation of electricity will return to the business within a reasonable timeframe, which is assumed to be under 12 years. The question raised in this study is whether electricity storage systems pay off for up to 10 years with and without additional support with the system's capital investments below 350 EUR/MWh for small systems and below 300 EUR/MWh for large systems. Gross earnings are assumed to be returns, which do not take into account the cost of capital, depreciation and degradation of equipment. Alternatives to the selected systems in the total number of 8 are selected from real living conditions, each using actual parametric values in the calculations. This is a high level of detail, which is also applicable in other countries. The results do not show the part of study which relates to the impact of the bank and financial support instruments on the project's payback period. Currently, Euribor rates are high and this affects this type of investment project.

The findings show that the gross payback period ranges from 8.8 years to 21.9 years. These fluctuations have different character traits that are specific to each of the selected peculiarities of enterprises. The minimum from the maximum is mainly distinguished by the choice of the accumulation system for the performance of the task in question. A 0.25 C discharge factor system was suitable for compensation of peak hours and peaks of a large hybrid consumer, while for a large balancing hybrid consumer, a slower charge/discharge system with a 0.125 C factor was chosen for peak hour compensation and all-hour sales. Consequently, the necessary investments also increased several times. From this, the author draws the conclusion that a lower C factor provides a wider range of activities that can provide activity over a longer period of time, but for economic calculations it creates a greater capital investment burden. This analysis focused on possible alternatives and scenarios rather than business logic. This methodology will help companies both in Latvia and abroad to obtain accurate results for the calculations of their business models.

The results show that the electricity storage system can definitely reduce the payback period if the project task sets as a goal to compensate not only peak hours but also the peaks of self-consumption of electricity. As a result, the consumer can reduce the nominal required by the input protection device and reduce the share of the transmission tariff of the monthly electricity bill. For consumers within the boundaries of high-voltage subscriber affiliation, the benefit is more significant than for low-voltage subscribers, which can also be seen at the difference in the payback period. For a large hybrid consumer, taking into account not only the maximum hourly compensation in the calculations but also the payback period of the consumer's peak compensation decreases by 17 %. In the given example, the amount of capital investment required does not change, but the habits of using the electricity storage system change, partially compensating for the consumer's peak need with the accumulated electricity. Peak consumption for this company is rare, therefore, it does not significantly affect the longevity of the battery system. Exactly the same results are also visible between the hour of the day and the hour of the day with the compensation of the peak hours. But the author also concludes that compensating for the hours of the day is less profitable than compensating for peak hours, since electricity prices are lower during the day compared to peak hours. So, if you have to choose between daily hours, peak hours and peak loads, then it is technically economically justified to compensate for peak hours and peak loads, regardless of the alternative to the customer profile.

The results of this study show how the electricity storage system creates synergies with solar energy. It can be concluded that the most efficient way to use the electricity storage system is to install it near a large electricity consumer who has PV installed without export capacity. In this alternative scenario, the shortest payback period is obtained, since the capital investment of the system is relatively lower with other alternatives per MWh due to the fact that for large systems the specific investment per MWh is lower than for small systems and the fact that there is an existing electricity connection.

It must be acknowledged that in real practice there would be adjustments to the results of alternatives with installed PVs, since the yield profile is seasonal in nature, in which case it is more challenging to effectively use excess electricity in line with stock exchange prices at battery charging, but these deviations would be compensated for by green certificates of origin, which are also not taken into account in the framework of this study.

The main point of this study is confirmed – the electricity storage system pays off for companies in a shorter period of time than 10 years. Such a system must be installed in a company with existing self-consumption of electricity, which wants to compensate for expensive electricity prices and its peak loads, and this company has PVs installed and stores the produced surplus during the day and sells it to electricity traders during the precious hours of the evening. Such a solution is clearly an excellent way to create additional energy independence for yourself, to be more sustainable and to increase the more efficient use of renewables by shifting it from day to day to peak hours, thus balancing the overall electricity market.

Sensitivity analysis for scenarios with the lowest gross return period in each of the alternatives

Given the rapid dynamics of technological developments and prices, a sensitivity analysis was carried out for scenarios that showed the shortest gross return period in each of the alternatives. The author predicts that factors such as excess demand or geopolitical fluctuations may temporarily raise the prices of lithium-ion electricity generation systems to 10 %. In the future, a sharp decrease in prices is expected, which may result in a decrease in prices for the end customer up to 30 %. The analysis indicates that the spread of this technology could increase rapidly, and already after 3–5 years it is possible to achieve a 30 % price reduction.

In addition, the analysis suggests that over the next 2–3 years, more alternatives and scenarios will emerge with a faster payback period, which could fall within 10 years without state support. This will affect the spread of technology, similar to what has happened with PVs. Rapid development of wind turbines is forecasted in the Baltic Sea region. For large free-standing electricity storage systems and storage systems connected to solar parks, the payback period does not decrease as rapidly as in cases where there is an existing consumer, since the cost of electricity connection does not decrease so rapidly. As for the support mechanisms with 30 % grants, they have a similar effect as a 30 % price reduction. State aid would not only improve the situation for companies but also reduce the load on electricity grid by offering opportunities to connect new electricity consumers. This would contribute to the efficient operation of the grid and improve the competitiveness of companies by reducing electricity distribution and transmission tariffs. The author concludes that one aid could contribute to several goals.

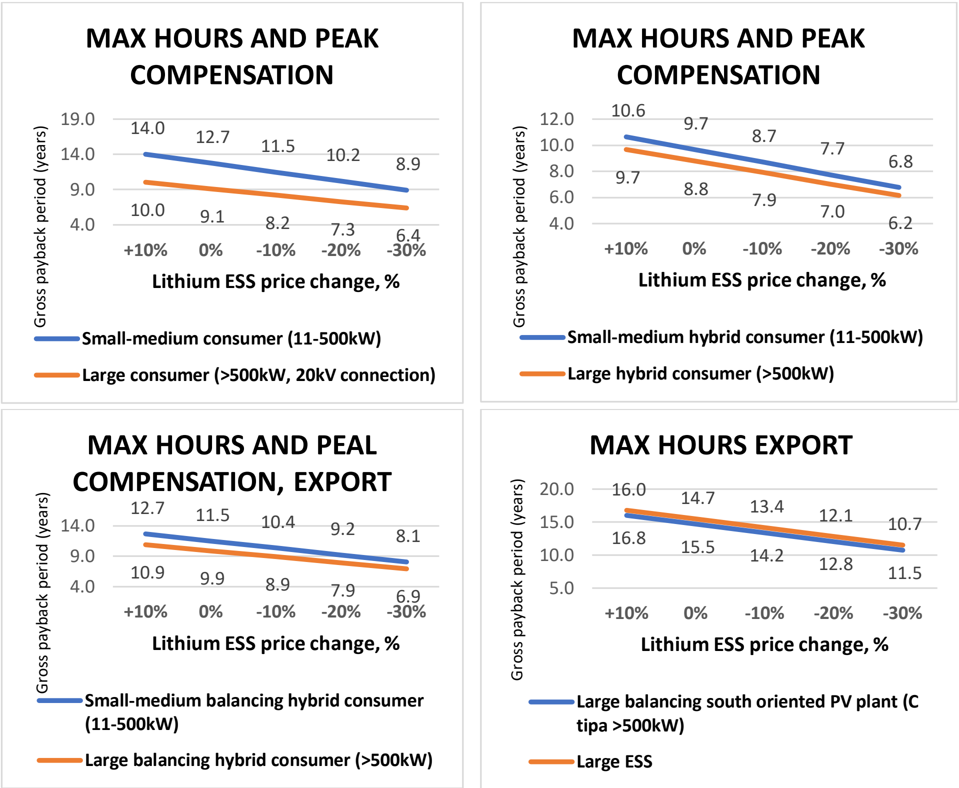

Fig. 2.11. Sensitivity analysis for scenarios with the lowest gross return period in each of the alternatives.

CONCLUSIONS

1. Currently, the most suitable electricity storage solution for RES is lithium-ion batteries and pumped storage hydropower.
2. Testing of the system dynamics model created confidence in its adequacy and reliability of the model. The results showed the potential for integrating battery storage into the household sector. From the scenario results, it can be concluded that a EUR 20 million 5-year subsidy for technologies with 50 % support intensity is not enough to significantly increase the implementation of the combined solar panel and battery system (from 21500 to 25000).
3. Accumulation of electricity provides several benefits:
   - increased use of RES;
   - backup in the case of network interruption;
   - economic security for RES investments.
4. Corporate and state-level lithium-ion storage solutions are paying off in less than 15 years, in some cases under 10 years. The payback period may decrease by 30 % in the next 3 years.
5. Accumulation of electricity is critically necessary to promote the transition to using renewable energy resources. Considering the wind potential of Latvia and the Baltic Sea region, it will be impossible to efficiently use the electricity produced without appropriate energy storage solutions.
6. Electricity storage installation should be started now, and it should be done gradually.

RECOMMENDATIONS

1. To expand the discussion of electricity accumulation in society citizens'awareness of its actuality and necessity.
2. To create additional support tools for research institutions in the sector of electricity storage solutions and their commercialization.
3. To work on political solutions to promote changes in the electricity consumption profile at the national level.

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