RIGA TECHNICAL
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Jana Teremranova

MULTI-LEVEL ASSESSMENT OF THE CONTRIBUTION OF END USERS TO THE PROCESS OF TRANSFORMATION OF THE ENERGY SYSTEM TOWARDS DECARBONISATION

Summary of the Doctoral Thesis

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RIGA TECHNICAL UNIVERSITY
Faculty of Electrical and Environmental Engineering
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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 the defence at the open meeting of RTU Promotion Council on 20 April, 2023 at 11:00 at the Faculty of Electrical and Environmental Engineering of Riga Technical University, 12 k-1 Azenes Street, Room 306.

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DECLARATION OF ACADEMIC INTEGRITY

I hereby confirm that the Doctoral Thesis submitted for the review to Riga Technical University for the 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 the promotion to a scientific degree.

Jana Teremranova .... (signature)

Date: ....

The Doctoral Thesis has been written in English. It consists of an Introduction, 5 chapters, Conclusions, 59 figures, 23 tables, 3 appendices; the total number of pages is 148. The Bibliography contains 198 titles.

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1. INTRODUCTION

Background and topicality of the research

Following the Paris Agreement objectives [1], the European Union (EU) has set ambitious greenhouse gas (GHG) emission targets for 2050 [2], including a decrease in net GHG emissions by **at least 55 % by 2030** (the *Fit to 55* package) [3]. To meet these targets, it is essential to **reduce emissions from the energy sector**, which account for around 75 % of the EU's GHG emissions [1]. Also, in order to accelerate the introduction of renewable energy sources, improve energy efficiency and energy security, as well as promote investment and accelerate the pace of renovation of buildings in the European Union, a package of documents, "Clean energy for all Europeans" [4], was developed by the European Commission.

The 2030 Climate and Energy Framework [5] includes targets for increasing the share of renewable energy sources (RES) in final consumption to at least 32 % by 2030 and improving energy efficiency by at least 32 %. The EU's GHG emissions from the generation and consumption of energy are more than 75 % [6], therefore, since a significant part (about 76 percent) of the total emissions comes from carbon dioxide (CO_2), decarbonisation of the energy sector is essential in order to meet the net-zero target by 2050. Thus, it is necessary to continue systematic efforts to reduce the consumption of combustible fuels by finding new, scientifically based opportunities and initiatives for the transition to clean energy.

Fuel substitution policies can reach their maximum impact in cities, which represent a concentration of population, production and consumption of resources. Striving to decarbonising the energy mix of the city, the maximum energy efficiency and GHG **emission reduction can be achieved by focusing on three main areas** [7]: in the transport sector, by switching to electric motors for the maximum amount of road transport, which can lead to a significant increase in efficiency; **in residential and commercial buildings, where it is necessary to invest in more efficient technologies using clean electricity and heat**, as well as in energy conservation technologies. Complex electrification should also take into consideration the source of electricity generation and gradually switch to clean electricity, which significantly increases the efficiency and speed of decarbonisation.

The role of energy consumers becomes very significant in the light of the ongoing changes. The European Commission has proposed new rules for consumer-centred clean energy transition [4], where consumers are stressed as central players in the energy markets of the future. Due to the central role of industrial, commercial and residential energy end users in the energy market, it becomes possible to resolve the issues of excessive costs for backup generation, make the market transparent for all participants and continue the development of renewable energy sources and new technologies. The International Energy Agency (IEA) [8] stress that it is impossible to imagine the implementation of the Net Zero 2050 scenario with the lifestyle and energy use habits of end consumers unchanged, since in this case the potential of individual consumers to influence with their choices the transformation of the entire energy system towards decarbonisation and the sustainability of the implementation of selected goals will remain unrealised.

However, the increase in electrification creates new difficulties for the electric power system of a country or region [9], especially in combination with the simultaneous replacement of several types of combustible fuel with renewable energy sources, such as photovoltaics (PV), heat pumps, wind energy, battery electric vehicles, etc. There are problems in terms of additional energy needs, energy shortages or surpluses, as well as the effective reduction of CO_2 emissions, which are useful to assess in dynamic and data-driven approaches. The need for a robust and flexible approach to modelling end-consumer impact at different involvement levels is obvious.

Thereby, this Doctoral Thesis aggregates a detailed analysis of different socio-economic levels with end-consumer impact assessment by introducing consumer-centric multi-level structure (see Fig. 2.3). Large-scale modelling is presented by both annual and hourly operation of the power system sustainable and flexible work simulation of the Baltic countries. This research provides a set of measures aimed at exploring and modelling the possible impact of energy consumers in Latvia and the Baltic States on the possibilities of increasing efficiency and flexibility and reducing energy consumption in the power system.

Thus, one of the main features of the energy transition are that today's consumers have the ability to control their energy consumption, have energy production, and thereby interact with the energy system. These new properties of consumers are changing the very system of energy supply and approaches in the energy sector. This Doctoral Thesis describes a multi-stage methodological approach of the contribution of end users to the process of energy system transformation toward decarbonization developed by the author. Each stage of the approach consists of a sequential solution of a single problem or several tasks of varying importance and complexity, for each of which special methods and models have been developed. The sectoral modelling represented by six scenarios of energy savings in dwellings when substituting gas stoves with electric and induction alternatives was offered. Additionally, the costs of electrifying stoves vs cars for Latvian households were compared. Following it, the modelling of energy behaviour in dormitories reflects the untapped potentialities of the end user in communities.

Hypothesis, objective and tasks of the Thesis

Hypothesis

The changes in the energy behaviour of different groups of end users have a significant impact on the possibilities of increasing the efficiency and flexibility of the overall energy system, contributing to the achievement of the national decarbonisation goals.

Objective

Impact assessment of the change in the behaviour of end users for the decarbonisation of the overall power system by modelling the end-consumer energy behaviour at different levels of energy environment.

Tasks

1. To study the smart urban environment potential and its influence on energy end consumers.
2. To devise the methodology for long-term, smart, decarbonised energy environment development, assessment and fixing of gaps.
3. To develop a survey for exploring the needs of end users and their awareness in terms of smart energy consumption.
4. To devise scenarios for modelling the impact of energy consumers/prosumers on the overall flexibility, security, and reliability of the power system.
5. To explore and model the potential of the building sector in the acceleration of the energy system decarbonisation process.

Research methods and tools

1. To model and analyse the transition of the Baltic energy system towards climate neutrality, a *Baltic Backbone* model has been adjusted on the basis of the ***Backbone*** **tool** (an adaptable energy system modelling framework). It has been developed in **GAMS** (General Algebraic Modelling System) and with its help multiple energy sectors, units, nodes and levels were introduced and analysed and the parameters of the Baltic countries and the neighbouring regions with different level of detail were modelled. For data input and result analysis, the **Microsoft Excel** and **GAMS** software has also been used. Additionally, various databases were utilised for gathering input information: Latvian, Lithuanian and Estonian statistical databases, the Danish Energy Agency and Energinet technology database, the ninja_europe_wind_v1.1 database, and the Nord Pool power market dataset.
2. A **survey** was used for studying the present energy consumption habits in various countries and specific conditions for developing smart cities, which make it possible for citizens to become more active and aware of energy efficiency, be more energy-saving and use new progressive technologies.
3. For the research of decarbonisation in cooking sector, **Microsoft EXCEL** software has been used for data input and result analysis.
4. For modelling the changes in consumers' energy behaviour in dormitories, **MATLAB** environment and **Microsoft EXCEL** software was applied.

Scientific novelty

The scientific novelty presented by this Thesis is as follows:

1. A detailed assessment of the role of smart cities for the energy consumers and energy system development towards decarbonisation targets was done proposing a multi-level approach.
2. A methodological decision-making approach for the development of the energy component of a smart city was developed. The algorithm allows to realise the general scheme of the energy development of the city, identifying weak points that require research and implementation. Thus, the assessment of the contribution of end users to the overall structure of energy development was noted as insufficiently developed in the studied literature review. Such a gap hinders the development of the entire energy system, leaving the potential of end consumers unused, and ultimately preventing energy goals from being reached within the specified deadlines.
3. A unique survey of end users was compiled and conducted, which explores in detail the energy behaviour of residents and identifies the beliefs and habits that prevent rapid implementation of climate plans.
4. The Baltic *Backbone* tool was approved as a suitable instrument for creating decarbonisation scenarios in the Baltic region with a particular focus on Latvia. The analysis of the contribution of end users to decarbonisation, efficiency, resilience and sustainability at country and regional levels was presented by modelling scenarios for the building sector of the Baltic region, which maximize the still-not-fully-tapped potential of active end users.
5. An analysis of the possibilities and impact for electrification of kitchens in the residential sector of Latvia was conducted. Six scenarios were offered for the replacement of equipment using liquified petroleum gas (LPG) and natural gas with electrical equipment. For comparison, a calculation was made of the possibilities for replacing cars with an internal combustion engine with electric vehicles and the comparative cost of such substitution was presented.
6. The modelling of the impact of changes in consumers' behaviour on energy consumption and efficiency in dormitories was presented as an example of a potential which can be used in energy communities for reaching energy goals.

Practical significance of the research

The results of the Thesis research were used in the following research projects:

- ERANet-LAC 2nd Joint Call on Research and Innovation for Latin America, Caribbean and European Union Countries project "An ICT Platform for Sustainable Energy Ecosystem in Smart Cities" (ITCity), (2017–2019).
- A project of the National Research Programme "Energy", "Future-proof development of the Latvian power system in an integrated Europe" (FutureProof) (2018–2021).
- Baltic-Nordic Energy Research Programme project "Fasten: Fast, flexible and secure decarbonisation of the Baltic states – possible progress in the next ten years" (2020–2021).
- Baltic-Nordic Energy Research Programme project "Amber: Impacts of ambitious energy policy pathways" (2021–2022).

Author's personal contribution

During the development of the Doctoral Thesis, the author participated in several international projects. The decision-making approach for urban energy environment development was produced by the author within the ITCity international project. State-of-the-art analysis, methodology development and criteria selection for smart city assessment was done within this project under the supervision of Professor A. Mutule. The author also conceptualised, developed and carried out the smart city survey, processed the data and performed the analysis of the results.

The Baltic energy system transition modelling was carried out together with Associate Professor D. Žalostība, VTT Technical Research Centre of Finland Ltd representatives T. Lindroos, N. Putkonen, Lithuanian Energy Institute (LEI, Lithuania) and Tallinn University of Technology (TalTech, Estonia). The author contributed in all parts of the research, especially in gathering information for the input database for Latvia, testing and validation of the results, modelling of scenarios for building sector impact assessment on the decarbonisation process in Latvia and the Baltics, and analysing of results.

The analysis of decarbonisation possibilities for Latvian kitchens was done by the author under the coordination of Professor A. Sauhats. The author contributed in all steps of the research, starting from state-of-the-art cooking equipment analysis and data gathering for Latvian households, to the modelling of sensitivity scenarios and analysing the results obtained.

Finally, modelling of the consumer's energy behaviour changes in dormitories was conducted together with Professor A. Mutule, Assoc.prof. A.-M. Dumitrescu and I. Zikmanis. The author contributed to all the stages of the research, especially in gathering the necessary data for input, the conceptualisation of the model and the analysis of the results.

Approbation of the results

The results of the Doctoral Thesis were presented at the following scientific conferences:

1. The 11th International Symposium on Advanced Topics in Electrical Engineerig , March 28–30, 2019, Bucharest, Romania.
2. The 2020 IEEE 61st International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON), November 2020, Riga, Latvia.
3. The 3rd International Conference on Smart and Sustainable Planning for Cities and Regions (SSPCR 2019), December 2019, Bolzano, Italy.
4. The 16th Conference on Sustainable Development of Energy, Water and Environment Systems (SDEWES), October 10–15, 2021, Dubrovnik, Croatia.
5. The 2022 IEEE 7th International Energy Conference (ENERGYCON'2022), Riga, Latvia, May 9–12, 2022.

The results presented in this Thesis have been published in the following scientific publications indexed in Scopus and Web of Science:

1. Mutule, A., **Teremranova, J.**, Antoskovs, N. "Smart City Through a Flexible Approach to Smart Energy". Riga: Latvian Journal of Physics and Technical Sciences, 2018, No. 1, pp. 3–14. DOI: 10.2478/lpts-2018-0001.

2. Mutule, A., **Teremranova, J.** "Introduction of Energy Saving Principles: Technologies and Awareness, Latvian Experience". Riga: Latvian Journal of Physics and Technical Sciences, 2018, No. 6, pp. 52–62. DOI: 10.2478/lpts-2018-0044.
3. **Teremranova, J.**, Mutule, A. "Sustainable city development as a result of close cooperation with citizens: Europe and LAC experiences". ISBN: 978-147997514-3. Proceedings of the 11th International Symposium on Advanced Topics in Electrical Engineerig, March 28–30, 2019, Bucharest, Romania. DOI: 10.1109/ATEE.2019.8724958.
4. **Teremranova, J.**, Sauhats, A. "Electrification and Decarbonisation Potential Assessment of Latvian Dwellings". Published in: Proceedings of 2020 IEEE 61sth International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON). DOI: 10.1109/RTUCON51174.2020.9316549.
5. **Teremranova, J.**, Mutule, A. "Smart Approach to Management of Energy Resources in Smart Cities: Evaluation of Models and Methods". Published in: Smart and Sustainable Planning for Cities and Regions, Green Energy and Technology, https://doi.org/10.1007/978-3-030-57332-4_1.
6. Putkonen, N., Lindroos, T. J., Neniškis, E., Žalostība, D., Norvaiša, E., Galinis, A., **Teremranova, J.,** Kiviluoma, J. "Modeling the Baltic Countries' Green Transition and Desynchronization from the Russian Electricity Grid". International Journal of Sustainable Energy Planning and Management. May 2022. DOI: 10.54337/ijsepm.7059.
7. **Teremranova, J.**, Zalostiba, D. "Modelling of Building Sector Impact on Decarbonisation of the Baltic Energy System". Proceedings of the 2022 IEEE 7th International Energy Conference (ENERGYCON'2022) in Riga, Latvia, May 9–12, 2022). Doi: 10.1109/ENERGYCON53164.2022.9830169.

The popular science articles were also published on the basis of the results of this Thesis:

1. Mutule, A., **Teremranova, J.** "Vai Rīga ir vieda pilsēta?" Enerģija & Pasaule, 1/2018, pp. 24–27.
2. Mutule, A., **Teremranova, J.** "Spēle kā viedo pilsētu transformācijas instruments". REA edition, No. 35 2018, pp. 4–6.

Additionally, the results of the Thesis were presented in the following online issue:

1. **Teremranova, J.,** Neniškis, E. "Fast energy transition and potential challenges in the Baltics". Nordic Energy Research newsletter. 26 Oct 2021. https://www.nordicenergy.org/article/fast-energy-transition-and-potential-challenges-in-the-baltics/

Volume and structure of the Thesis

The Doctoral Thesis has been written in English. It contains an introduction, five main chapters, conclusions and a bibliography with 198 references. The total number of pages is 148, including 59 figures, 23 tables, and 3 appendices.

The **Introduction** substantiates the growing role of energy consumers in the context of smart cities, which is becoming very significant in the light of ongoing climate change.

Chapter 2 provides an overall analysis and structure of end users, their ability to influence climate and energy goals, and an overview of legislation related to end-user energy consumption. To understand the multilevel approach to the study of the contribution of end users applied in the Thesis, a consumer-centric, multilevel approach structure was presented.

Chapter 3 deals with the creation of a decision-making algorithm for smart management of energy supply, infrastructure and energy flows in urban environment. It contains an overview of approaches to modelling and developing a smart urban energy environment and end users involved in this transition; also, evaluation criteria were selected for understanding the strengths and weaknesses of each approach.

Chapter 4 is dedicated to evaluation of end-user energy behaviour in urban areas through a smart-city survey. With the help of the international ITCity project, the specific conditions for developing smart energy cities with citizens, which become more active and more aware of energy efficiency as well as more prone to energy saving, were analysed and the conclusions systematized. Special attention is paid to the analysis of the needs and awareness of electricity customers in Latvia, their energy behaviour and transition towards a decarbonised and smart city.

Chapter 5 contains modelling of the transition of the Baltic countries' energy system towards climate and energy goals and gives an assessment of the impact of end users on the decarbonisation process. The 2030 reference scenario has been created to introduce the main changes in the Baltic system, and various sensitivity scenarios have been developed for building a sector impact assessment as a result of renovation and implementation of renewables using modern technologies.

Chapter 6 is dedicated to a detailed study of the impact of different end-user groups on electrification and decarbonisation by modelling new end-user energy behaviour in kitchens and dormitories.

Finally, the **Conclusions** summarize the overall results of the Thesis.

2. ANALYSIS OF ENERGY END USERS IN URBAN ENERGY ENVIRONMENT

Depending on the functions performed, the possibilities of providing an external power supply scheme, the magnitude and modes of energy consumption, tariffs and systems for calculating energy, and the features of the rules for energy using, energy consumers are usually divided into the following conditional groups (see Fig. 2.1):

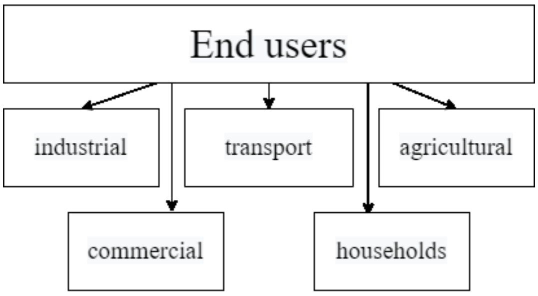


Fig. 2.1. The structure of end users.

While the industrial, agricultural and transport sectors as energy end users are closely related to the energy intensity of introduced production and applied technologies, and therefore is characterised by heavy inertia in terms of fast shifts of energy efficiency, the commercial sector and especially the residential sector are much more influential towards the above-mentioned energy and climate goals. Therefore, it was decided to focus the research within this Thesis on studying and modelling the impact of consumers of the residential and commercial sector.

At the forefront of the European Commission Winter Package [10] are **citizens as potential active customers** – prosumers –, who are encouraged to create, store, consume and sell their electricity generated in all organised markets, both individually and through aggregators. The Winter Package proposes a policy that will enable Europe to achieve an energy-efficient and decarbonised housing stock by 2050, create an enabling environment for investment, and enable consumers and businesses to participate meaningfully in policies to improve the efficiency of the energy system as a whole. End users make a significant contribution to all of the above processes; and analysis, modelling and evaluation of this contribution to the transition to smart energy is required. Therefore, the Thesis aims to study the issues of the importance of the role of end users in an energy transition towards sustainability in Latvia and Baltics and how deeply end users can support their country in energy and climate challenges.

The household sector energy consumption has reached 23 % of the final energy use in the EU countries and is continuing to grow. The impact of this segment on the reduction of energy consumption is critical and is certainly related to the opportunities of achieving the climate goal. According to Eurostat's data [11], the Baltic countries are among countries with the highest proportions of energy used for space heating (Estonia – 71.4 %, Lithuania – 70.2 %, and Latvia – 65.8 %) of the total energy consumed by the residential sector in 2019. This opens additional opportunities for decarbonisation and the introduction of green energy resources and innovations in the end-user sector.

In general, we see a slow positive trend towards reducing heat consumption for space heating (see Fig. 2.2); however, considering that 83 % of the resources consumed by households in Latvia are used for heat and hot water, there is untapped potential in changing the fuel to a more environmentally friendly one and reducing heat consumption by changing technologies and consumption habits.

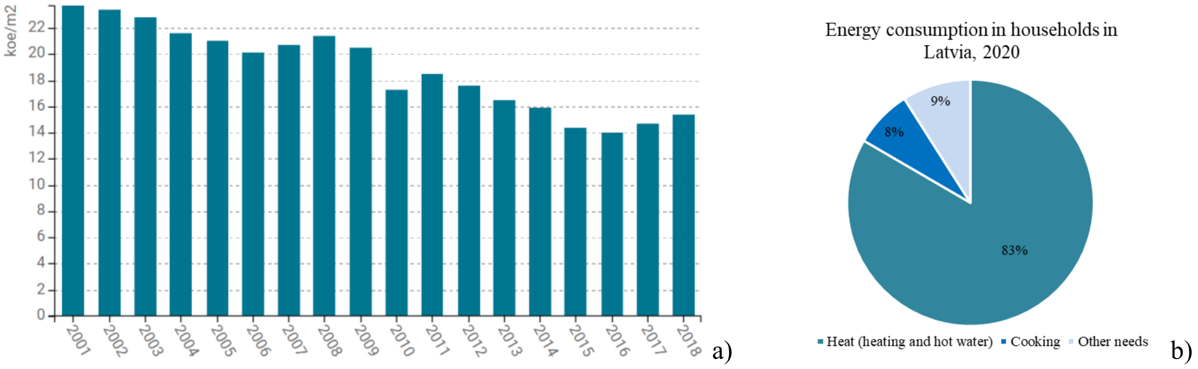


Fig. 2.2. Energy consumption for space heating per m^2 (normal climate) and types of energy resource consumption in Latvian households (%). Source: ODYSSEE [12] and Central Statistical Bureau of Latvia [13].

In order to accurately determine the effective way of reducing, in the long term, energy consumption in the provision of energy services, multiple factors associated with consumption should be investigated as a complex: the use of new technologies, the willingness of residents to change their energy consumption habits (energy efficiency), the level of knowledge about energy resource consumption savings and new technologies available, the financial capabilities, the degree of involvement in the energy and climate goals, and objectives of the country/city.

Since most of the world’s inhabitants live in cities, and by 2050 may reach 80 % of the total population, in the Thesis an important place is given to the study of smart urban organisation of energy processes. Thus, the following tasks are set to make it possible to measure the impact of urban technical-behavioural changes needed: a) to model the decarbonisation scenarios through transition to new types and methods of energy consumption by end users, completely or partially replacing combustible fuels by new technologies; b) to analyse the general approaches to the organisation of the city as a smart energy city, as an environment for the implementation of the goals of decarbonisation and increasing the efficiency of consumption; c) to consider the possibilities of decarbonisation of single sectors where the consumers’ impact can be most influential; d) to develop new modelling methods for an energy community/a group of end users that will allow using smart measurement tools to show the benefits of changing energy behaviour.

In order to explore the possibilities of decarbonisation of a selected part of end consumers, a consumer-centric multi-level system was taken as a basis (see Fig. 2.3).

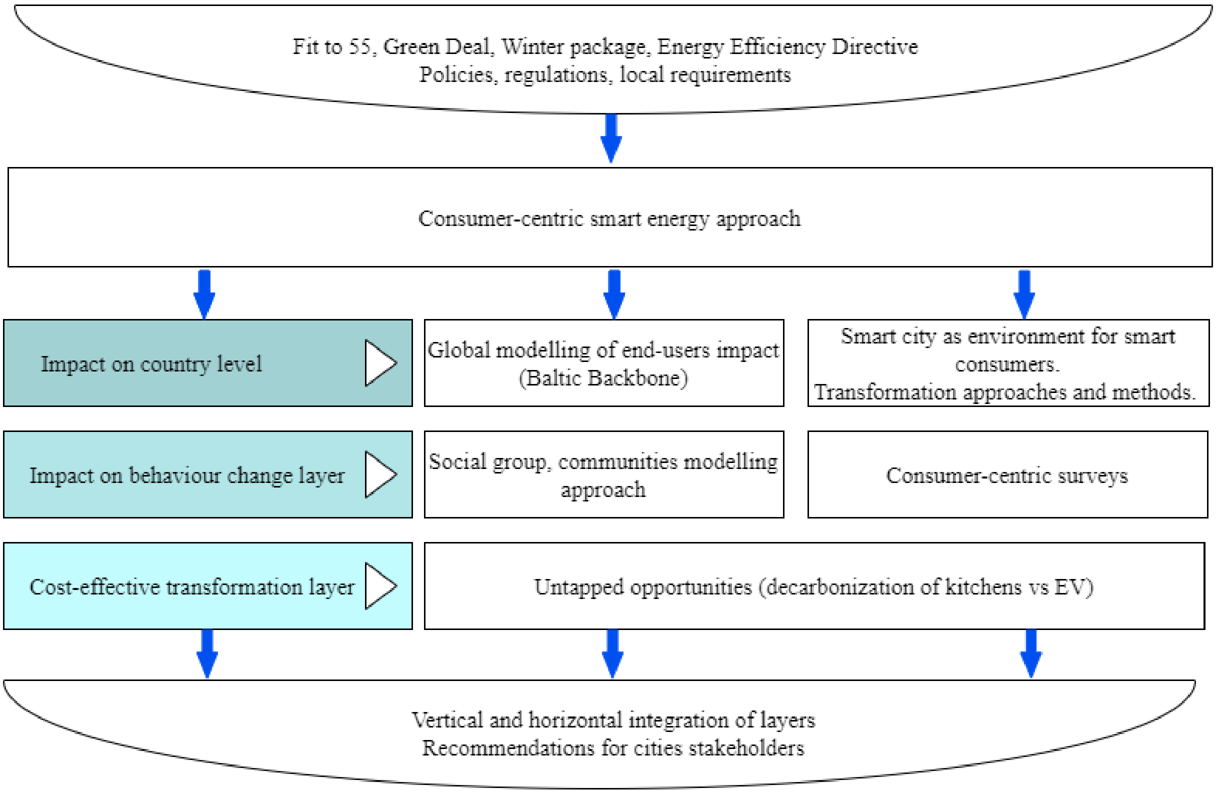


Fig. 2.3. Consumer-centric multi-level structure for the study of the contribution of end users to the overall decarbonisation goal.

The offered structure allows to find the gaps and their solutions at various layers, which contributes to a much more complete coverage of the problem and decision findings.

3. DECISION-MAKING APPROACH

In the smart city or a city in general, end users are a significant part of the energy system and each user is able to affect the city in a unique way. The user behaviour should be addressed as a correlation of energy awareness to changes in the energy consumption. To correctly simulate an increased user awareness, an impact on the energy consumption must be made. There is a gap in understanding the contribution that each participant group makes to the development of a smart city as a whole system and a **lack of methodology for measuring the impact of end consumers**. The abundance of different approaches to urban environment infrastructure, as well as the existence of many approaches to the interpretations of ways of how a city can become smart and efficient did not allow to have a clear understanding of the importance of end consumers in this process and a methodology or approach which can significantly increase the understanding of the role and contribution of end users to the goals set for the city.

In Table 3.1, different methods of the smart city development are considered, providing an overview of approaches to the modelling and developing of smart urban energy environment and end users involved in this transition.

Table 3.1

Regimentation of Approaches to Smart Energy City Development

Smart city approach	***Description***	***Sources***
Employment of optimisation or automation to single sectors of development	Smart energy solutions aimed at solving the energy issues of single city areas. Additionally, the key performance indicator (KPI) sets, standardisation and innovative IT-based approaches are used to create a suitable solution.	[14], [15], [16]
Smartainability	This approach uses qualitative and quantitative indicators of technology assessment for intelligent solutions that are designed to improve energy efficiency and environmental sustainability of the city; it is more focused on integrated intelligent mobile platforms.	[17], [18], [19]
New city planning	Planning and implementation of new smart districts or a city with pre-laid smart energy infrastructure (e.g. the use of 100 % renewable energy sources for energy consumption and heating/cooling of buildings, use of electric vehicles only, use of sensors, etc.) for further development and expansion. The approach considers state-of-the-art technologies and requirements for the level of comfort of residents and the preservation of the environment.	[20], [21]
Smart city infrastructure architecture model (SCIAM)	Multi-level holistic approach to energy in a smart city; it uses separation of the energy infrastructure of the city into layers, levels and zones, considering their interactions.	[22], [23]
Development of a smart energy city (SEC)	Smart energy is presented as the most important and necessary aspect of the successful and sustainable development of a smart city.	[24], [25], [26], [27]
Energy hubs, multi-energy systems	Development and operation of a smart city through the creation of the so-called energy hubs aimed at the flexible integration of the diversity of the city's energy resources for the most efficient, cost-effective and stable resource management.	[28], [29], [30], [31], [32], [33], [34]
Blockchains	Consider blockchain technology application in a smart city context and in the energy aspect as a focused task, for energy supply operations, measuring the amount of electricity consumed, billing for consumed resources and making payments.	[35], [36], [37], [38], [39], [40], [41], [42], [43], [44], [45], [46]
Frugal Social Smart City	A new concept for a smart city, proposed for Casablanca, Morocco. It is based on a global bottom-up multidisciplinary approach that relies on the informational and functional cost-effective integration of various urban complex systems such as energy, transport, health, governance, etc.	[47], [48]
Platformisation	Combining information resources on energy generation, transmission, distribution and use in a smart city, which usually are not connected to one another on a unified platform; therefore, it makes it possible to simplify and	[49], [50], [51], [52], [53], [54], [55], [56], [57], [58], [59]

Smart city approach	***Description***	***Sources***
	clarify the procedure for monitoring and managing energy resources for both the citizens and the administration of the city.	
Citizen-centric energy approach	Approaches based on the acceptance of the significant role of end consumers in the development of the city, stressing the role of active participation of consumers or prosumers in the pathway towards climate and energy goals.	[60], [61], [62], [63], [64]

To promote an understanding of the strengths and weaknesses of the approaches, a variety of criteria has been proposed in the Thesis that allows for a comprehensive assessment of each of the approaches. An evaluation is provided of each criterion based on the frequency of occurrence in the literature and the importance of the particular criterion provided by experts. The evaluation is presented in Table 3.2.

Table 3.2

Evaluation of Models of Smart City Development According to the Criteria Selected

Evaluation criteria	***Model***								
	Single sector optimisation	***New city planning***	***Smart energy city (SEC)***	***Energy hubs, multi-energy systems***	***Smart city infrastructure architecture model (SCIAM)***	***Blockchains***	***Platformisation***	***Frugal Social Smart City***	***Citizen-centric***
Flexible response to changing needs	░	▨	░	▨	░	▨	▨	░	▨
Transparency	░	░	░	░	░	░	▨	░	▨
Economic affordability of the model for implementation	▨	□	░	░	░	░	▨	▨	░
Attraction of citizens in active participation in city's life	░	░	░	░	░	▨	▨	▨	▨
Unification and standardisation is available	▨	░	░	░	░	□	░	░	░
Application of information and communication technologies	▨	▨	▨	▨	▨	▨	▨	░	▨
Top-down approach	▨	▨	▨	▨	▨	░	▨	░	░
Bottom-up approach	□	□	□	□	□	▨	□	░	░
Opportunities for further development after the implementation of the model	░	▨	░	▨	░	░	▨	░	░
Environmental-friendly	░	▨	░	░	░	░	▨	░	░

▨ expressed criterion ░ is possible (average value) □ unexpressed criterion

Based on the above analysis of the approaches to the development of the urban environment and the analysis of criteria, a general algorithm for the development of the energy component of a smart city was created by the author (see Fig. 3.1).

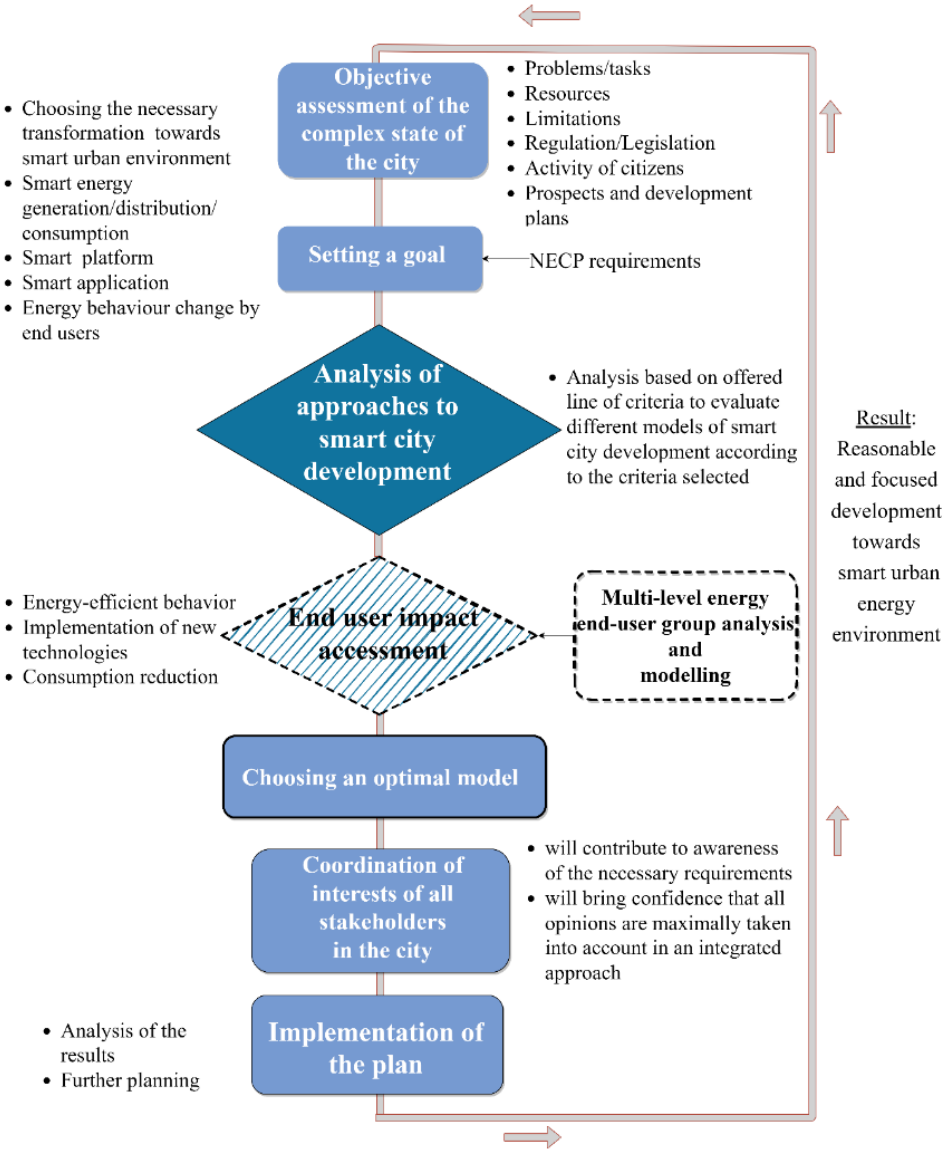


Fig. 3.1. Decision-making algorithm for choosing the development methodology in a smart city.

It should be noted that the weakest link of this algorithm at the moment is close interaction with end users and the comprehensive assessment of their contribution to the energy transformation process within the country or region.

Chapter conclusion

The proposed decision-making algorithm for selecting a smart city development methodology and a block-integrated approach will consider all the results obtained from the analysis of the opportunities and resources of the region as well as contribute to the accumulation and replication of best practices. This is the key for a successful, good-quality and long-term development towards climate and energy goals. Serving as a guideline for selecting an optimal model, the evaluation criteria for a smart city development model help administration, urban planners and stakeholders. The most viable, efficient and stable smart city model must be flexible and adaptive to the resources and needs and take into consideration the undoubtedly significant contribution of end users to the process of transition to carbon-free energy development. Such a reliable model, along with a good-quality assessment using the multifunctional criteria proposed, can satisfy the needs of residents and other participants of the urban infrastructure with any request and affordability level, and the positive experience can be disseminated and replicated to other cities and areas.

Further, since the assessment of interaction and modelling of the impact of end users were recognised as the most vulnerable point in the development of the urban environment, the next part of the Thesis explores in more depth specifically the energy behaviour of residents in order to identify those beliefs and habits that prevent rapid implementation of climate plans.

4. DEVELOPMENT OF THE SMART CITY SURVEY

In this part of the Thesis, a goal was set to find out to what extent the level of dissemination and application of intelligent solutions in the energy sector depends on a person's decision to use them or not, as well as to find the most compelling motivation for residents of cities in Europe and Latin America, which will allow them to change the existing situation to a more dynamic, progressive, energy-saving and moving towards smartness. To investigate this problem, a study was conducted in the following countries: Latvia, Romania, Brazil, and Chile. The respondents were residents of different ages, with different levels of well-being and different cultural and linguistic features.

Respondents were asked in an anonymous way if they knew about smart solutions and initiatives within smart cities, if they knew whether they have ever been used, how much they trusted energy-efficient solutions, how much money they were willing to invest in energy-saving technologies, and which of the proposed options motivated them most of all. General results are shown in Table 4.1.

Table 4.1

Findings of the Survey: Differences and Commonalities

Commonalities
The survey showed that residents of all the project partner countries had little knowledge of what a smart city is and what kind of smart initiatives exist in the towns they live in. Almost all of the respondents are interested in saving energy. The most popular attitude was: "I know [energy saving technologies] and use them a little bit." Although about 80 % of respondents accept introduction of automatic energy-saving devices, about 20% prefer to control energy consumption manually. The absolute majority feel that it is important to use modern technologies in their homes.
Differences
The most popular motivations which can encourage peoples to make more use of energy-saving technologies, differ from country to country: • respondents from Chile and Romania first seek to save natural resources that they already have: the most popular answer about the motivation for using new technologies was "understanding that I will save the nature and earth resources for my children"; • respondents from Brazil and Latvia were more pragmatic, marking "vividly presented savings of energy and money" first.

Results and discussion

The survey showed (see Fig. 4.1 a)) that citizens of Romania were more informed about what a smart city is, and what initiatives aimed at increasing city smartness were being undertaken in their native city (76 % have answered that they know about it). In Brazil and Chile, the percentage was a little lower (about 50 %), whereas the lowest percentage was observed in Latvia – 32 %.

Despite the fact that it is Latvia where the most varied possibilities of choosing optimal management of energy resources and energy saving are observed, it has to be admitted that just here the level of citizens' awareness about those possibilities is the lowest – about 25 % do not know anything about the opportunities in that sphere (see Fig. 4.1 b)). It is evident that in-depth studies are needed to find out how to motivate people to become more active as regards management of their energy resources.

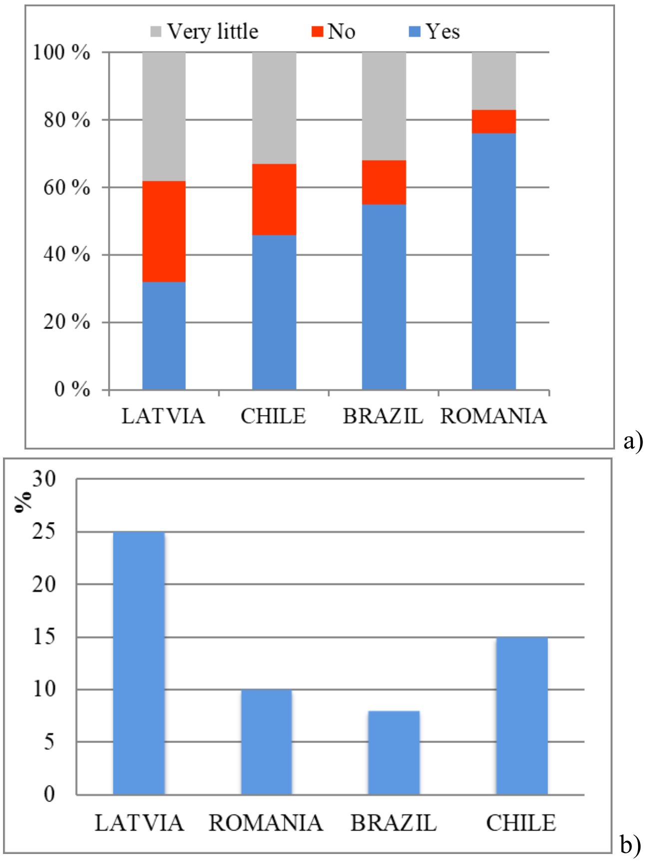


Fig. 4.1. a) Citizens' awareness about smart initiatives in their cities; b) citizens' awareness about energy-saving options available in the country: the percentage of citizens who know nothing about the possibility of changing their energy consumption mode to a more efficient one.

This will serve as an impulse for citizens to change the paradigm of their old-fashioned way of thinking and to become ready for co-operation, smart consumption, and even energy generation. This does not necessarily imply that there is no or little information about such opportunities in Latvia. Rather, the reason is citizens' excessive conservatism and distrust, as well as the choice of appropriate communication channels through which information about energy-saving technologies will reach people and motivate them; here, the method of such information dissemination is of crucial importance.

The government of Chile is paying a great deal of attention to the interaction of administration, citizens and companies involved in the process of energy generation, distribution and trading so as to enhance their interaction and to raise the citizens' awareness about energy consumption, generation and saving, and using new technologies. The result can be seen in Fig. 4.2, which show that Chileans have a high readiness to changes as regards a potential prospect of changing the energy consumption and control mode to a more energy-efficient one, as well as readiness to participate in a mobile application, by mastering principles of energy saving and control of the consumed resources by means of a game.

On the other hand, the different motivation of citizens of the selected countries can be explained by the difference in electricity prices. For example, for citizens of Romania, the principle of preserving country's resources for future generations is more important than saving money because due to a low electricity price, saving resources will not significantly increase households' budgets. In turn, in Latvia and Brazil, citizens are more concerned about their electricity bills, and as a consequence, the possible ways to lower them.

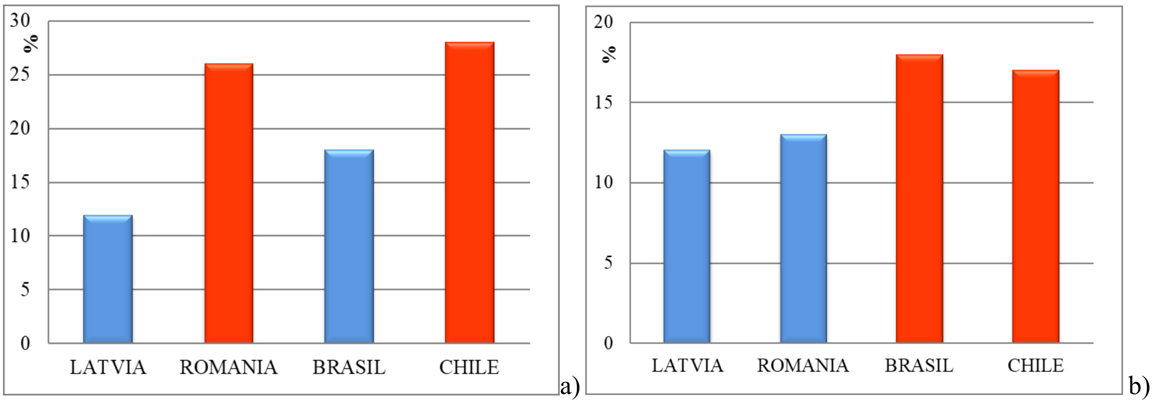


Fig. 4.2. a) and b). The readiness of citizens of Europe and Latin America to change their energy consumption habits:

a) percentage of citizens ready to change their energy consumption option;
b) percentage of citizens ready to use a mobile application to become familiar with energy-saving behaviour.

Therefore, these issues should form the basis for educational and advertising activities oriented towards the citizens of those countries. The policy of green energy support also has a significant influence and should be taken into consideration.

According to the market research conducted in Latvia by *Lattelecom* [65], despite the fact that the electricity market in Latvia was opened on 1 January 2015, currently 97 % of households in Latvia are using the services of the main trader and only 3 % of the population exploit the new possibilities of reducing power consumption expenses by changing their consumption tariff and/or changing the trader.

In addition, effective interaction with consumers is crucial for the electricity supplier [66] who installs smart meters and systems and suggests using different tariffs of energy consumption, including a dynamic tariff, i.e. a variable price each month in accordance with the price at the electricity exchange. Commonly, consumers do not have or have insufficient experience of interaction with smart meters, hour-to-hour data provided by smart meters and control of energy consumption in their households. Some utility services are introducing new time tariffs, e.g. the dynamic tariff, i.e. a variable price each month in accordance with the price at the electricity exchange, load management as well as other user-oriented programmes that help them to study their power consumption models, understand how the programmes will affect the tariffs and, in the long run, make validated decisions regarding the use of energy and controlling it. These programs only are effective when customers have a good understanding of the costs, profits and value of the offer and decide to play a more significant role in the management of their energy consumption and expenses.

The data obtained from Latvian inhabitants reflect an insufficient level of informedness as regards initiatives on implementing smart technologies in smart city. Respondents were asked a question: “What is your attitude to energy-saving technologies?” Their replies show the level of awareness existing in Latvia nowadays (see Fig. 4.3). 74 % (groups marked red) responded that they knew about energy-saving technologies but do not use them or use a little. When working with that kind of customers, it is crucially important to find out the causes why a person refuses to try to apply “smart” technologies. Quite frequently, the focal point is distrust and/or willingness to follow a customary way of living and consumption; a little less than 1/5 of the inhabitants are not aware of energy saving but wish to know about it. In this case, it is important to study further the ways people use information and what sources should be used to exchange information and communicate with them. Say, mobile applications and information in social networks would suit young people best, whereas for middle-aged and elderly people, personal contact would have a decisive role.

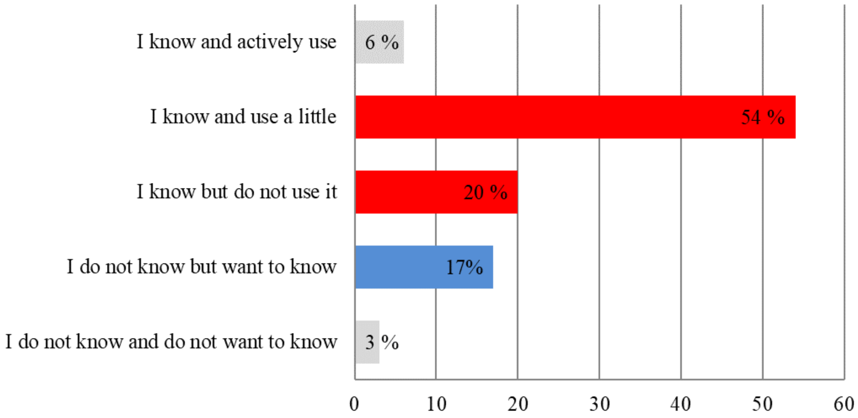


Fig. 4.3. Respondent attitude to energy saving technologies in Latvia.

The topic of Latvian citizens’ motivation to use energy-saving technologies (see Fig. 4.4) is quite interesting and important (the respondents could tick off several techniques that are close and motivating for them). An overwhelming majority of the respondents, i.e. 63 %, are sure that they would benefit from vividly represented savings of energy and money; for 39 % of the respondents, it is important to promote preservation of nature for their offspring.

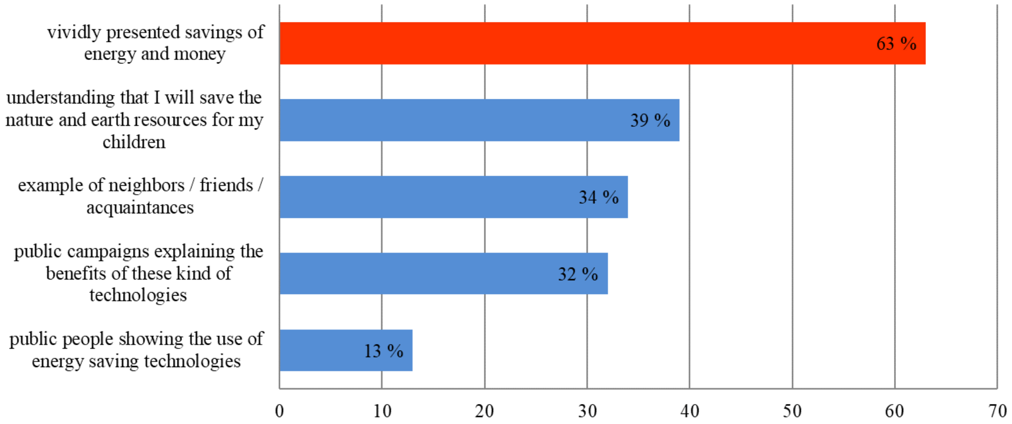


Fig. 4.4. Motivation to use energy-saving technologies. The question asked: "What would make you to more frequently use energy saving technologies?"

In the course of the survey, the author has also examined the existing perception stereotypes of the inhabitants of Latvia regarding new possibilities of controlling and saving energy, for instance, readiness/unreadiness to change a service trader or to switch to a different mode of energy consumption and payment, as well as willingness and readiness to model their consumption by using mobile applications with game elements (see Fig. 4.5).

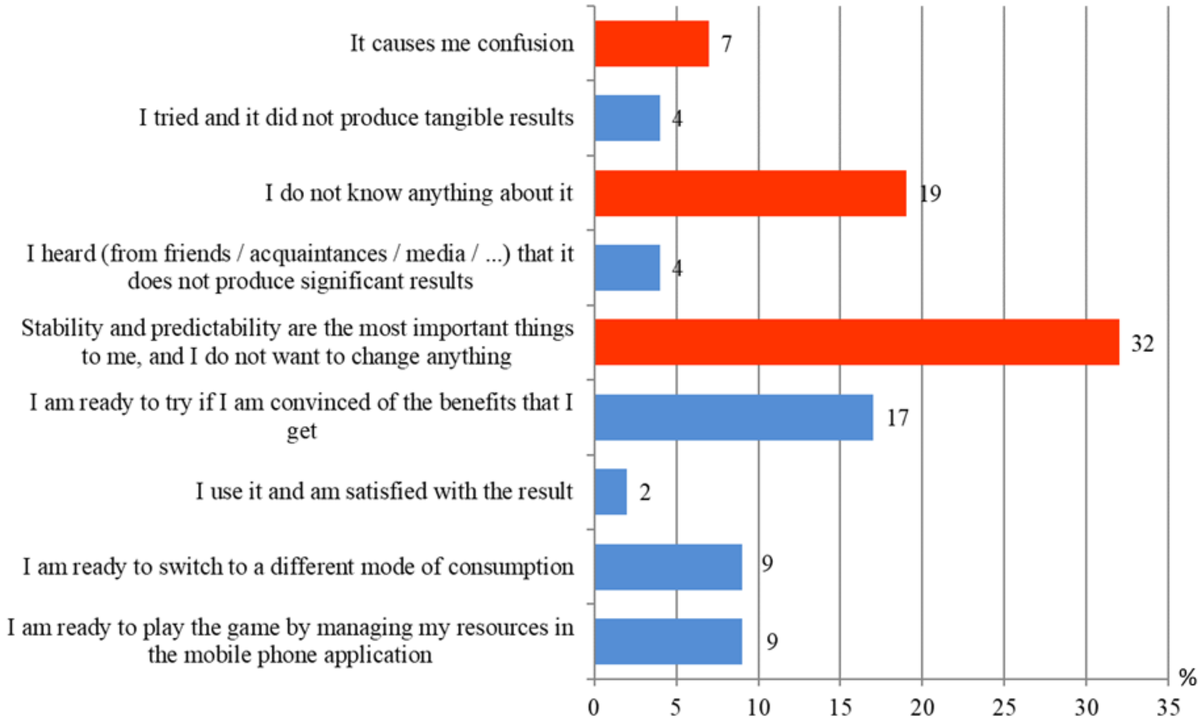


Fig. 4.5. Readiness to choose a different electricity consumption mode: "What do you think about choosing a different electricity consumption mode in order to save resources and money?"

Overall, the survey findings show that the awareness of the inhabitants of Latvia of the processes related to formation of smarter, or more intelligent, cities is not very high. Many people prefer not to try out new possibilities and technologies enabling one to be energy-efficient in the field of resource consumption. Conservatism and unwillingness to lose today's comfort level reached make them stick to frequently unprofitable consumption conditions from the economic point of view, but the lack of information does not make for broadening the knowledge of the topic.

Chapter conclusion

The research conducted in the cities of Latvia, Romania, Chile, and Brazil has revealed a large gap between the theoretical knowledge of the citizens in the sphere of new technologies of energy consumption and practical mastering and using of innovations in everyday life. On average, the awareness of the adult population of different cities regarding smart solutions is two times higher than the share of smart solution users. Besides that, solutions that allow applying digital technologies to existing widespread processes are gaining more popularity than those that require changing existing behavioural stereotypes to new ones. As a rule, consumers have little or no experience of interacting with smart meters, the hourly data that they provide, and managing energy consumption in their household.

Based on the analysis performed, certain measures are to be developed that motivate and stimulate the transition of passive consumers of energy resources to active consumers and/or prosumers. The new technologies and practical solutions appearing in the market should include knowledge of the behaviour model that the inhabitants of a particular region exhibit as well as possible ways of changing non-ecological behaviour based on the regularities discovered.

As the results of the survey on the smart city show, more responsible energy consumption and smarter use of energy is one of the primary tasks of smart energy city development. Consumers make a significant contribution to achieving flexibility in energy systems by changing the amount and method of energy consumption, which can contribute to increasing the stability of the entire energy system and reducing the load on the system during peak hours.

Nevertheless, as the research shows, many people are willing to learn more and it is important to them to have and broaden the overall picture of what is happening in the energy market so as to be able to actively participate in decision-making. This would make it possible to achieve more efficient consumption of resources not only on an individual basis, but also at the country and regional level. This requires calculating the contribution of end users to decarbonisation, efficiency, resilience and sustainability at the country and regional level by modelling scenarios that maximise the still-not-fully-realised potential of active end users. The next chapter explores this potential by modelling decarbonisation scenarios in the Baltic region with a particular focus on Latvia.

5. MODELLING THE ENERGY SYSTEM TRANSITION

For modelling end-user impact on the overall energy system, a modelling system has to include the aggregation of modelling approaches from the various groups mentioned above. It means that a multisectoral, flexible, multilevel approach needs to be chosen for the required task. Considering the above challenges, the *Backbone* modelling tool was selected as the most appropriate one for solving the tasks set in this section of the Thesis. The *Backbone* framework was elaborated by VTT Technical Research Centre of Finland and is a well-established, highly flexible and open-source energy system modelling tool. *Backbone* allows modelling an interconnected energy system, combining different sectors (including a detailed building sector, which is of interest to us) and regions with hourly time resolution and simulating different decarbonisation pathways, taking into account the stochastic behaviour of the variables.

Therefore, the following tasks were set in this section of the Thesis to be solved with the *Backbone* modelling framework: (a) identifying the potential of the building sector of Latvia and the Baltic States in 2030 towards the decarbonisation goal 2050; (b) determining the necessary changes in the energy behaviour of energy consumers (end users) in the building sector; and (c) modelling the impact of the introduction of new technologies in this sector. To reflect the above tasks, different building stock energy modelling scenarios have been elaborated by using the *Backbone* model to find cost-effective ways to meet all requirements and needs. This part of the Thesis focuses on the analysis of the impact of the building sector (which includes residential and commercial end users) on the decarbonisation of the Baltic energy system, considering the targets set by the National Climate and Energy plans and the EU Climate and Energy Framework.

5.1. Modelling the Baltic energy system transformation

The objective function of the model implies minimisation of the annual energy system cost and includes the following parameters:

$$v^{obj} = \sum_{f,t \in FT} p_{f,t}^{prob} \ x \ (v_{f,t}^{vomCost} + v_{f,t}^{fuelCost}) + v^{stateValue} + v^{fomCost} + v^{unitInvestCost} + v^{lineInvestCost}, \tag{5.1}$$

where

$\mathrm{p}_{f,t}^{prob}$ – the probability or weight of interval f, t;

$v_{f,t}^{vomCost}$ – variable operational and maintenance costs;

$v_{f,t}^{fuelCost}$ – fuel and emission costs;

$v^{stateValue}$ – value of state change;

$v^{fomCost}$ – fixed operational and maintenance costs;

$v^{unitInvestCost}$ – unit investment costs;

$v^{lineInvestCost}$ – transmission line (network investments) costs.

All sectors are simultaneously optimised, running the whole year with hourly time resolution, in order to minimize the overall annual system costs. The simulation results include generation, transmission, capacity values, costs, CO_2 emissions, RES shares, and energy security indicators at annual and hourly level. It is well suited for analysing scenarios of both whole energy systems and single regions and sectors. A more detailed description of parameters and constraints can be found in [67].

To model and analyse the Baltic energy system transition towards climate neutrality, an open source dataset was created and the *Baltic Backbone* model have been developed on the basis of the *Backbone* modelling framework. The model has been developed in GAMS (General Algebraic Modelling System) and allows introducing multiple sectors and regions with different levels of detail. The *Baltic Backbone* model and the dataset used have been described and are openly available in GitLab [68].

The *Baltic Backbone* model has been validated against historical data within the research projects "FasTen: Fast, flexible and secure decarbonisation of the Baltic States – possible progress in the next ten years" (2020–2021) and "Amber: Impacts of ambitions energy policy pathways" (2021–2022), funded by the Baltic-Nordic Energy Research Programme of Nordic Energy Research. The *Baltic Backbone* model has been built with the *Backbone* modelling framework.

To simulate the scenario, it was decided to present the electricity grid by the Estonian, Latvian and Lithuanian power networks and their cross-border connections to Finland, Sweden, Poland, Russia, and Belarus. For district heating, it was decided to divide each country into two areas: the capital and the aggregate of all the other regions. To model in more detail the energy use by buildings, the same division between the capital and other areas was choosen.

The model runs in hourly time steps with a rolling horizon, using linear optimisation. It takes units as given assets and optimises their annual and hourly use in order to minimise overall annual system costs while maintaining the supply and demand balance, the reserve requirements, and other set constraints. The main parameters for electricity and DH modelled for 2030 are depicted in Table 5.1.

Table 5.1

Summary of Modelled Electricity and District Heating Demands by Country in 2017 and changes in 2030

	Annual demand [GWh]					
	Estonia		***Latvia***		***Lithuania***	
	2017	**2030**	**2017**	**2030**	**2017**	**2030**
Electricity	**7736**	**+7 %**	**6485**	**+9 %**	**10730**	**+6 %**
Transport	46	**+168 %**	104	**+67 %**	74	**+209 %**
Buildings	4656	**0 %**	4423	**0 %**	6145	**0 %**
Other	3034	**+16 %**	1958	**+26 %**	4511	**+11 %**
District heating	**4602**	**−10 %**	**7034**	**−10 %**	**10817**	**−19 %**
Buildings	3812	**−10 %**	5986	**−10 %**	7873	**−22 %**
Other	790	**−10 %**	1048	**−10 %**	2944	**−11 %**

National estimates and other forecasts project a 10 % decrease of heating and hot water demand in building sector from 2017 to 2030. This would reduce the use of fossil fuels and district heating. The number of heat pumps is assumed to increase from 160 000 units in 2017 (0.6 TWh) to 300 000 units in 2030 (1.1 TWh). Together, these factors result in reduced use of fossil fuels, biomass, and DH in the sector of buildings. Based on national projections, the total demand of DH in the sector of buildings is expected to diminish by10 % in Estonia and Latvia, and by 22 % in Lithuania. The assumed changes in the use of fossil fuels are based on [69].

Modelling 2017 and 2030 reference scenarios: the change of energy generation and consumption patterns

For *Baltic Backbone* model, the 2017 data were chosen for validation. The differences between the statistical data and the modelled results are relatively small, and the model is considered as sufficiently calibrated and applicable for the analysis.

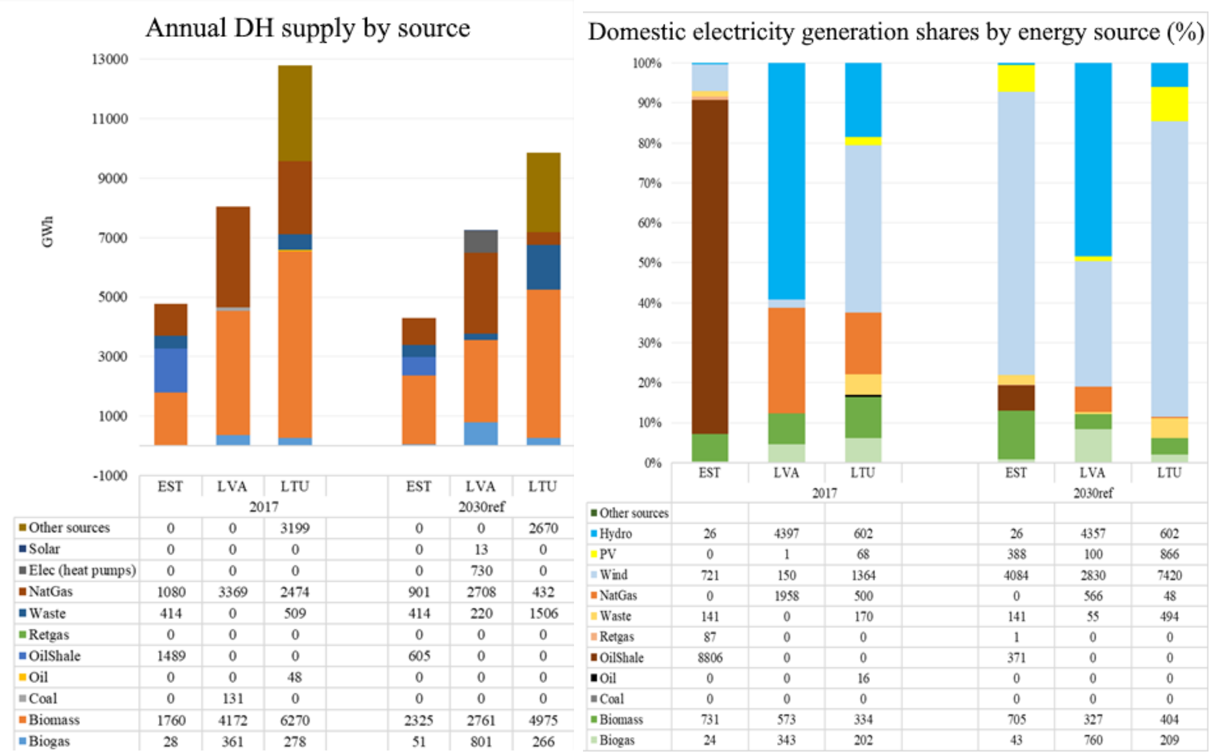
The 2030 reference scenario has been created to introduce the main changes in the Baltic system. It includes RES replacing fossil fuels and the decrease in the total energy consumption in Estonia, Latvia, and Lithuania; the main changes shown in Table 5.2 are based on NECPs targets and expert opinions.

Table 5.2
Assumed Main Changes in Energy Consumption from 2017 to 2030 reference scenario

	Estonia	***Latvia***	***Lithuania***
Coal	–75 %	–75 %	–50 %
Oil and petroleum products	–40 %	–40 %	–35 %
Natural gas	–10 %	–10 %	–5 %
Solid biomass	–15 %	–8 %	0 %
Electricity	0 %	0 %	0 %
District heating	–10 %	–10 %	–22 %
Heating and hot water	–10 %	–10 %	–10 %
Number of heat pumps (HPs)	225000	20000	60000
Energy produced by HPs (GWh)	0.81	0.07	0.21
Share of residential HPs	0.9	0.9	0.9
Share of commercial HPs	0.1	0.1	0.1
PV capacity introduced, MW	415	107	895

As can be seen from the numbers above, the disconnection of oil-shale based generation capacities in Estonia, the substitution of fossil fuels by wind and solar power as well as by heat pumps for all the countries, and the disconnection from BRELL cause significant changes in electricity and heat generation, export/import, and the share of renewable resources from local generation.

The reduction in fossil fuels used and their substitution by green energy yields a significant emission reduction in 2030 (11.011 kt of CO_2 for ETS and 61 kt of CO_2 for non-ETS sectors). The main results of the 2030 reference scenario are depicted in Fig. 5.1.



	EST	LVA	LTU	EST	LVA	LTU
	2017			2030ref		
■ Other sources	0	0	3199	0	0	2670
■ Solar	0	0	0	0	13	0
■ Elec (heat pumps)	0	0	0	0	730	0
■ NatGas	1080	3369	2474	901	2708	432
■ Waste	414	0	509	414	220	1506
■ Retgas	0	0	0	0	0	0
■ OilShale	1489	0	0	605	0	0
■ Oil	0	0	48	0	0	0
■ Coal	0	131	0	0	0	0
■ Biomass	1760	4172	6270	2325	2761	4975
■ Biogas	28	361	278	51	801	266

a)

	EST	LVA	LTU	EST	LVA	LTU
	2017			2030ref		
■ Other sources						
■ Hydro	26	4397	602	26	4357	602
■ PV	0	1	68	388	100	866
■ Wind	721	150	1364	4084	2830	7420
■ NatGas	0	1958	500	0	566	48
■ Waste	141	0	170	141	55	494
■ Retgas	87	0	0	1	0	0
■ OilShale	8806	0	0	371	0	0
■ Oil	0	0	16	0	0	0
■ Coal	0	0	0	0	0	0
■ Biomass	731	573	334	705	327	404
■ Biogas	24	343	202	43	760	209

b)

Fig. 5.1. a) Annual district heat generation by energy source; b) domestic electricity generation shares by energy source.

The share of domestic electricity generation from renewables increases, and that is in accordance with national energy plans. Nevertheless, in general, the Baltics remain dependent on imports; additional balancing capacity is still needed for variable RES; insufficient decarbonisation of heat and electrification of end users are still present. To determine the possible impact of the sector of buildings on the decarbonisation of the Baltic energy system, sensitivity analysis needs to be performed, changing key variables and running simulations.

Sensitivity analysis of developed scenarios

To study the possible impact of the end users' energy behaviour on changes in the overall energy system of the Baltic States and to evaluate it in numerical values, the following scenarios have been developed (see Table 5.3).

Table 5.3

Scenarios Introduced for Building Sector Modelling

Scenarios	***Description***
2030ref	–10 % of DH consumption from 2017 (DH system efficiency increase, beginning of renovation of buildings)
2030ref_lowDH1	–25 % of DH consumption from 2017 (renovation of buildings)
2030ref_lowDH2	–45 % of DH consumption from 2017 (deep renovation of buildings, introduction of large-scale DH HPs (heat pumps))
2030ref_locHP1	+200 GW of energy produced by local heat pumps (compared to 2030ref) for each country
2030ref_locHP2	+500 GW of energy produced by local heat pumps (compared to 2030ref) for each country
2030_PV_Eps	no adding of new PV capacities

Additional scenarios include the combination of the scenarios above. The baseline scenario 2030ref was taken as a basis and supplemented by scenarios considering a decrease in district heat consumption as a result of renovation of buildings. For modelling purposes, it was assumed that the renovation process will be speeded up by political support and introduction of modern technologies (e.g. centralised and decentralised heat pumps); therefore, 25 % and 45 % of district heating consumption reduction is modelled.

Since the heat pumps represent the most beneficial technology to be implemented by 2030, scenarios with an additional increase in the number of individual HPs in private houses and apartment buildings have been simulated.

The installation of decentralised solar panels is modelled according to the 2030ref scenario (+1335 MW for the Baltics), maintaining the 2017 PV capacity level (84 MW) in accordance with the 2030_PV_Eps scenario. In addition, the sensitivity analysis has been conducted by changing two variables (e.g. the share of HPs and DH, PV and DH, PV and HPs). The main results are described and summarised in the next section. For comparing the scenarios and assessing the results, a range of indicators was introduced.

5.2. Modelling the impact of the building sector on decarbonisation

5.2.1. Scenarios for district heat reduction as a result of the renovation process in Latvia

During the years 2014−2020, several programmes were available in Latvia for supporting renovation activities [70], [71]. Assuming that the renovation of the building stock will maintain the same speed as before – around 1700 buildings during 2014−2020 [5], [8] – the calculated number of renovated buildings during the reference years 2017 and 2030 can reach four thousand for Latvia. Thus, the total heat energy savings of Latvia's households renovated apartment blocks by 2030 can reach 800 GWh as a minimum (Table 5.4).

Table 5.4

Forecasted Saving of District Heat of Building Stock Renovation till 2030 in Latvia

	Household sector		***Public sector***	***Commercial sector***	***Total***
	apartment blocks	***private houses***			
Saved heat, GWh	800	30	97	60 [a]	987

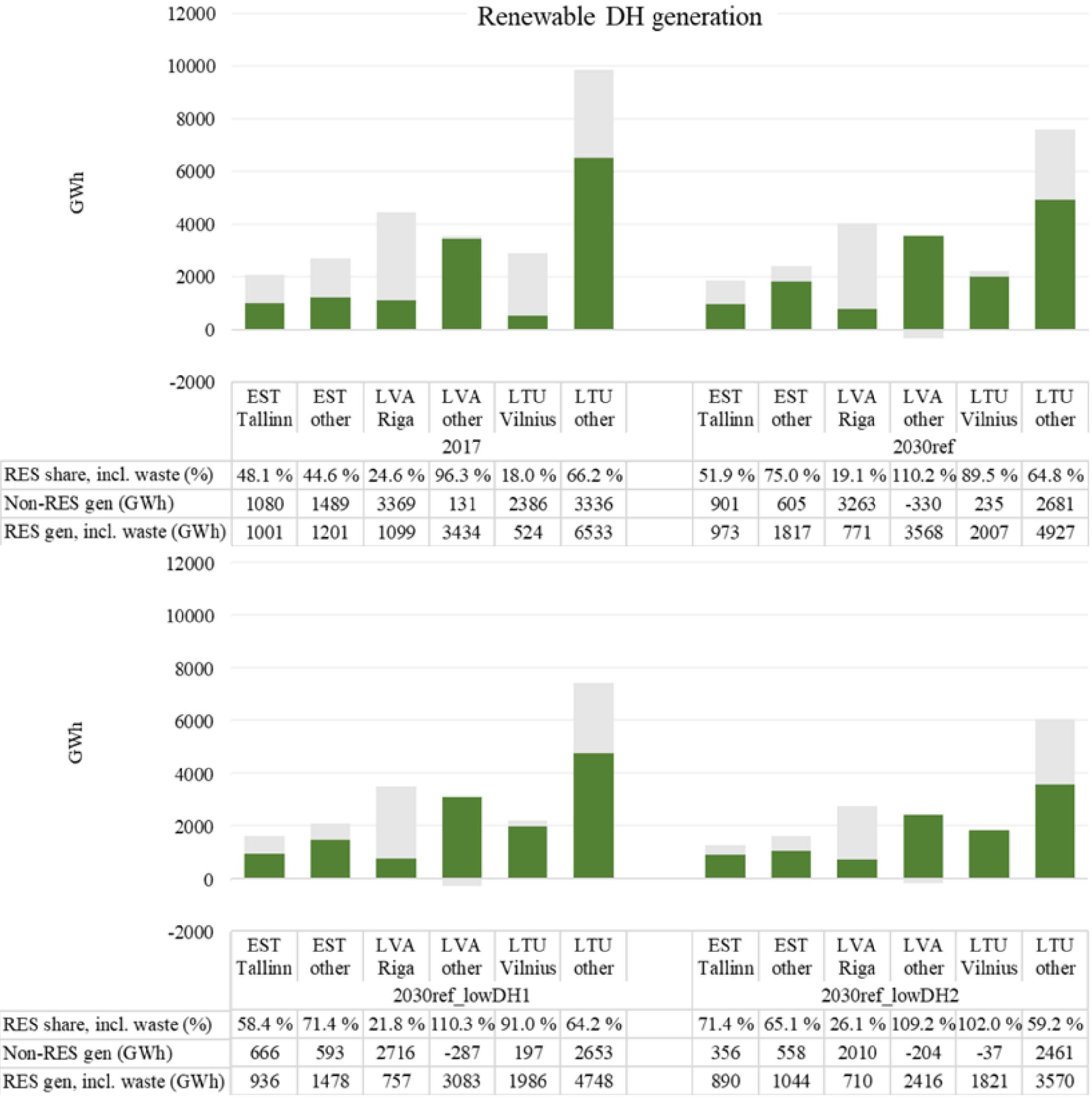
[a] The assumption made by the author. Commercial sector energy savings are more dependent on modern technology installation and less on the renovation of buildings.

In the experts' opinion [72], by 2030 it is possible to carry out a cost-effective renovation of 70 % of the total amount of buildings, as it will not be useful to renovate the remaining 30 %. Towards the target of renovating 30 % of apartment blocks by 2030, a total of 8,100 apartment blocks needs to be renovated. Considering the relationship with potentially interested homeowners who are ready to implement energy efficiency measures to achieve the goal, it is necessary to renovate 4,860 apartment blocks, which should be identified as the primary objective. This target is close to our calculation of 4,000 apartment blocks that could be renovated by 2030 and were taken as a baseline scenario for calculating heat consumption reductions. As a result of the financial support, it is planned to reduce the primary energy consumption in state and municipal buildings by 2030 to indicatively 29,714 and 68,000 MWh/year, respectively [72]. The total heat energy savings from implementing all the building stock renovation programme may reach 987 GWh in Latvia, which is 17 % of the total district heat consumed in 2017.

The electrification of the heating (and cooling) sector would provide a cost-effective way of applying low-carbon technologies, increasing the share of RES. Power-to-heat technologies can be implemented at the centralised or decentralised level. Since the focus of this study is energy use by buildings, only the latter is considered. Heat pumps represent a beneficial, sector-coupling and low-CO_2-emission technology in residential heating [73]. As illustrated in [8], local/individual heat pumps could be competitive with DH even in apartment blocks and their use is sustainable in the Baltics; however, dependence on DH prices and technologies used needs to be evaluated.

5.2.2. Case study results and discussions

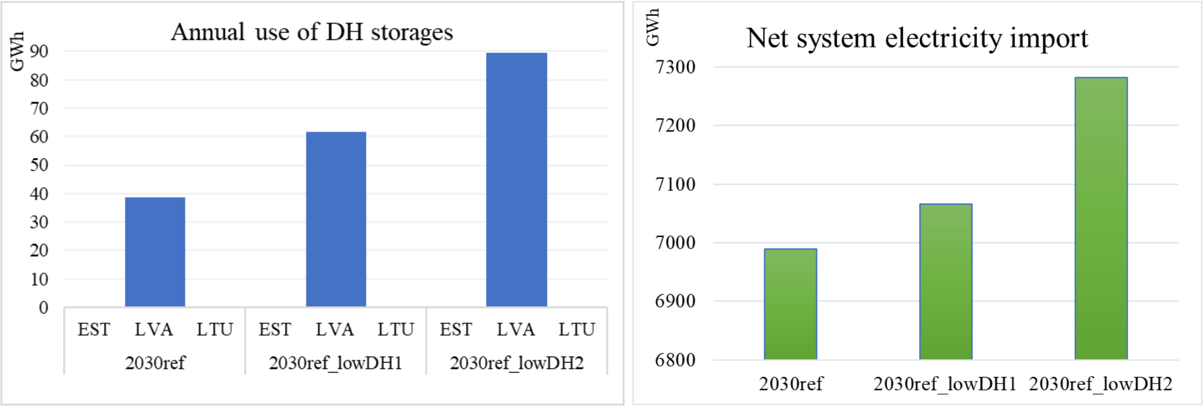
The scenarios with lowered DH consumption as a result of building renovation (see Figs. 5.2 and 5.3) show an increase in the generation share of renewables.



	EST Tallinn	EST other	LVA Riga	LVA other	LTU Vilnius	LTU other	EST Tallinn	EST other	LVA Riga	LVA other	LTU Vilnius	LTU other
	2017						2030ref					
RES share, incl. waste (%)	48.1 %	44.6 %	24.6 %	96.3 %	18.0 %	66.2 %	51.9 %	75.0 %	19.1 %	110.2 %	89.5 %	64.8 %
Non-RES gen (GWh)	1080	1489	3369	131	2386	3336	901	605	3263	-330	235	2681
RES gen, incl. waste (GWh)	1001	1201	1099	3434	524	6533	973	1817	771	3568	2007	4927

	EST Tallinn	EST other	LVA Riga	LVA other	LTU Vilnius	LTU other	EST Tallinn	EST other	LVA Riga	LVA other	LTU Vilnius	LTU other
	2030ref_lowDH1						2030ref_lowDH2					
RES share, incl. waste (%)	58.4 %	71.4 %	21.8 %	110.3 %	91.0 %	64.2 %	71.4 %	65.1 %	26.1 %	109.2 %	102.0 %	59.2 %
Non-RES gen (GWh)	666	593	2716	-287	197	2653	356	558	2010	-204	-37	2461
RES gen, incl. waste (GWh)	936	1478	757	3083	1986	4748	890	1044	710	2416	1821	3570

Fig. 5.2. The share of renewables for district heating generation.



a) b)

Fig. 5.3. a) Use of DH storage; b) net electricity import in the Baltic.

The greatest impact in RES-h (heat from renewable energy sources) share increase was in Tallinn, Vilnius, and Riga (which is connected with high DH use in capitals). There is no impact on RES-e (electricity from renewable energy sources) generation share and domestic electricity generation. The increase of DH storage capacity is observed as a result of more rational use of heat energy.

In the model, preference is given to wind, PV, hydro, and waste energy. DH reduction in scenarios is reflecting in decrease of natural gas, biogas and biomass use rateably and mostly on the import/export of the system. DH heat storage used capacity increased in the case of Latvia. Low DH scenarios provide significant savings in system operation costs (see Fig. 5.4).

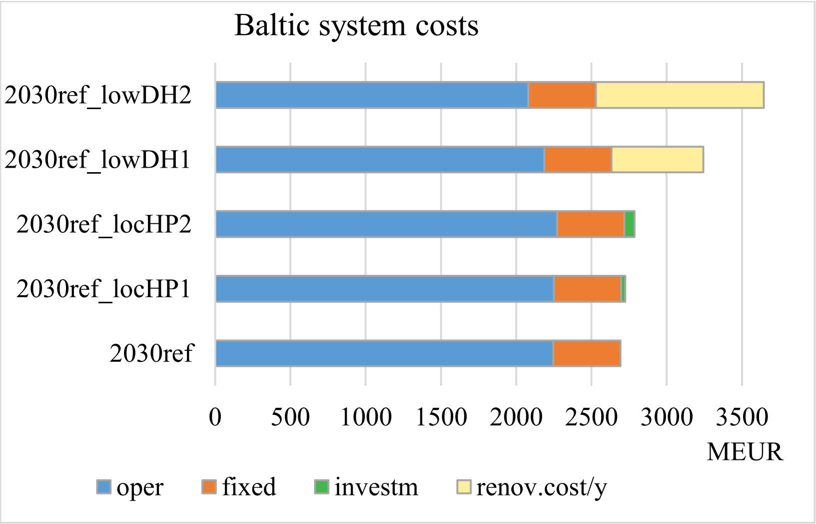


Fig. 5.4. Baltic system costs for the 2030 scenarios.

The investment in renovation noticeably increases the overall costs of the system. However, as stressed in [74], it is important to forecast and calculate the necessary investment, since the actual volume of allocated funds may differ a lot from the utmost amount required for renovation.

Nevertheless, the reduction in emissions and energy consumption in the residential sector as well as the comfort of the residents must also be considered as part of the investments goal. Figure 5.5 shows the cutback of ETS emissions.

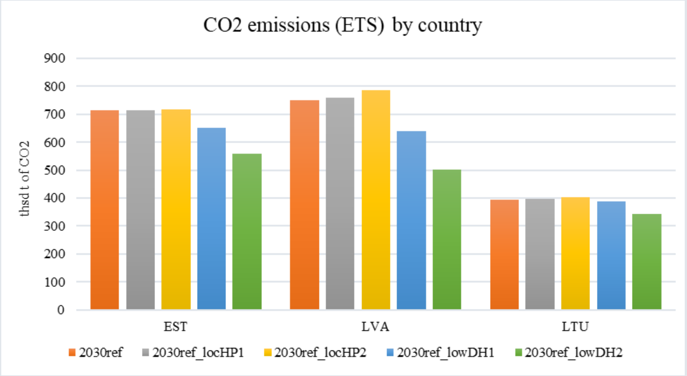


Fig. 5.5. Baltic system emissions.

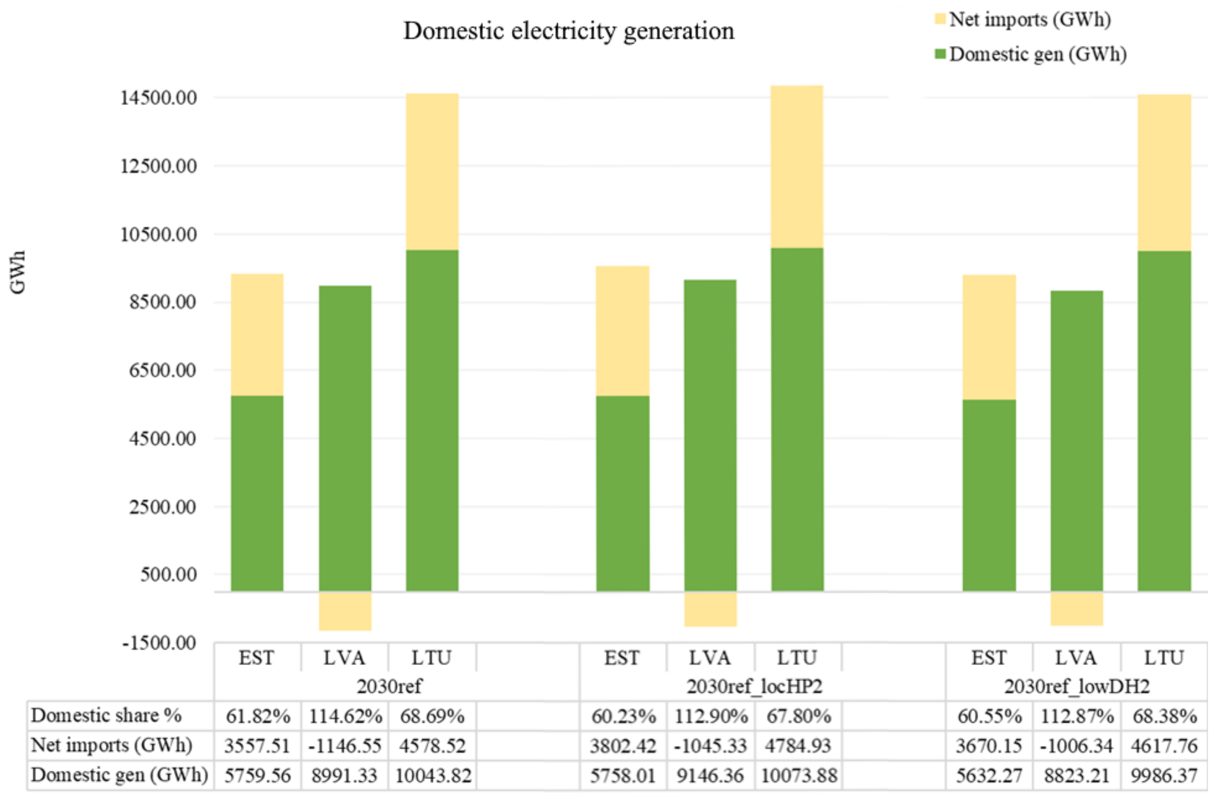
The lowDH1 and lowDH2 scenarios reflect the largest emission drop for Latvia: 109 kt and 248 kt of CO_2; for Estonia: 63 and 158 kt of CO_2; for Lithuania the impact was minimal – 7 kt and 51 kt of CO_2, respectively. The reduction of the non-ETS CO_2 emissions reflects more for the local HP1 and HP2 scenario case.

The model noticeably increases net system electricity import to compensate for the increased demand of electricity consumed by heat pumps in the case of local HP increase scenarios. These scenarios are especially cost-effective for Latvia from an electricity and heat generation point of view, peaking for non-capital regions.

The introduction of local HPs has an effect on DH fuel use. Higher electricity prices at some hours affect the use of district heating HPs (a decrease) and natural gas (an increase). Analysis shows stable use of DH storage in Latvia with a small increase in the locHP2 scenario.

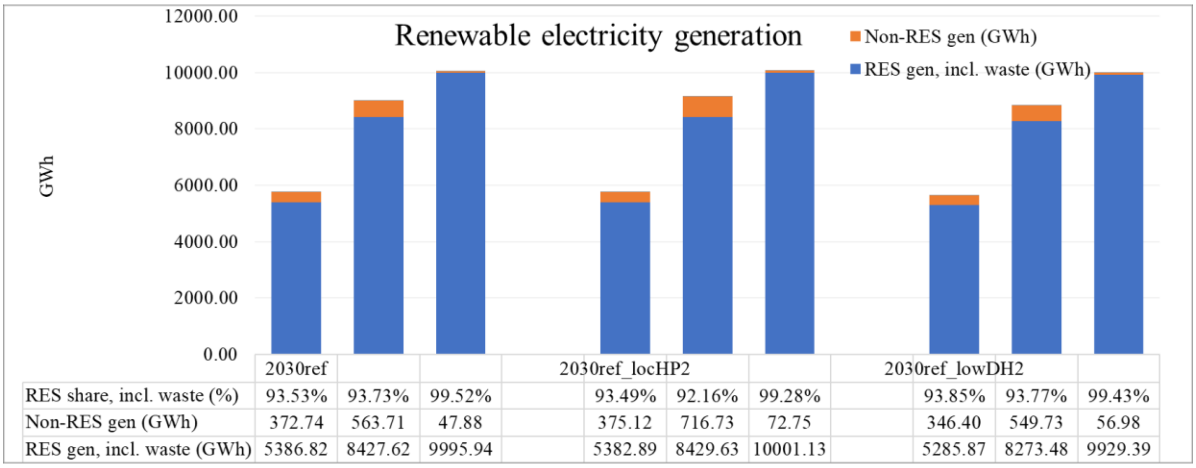
5.2.3. The overall impact of the modelled scenarios on the Baltic energy balance

Latvia, Lithuania, and Estonia are in different positions regarding the production of local electricity (see Fig. 5.6). In the simulated scenarios, Latvia fully meets its electricity needs, also providing exports from locally generated electricity, while Estonia and Lithuania only partially use local electricity for consumption, still being dependent on imported energy.



	2030ref			2030ref_locHP2			2030ref_lowDH2		
	EST	LVA	LTU	EST	LVA	LTU	EST	LVA	LTU
Domestic share %	61.82%	114.62%	68.69%	60.23%	112.90%	67.80%	60.55%	112.87%	68.38%
Net imports (GWh)	3557.51	-1146.55	4578.52	3802.42	-1045.33	4784.93	3670.15	-1006.34	4617.76
Domestic gen (GWh)	5759.56	8991.33	10043.82	5758.01	9146.36	10073.88	5632.27	8823.21	9986.37

Fig. 5.6. Domestic electricity generation share.



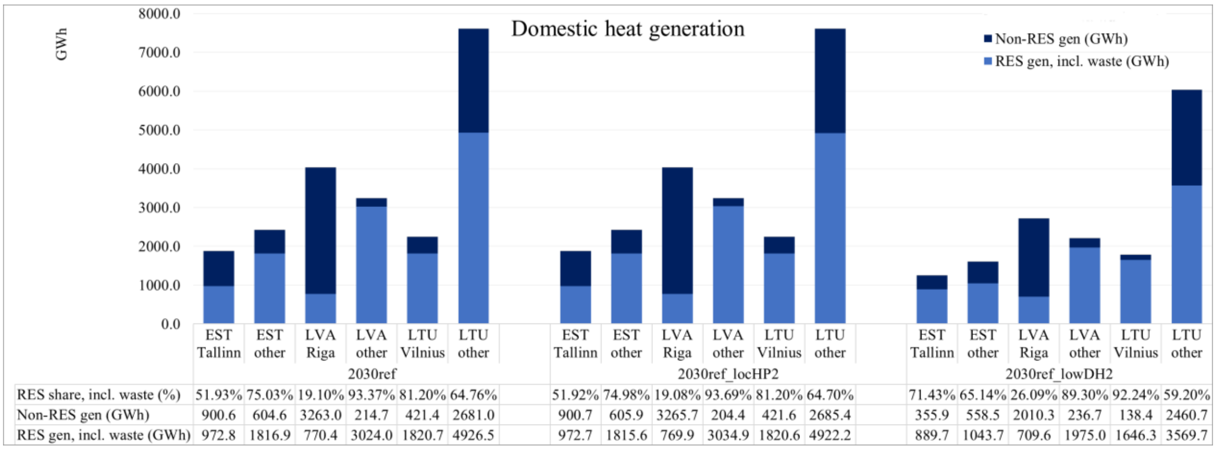
	2030ref			2030ref_locHP2			2030ref_lowDH2		
RES share, incl. waste (%)	93.53%	93.73%	99.52%	93.49%	92.16%	99.28%	93.85%	93.77%	99.43%
Non-RES gen (GWh)	372.74	563.71	47.88	375.12	716.73	72.75	346.40	549.73	56.98
RES gen, incl. waste (GWh)	5386.82	8427.62	9995.94	5382.89	8429.63	10001.13	5285.87	8273.48	9929.39

Fig. 5.7. The electricity generation share of renewables.

Estonia, according to the simulation, will produce 60–62 % of electricity from local resources, Lithuania – 68–69 %, while Latvia will reach a new level of safety and produce 112–115 % of the required level of consumption, i.e. providing also export.

Figure 5.7 reflects the level of electricity production from renewable resources, including waste. Here, the situation is more favourable, especially in Lithuania, which has closed the old combined heat and power plants and switched to biofuels.

Lithuania almost completely ensures the production of electricity from renewable resources and waste (about 99.5 %), Estonia and Latvia are only slightly behind with 93–94 % and 92–94 %, respectively. Heat generation from local fuel (see Fig. 5.8) is more heterogeneous, differing for the capitals of the Baltic States and their regions. The maximum percentage of heat production from local resources, including waste, is observed in the regions of Latvia – 89–93 %, while in the capital of Latvia this percentage is minimal – 19–26 %, due to the historical use of large-scale cogeneration with natural gas. However, even in Estonia, a large proportion of heat production from local resources is maintained in the regions, while in Lithuania the situation is reversed.



	2030ref						2030ref_locHP2						2030ref_lowDH2					
	EST Tallinn	EST other	LVA Riga	LVA other	LTU Vilnius	LTU other	EST Tallinn	EST other	LVA Riga	LVA other	LTU Vilnius	LTU other	EST Tallinn	EST other	LVA Riga	LVA other	LTU Vilnius	LTU other
RES share, incl. waste (%)	51.93%	75.03%	19.10%	93.37%	81.20%	64.76%	51.92%	74.98%	19.08%	93.69%	81.20%	64.70%	71.43%	65.14%	26.09%	89.30%	92.24%	59.20%
Non-RES gen (GWh)	900.6	604.6	3263.0	214.7	421.4	2681.0	900.7	605.9	3265.7	204.4	421.6	2685.4	355.9	558.5	2010.3	236.7	138.4	2460.7
RES gen, incl. waste (GWh)	972.8	1816.9	770.4	3024.0	1820.7	4926.5	972.7	1815.6	769.9	3034.9	1820.6	4922.2	889.7	1043.7	709.6	1975.0	1646.3	3569.7

Fig. 5.8. Domestic heat generation share.

Another important metric – the share of renewables in district heat generation – retains low amounts of change in local HP scenarios and are pronounced in low DH scenarios (see Fig. 5.9).

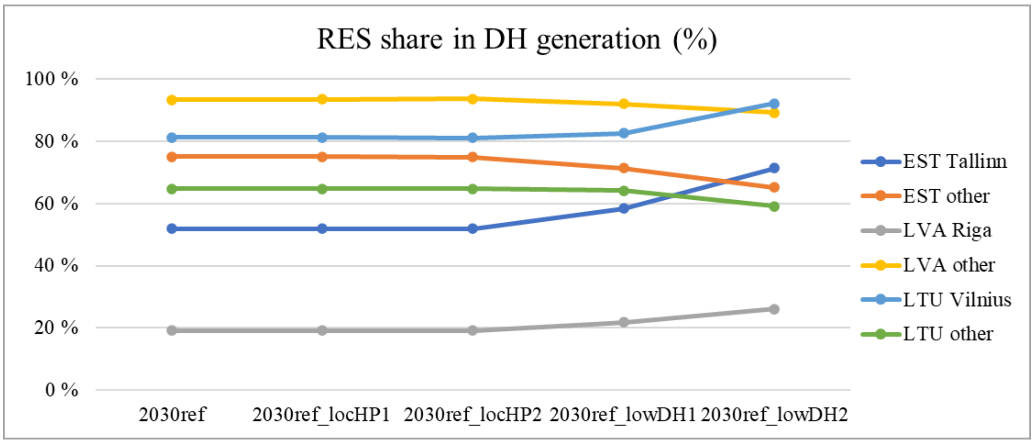


Fig. 5.9. The share of renewables in DH generation.

Lower heat consumption for heating buildings as a result of renovation significantly affects the percentage composition of heat produced from local raw materials, creating a favourable situation in Riga, Vilnius, and Tallinn and reducing the figure for other regions.

5.2.4. The impact of scenarios on electricity prices

The impact of the 2030ref baseline scenario and the selected scenarios on electricity prices (Eur/MWh) can be seen in Figs. 5.10–5.11.

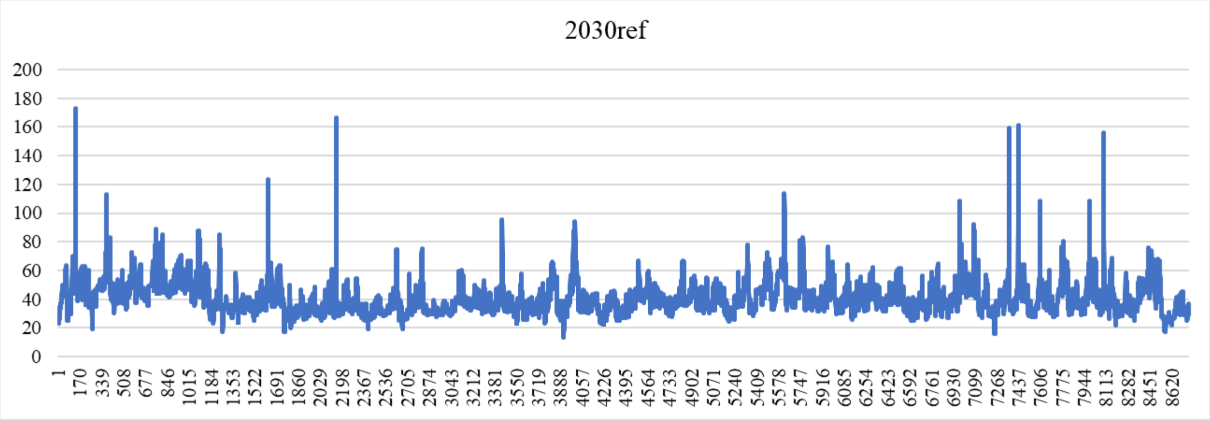


Fig. 5.10. Marginal electricity prices for 2030ref, Eur/MWh.

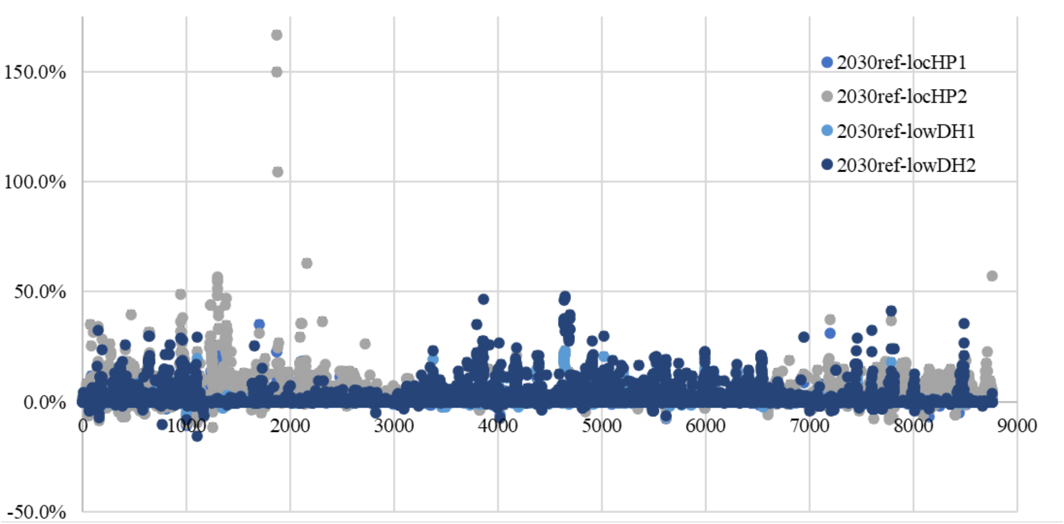


Fig. 5.11. Comparison of price differences with base 2030ref scenario.

High prices during several hours indicate the lack of capacity. The locHP2 scenario leads to excessive price increases during certain hours due to increased energy consumption for heat pumps. This pathway also shows higher prices during certain hours, which may be caused by a change in the CHP plant operating mode with a decrease in heat production.

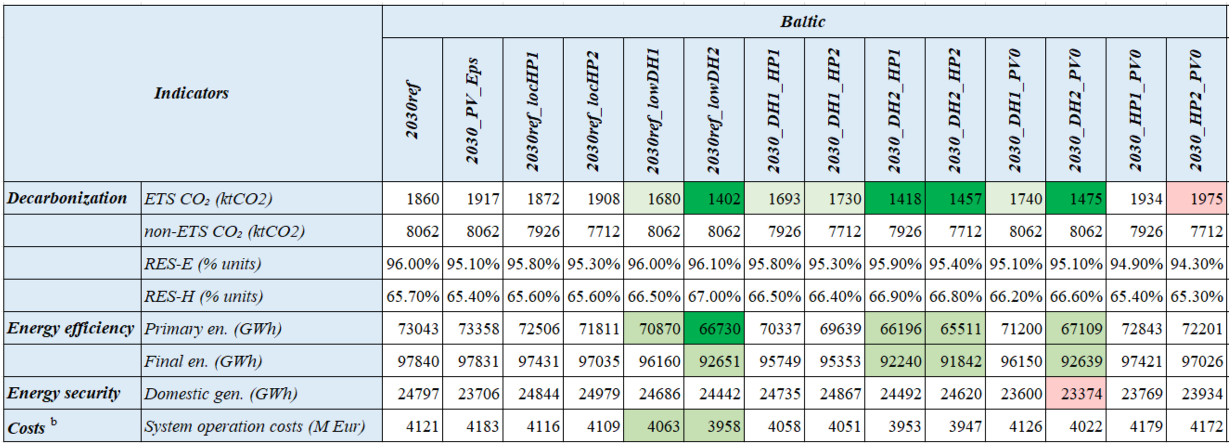
5.2.5. Result indicators

To evaluate different scenarios, the following result indicators have been summarised and compared: 1) for decarbonisation: the amount of ETS CO_2 and non-ETS CO_2, the share of RES-E and RES-H; 2) for energy efficiency: the amount of primary and final energy; 3) for energy security – domestic generation; and 4) for costs – system operation costs. Each single scenario assumes its own benefits and/or weaknesses. Therefore, it is the most beneficial to combine two or more scenarios (changing just a few variables) to maintain the flexibility of the system and increase its stability as well as to find the possibility for reducing overall investment costs and net imports.

The main indicators of the simulated scenarios are presented in Table 5.5; the dark green areas reflect a positive impact, light green – a slightly positive impact, pink – a slightly negative one and red – a negative impact.

Table 5.5

Benefits from Different Measures by Main Indicators



Indicators		***Baltic***													
		2030ref	***2030_PV_Eps***	***2030ref_locHP1***	***2030ref_locHP2***	***2030ref_lowDH1***	***2030ref_lowDH2***	***2030_DH1_HP1***	***2030_DH1_HP2***	***2030_DH2_HP1***	***2030_DH2_HP2***	***2030_DH1_PV0***	***2030_DH2_PV0***	***2030_HP1_PV0***	***2030_HP2_PV0***
Decarbonization	*ETS CO_2 (ktCO2)*	1860	1917	1872	1908	1680	1402	1693	1730	1418	1457	1740	1475	1934	1975
	non-ETS CO_2 (ktCO2)	8062	8062	7926	7712	8062	8062	7926	7712	7926	7712	8062	8062	7926	7712
	RES-E (% units)	96.00%	95.10%	95.80%	95.30%	96.00%	96.10%	95.80%	95.30%	95.90%	95.40%	95.10%	95.10%	94.90%	94.30%
	RES-H (% units)	65.70%	65.40%	65.60%	65.60%	66.50%	67.00%	66.50%	66.40%	66.90%	66.80%	66.20%	66.60%	65.40%	65.30%
Energy efficiency	*Primary en. (GWh)*	73043	73358	72506	71811	70870	66730	70337	69639	66196	65511	71200	67109	72843	72201
	Final en. (GWh)	97840	97831	97431	97035	96160	92651	95749	95353	92240	91842	96150	92639	97421	97026
Energy security	*Domestic gen. (GWh)*	24797	23706	24844	24979	24686	24442	24735	24867	24492	24620	23600	23374	23769	23934
Costs [b]	*System operation costs (M Eur)*	4121	4183	4116	4109	4063	3958	4058	4051	3953	3947	4126	4022	4179	4172

b Investment costs are not included

The following findings are derived from the modelling results.

- Renovation of buildings with a subsequent decrease in the consumption of district heating by 25 % and 45 % makes a significant contribution to the reduction of ETS CO_2 emissions (180 and 1119 thousand tonnes of CO_2, respectively), although the scenario with a 45 % reduction in heat consumption is rather too optimistic for implementation in 2030 for the Baltics and can only be realised by decisively strengthening all decarbonisation measures in full.
- An accurate calculation of investments for the renovation of buildings in the baseline scenario 2030ref and the added value when calculating the selected measures with reduced consumption of district heating is not possible in the framework of the present study due to multiple influencing factors, such as government decisions over the next 10 years on the amount of assistance in renovation, a forecast of the variable activity and awareness of residents, the stability of the economic situation in the region, the percentage of rented apartments and many more.
- Combining renovation with the installation of heat pumps enhances the effect of decarbonisation.
- The introduction of heat pumps as an innovative technology to reduce emissions and increase the level of decarbonisation does not work effectively without the involvement of another progressive technology, e.g. solar PV technology, which can meet the increased demand for electricity without increasing the amount of annual CO_2 emissions. As an alternative, a scenario with decentralized PV installations and smart electric thermal storage systems could be considered [73], [75].
- The model gives strong response through increasing or decreasing electricity import under different scenarios. Therefore, the next steps can be the study of the sensitivity of changes in the electricity import/export prices, CO_2 emissions and fuel price changes to LCOE (levelized cost of energy) and fuel used.

- The simulation results have shown that due to large-scale implementation of RES and desynchronisation from BRELL the energy prices could increase significantly during some hours/periods. This could negatively affect energy-poor households and their ability to keep their homes adequately warm and to pay the utility bills; special measures need to be included to diminish the impact [76]. One of such initiatives could be local energy communities which foster both technological and social innovations. As shown in [77], different technologies and business models could be used, facilitating achievement of the 2030 and 2050 energy and climate change mitigation goals as well as introducing new supply tariffs or schemes. Another way is to plan the necessary changes in the framework of the smart city [78], which allow energy consumers to choose and implement exactly those energy resources and models that will bring the most cost-effective results for all the energy stakeholders [79].

5.3. Chapter conclusion

According to the results of the present study, the planned change of the Baltic energy systems towards 2030 seems both possible and viable. The scenarios selected have shown the benefits of the transition but also raised possible concerns in energy security for each country; the study presented challenges in reaching emission reduction targets in effort-sharing sectors and analysed the possible cost impacts of planned investments.

The modelling results suggest that the Baltic countries need to act fast and proactively in updating the energy system but also remain reactive to changes in operating environment. While the challenges faced by the three Baltic countries are different, regional cooperation in planning and investments is encouraged. In order to achieve the indicated energy system transition securely, the focus on renewable generation should be accompanied by policies to support energy security as well as electrification and flexibility of transport and buildings.

The building sector can bring an important impact to the Baltic energy system as a whole through increasing the awareness of so-called green technologies. The installation of heat pumps and solar panels, as well as the renovation of buildings directly depends on the awareness of residents and their willingness not only to reduce their energy costs, but also to contribute to the overall decarbonisation goal. Whereas the modernisation of large-scale heat plants and the transition to green energy at large CHPPs depends on top-down solutions, the introduction of local green power generation in the building sector is guided by a bottom-up approach. In this case, a high level of awareness of modern technologies, the availability of implementation and economic calculations can make a significant contribution to the implementation of NECPs and of the set goals.

The analysed scenarios provide the feasible options for the development of decarbonisation pathways in the building sector. The introduction of innovative technologies contributes to an increase in the share of variable RES and to the production of local energy to enhance the safety of the system; however, it contributes to an increase in the costs of implementing the scenario. Renovation of buildings is one of the most effective measures for implementing national plans, but only if end users/consumers are actively involved in the decarbonisation process.

After examining the potential of end consumers in the Baltic region, let's move on to discover untapped opportunities within the country and look in more detail at the decarbonisation process and the way energy resources are used. Despite small changes at the level of an individual household, in general, the process of electrification can be a clear example of the realisation of untapped potential within a country or a particular sector.

6. SCENARIO MODELLING OF INFRASTRUCTURAL AND SECTORAL CHANGES FOR THE DECARBONISATION PROCESS ACCELERATION

Changes in certain sectors and infrastructures can have a significant impact on the decarbonisation process. Different energy structures and sectors must compete in search of priority for decarbonisation goals [80]. One of the main challenges is to reduce the use of fossil fuels and substitute them with renewable energy sources, which is done by end-user sectors. As the electrification of urban infrastructure and particular households has been approved as one of the effective decarbonisation measures, the need to identify the most acceptable solution on this issue appeared. In order to determine the maximum potential for reducing CO_2 emissions, the impact of end users in various groups and sectors was investigated.

6.1. Electrification of cooking in Latvia

One of the areas of decarbonisation and electrification, which has not been studied thoroughly enough, remains the electrification of the cooking equipment. Apparently, this phenomenon is associated with the features of the equipment used in kitchens and the fuel burned in stoves in each country. Nevertheless, analysis of the operation parameters of stoves operating on LPG (liquefied petroleum gas), electric and induction stoves shows that stoves using LPG significantly increase the emissions of CO_2-e (carbon dioxide equivalent) in the atmosphere [81] and have a longer cooking time and a lower efficiency as compared to induction stoves.

Looking at the local level, there is a **complete lack of research on the decarbonisation potential of kitchen electrification in Latvia** by substitution of appliances operating on fossil fuels (natural gas and LPG) for electric and inductive stoves. This untapped potential can bring a significant impact by reducing GHG emissions and introducing more secure and effective technologies. Therefore, this section explores the possibilities and potential of electrification procedures that can be introduced in Latvia. The present study determined the estimated number of households with replaced stoves – from gas to electrical ones – helping to achieve for Latvia its climate goal, and the corresponding CO_2 emissions were calculated. For comparison purposes, in the same manner, calculations were made regarding the necessary number of passenger vehicles in Latvia that need to transfer from internal combustion engine (ICE) to electrical vehicle (EV), and the resulting reduction in emissions.

In 2020, Latvia’s households used 7.6 % of their total energy consumption for cooking (see Table 6.1).

Table 6.1

Types of Energy Resource Consumption (%)

	1996	2006	2010	2015	2020
Total	100	100	100	100	100
Heat (heating and hot water)	87.2	75.4	79.5	83.4	83.4

	1996	2006	2010	2015	2020
Cooking	8.8	13.9	11.4	7.3	7.6
Other needs	4.0	10.7	9.1	9.3	9.0

Data source: Central Statistical Bureau of Latvia [82]

According to the 2020 statistical data for Latvia, 25.6 % of the households use electric stoves, 28.7 % of the households use gas stoves (operating on natural gas) and 19.8 % use LPG appliances (see Table 6.2).

Table 6.2

Types of Energy Resources Used for Cooking (%)

	1996	2001	2006	2010	2015	2020
Total	100	100	100	100	100	100
Electricity	6.6	7.2	11.0	17.9	32.7	39.4
Natural gas	37.8	35.4	34.9	41.2	29.7	28.7
Liquefied petroleum gas	30.8	31.6	29.3	25.2	24.1	19.8
Other fuels (wood, etc.)	24.8	25.8	24.8	15.7	13.5	12.1

Data source: Central Statistical Bureau of Latvia [82]

Statistics data during the period from 1996 to 2020 show that more and more households in Latvia are taking the opportunity to use an electric stove as a more innovative piece of equipment; partially it is a result of new buildings without gas infrastructure being constructed, which significantly reduces the value of real estate per 1 m^2. Nevertheless, the entire transition process is not fast enough, and the number of gas stoves is still large. This process is especially slow in households with LPG stoves, which is probably due to the fact that most of them are located in rural areas of Latvia with no natural gas pipelines. The financial possibilities of the inhabitants of these areas are usually limited, and the use of old gas stoves continues.

6.1.1. Modelling approach

For the purpose of comparing indicators of cooking on stoves with different kinds of fuel used, in Table 6.3 the consumption of natural gas and electricity for cooking was calculated.

Table 6.3

Comparative Analysis of Household Energy Consumption in Kitchens

Average household consumption when cooking					
	on natural gas stove		***on electric stove* with***		***on induction stove***
			electric coils	***glass ceramic plate***	
per month	8 m^3	74 kWh	35 kWh	26 kWh	19 kWh
per year	96 m^3	931 kWh	396 kWh	317 kWh	233 kWh
Efficiency of cooking	28–55 %		39–60 %	70 %	70–90 %
CO_2 calculations, t CO_2-e/year	0.18		0	0	0
Costs for cooking, EUR/year (including fixed payments)**	72		108	86	64

* The author has assumed that the electricity used by electric and induction stoves is totally green, i.e. only renewable energy sources have been used for electricity production.

** This research uses the prices of 2019–2020 for calculating the costs.

The data obtained for electricity consumption using induction stoves is taken from [83], where it is based on practical experience. The data on efficiency of cooking has been taken from different sources [84]–[86], both theoretical and practical, to compare and keep the average line. The same sources suggest that the efficiency of the glass ceramic plate is about 20 % higher than that of an electric coil stove. The CO_2 emissions for natural gas combustion has been calculated in [87].

In turn, the author used the methodology shown below to calculate carbon dioxide emissions from cooking on a stove with liquefied petroleum gas (LPG). One litre of LPG weighs 550 grams; it is a mixture of liquid butane (C_4H_{10}) and propane (C_3H_8), consists (by mass) of 82 % carbon and 18 % hydrogen, or 454 grams of carbon per litre of LPG. The combustion of 1 kilogram of LPG requires about 15.6 kilograms of air (that is about 12 kilograms of nitrogen and 3.6 kilograms of oxygen); the reaction produces about 12 kilograms of nitrogen (this gas being chemically neutral, this gas did not participate in the combustion), 3 kilograms of carbon dioxide (CO_2) and 1.6 kilograms of water (H_2O). In order to combust 454 grams of carbon to CO_2, 1211 grams of oxygen is needed. The sum is then 454 + 1211 = 1665 grams of CO_2/litre of LPG.

According to gas density parameters, one litre of liquefied petroleum gas (propane + butane) contains 0.230 m^3 of free gas. The results of the survey held by the author in the Latvian city of Aizpute, where natural gas pipelines are not available and LPG gas is used in stoves, show that the average consumption of LPG by one person for cooking is 1.8 m^3 per month. One litre of liquefied petroleum gas contains 0.230 m^3 of free gas, therefore, the average consumption in litres is 1.8/0.23 = 7.82 litres. As it was mentioned above, this kind of stoves are old equipment, historically their use started in the Soviet times, and appropriate documents contain data on LPG consumption rates for cooking, which correlate with the data in [88].

Thus, an average family of three people, using liquefied petroleum gas for cooking, 7.82 × 3 = 23.5 litres per month or 282 litres per year, gives rise to the release of an annual 0.5 tonnes of CO_2 into the atmosphere. This amount greatly exceeds even the same parameter for gas stoves, and even greater is the difference from electric and induction stoves powered by green energy.

Table 6.4 reflects the statistical data concerning Latvian households using gas stoves (operating on both natural gas and LPG) for cooking. The author did the calculation on the basis of data from the Central Statistical Bureau of Latvia, “Energy consumption in households” survey [82].

Table 6.4

Use of Natural Gas and LPG Stoves in Latvia for Cooking

Characteristics of dwellings	**2020**	**Total**
Total household number, thsd.	834.7	
Average number of people in one household in Latvia	2.2	
The number of households using natural gas for cooking, %	28.7	
The number of households using LPG for cooking, %	19.8	
The number of households using natural gas stoves in Latvia, thsd.	**239.6**	**404.9 thsd.**
The number of households using LPG stoves in Latvia, thsd.	**165.3**	

Thus, it was noted that Latvia has significant untapped potential in electrification and reduction of CO_2 level in households. Nearly 30 per cent of households, or 404.9 thousand, use gas stoves, which contribute to the release of greenhouse gases into the atmosphere.

As a next step, the identification of better potential for decarbonisation was done by comparing the electrification of stoves to the electrification of passenger cars in Latvia. Table 6.5 contains characteristics of passenger cars taken from the Road Traffic Safety Directorate of Latvia and the Central Statistical Bureau of Latvia, as well as calculations of CO_2 emissions for the average fuel car in the case of Latvia.

Table 6.5

Fuel Passenger Car Characteristics and Emission Calculation

Characteristics	**Value**
Number of active passenger cars in Latvia	739 124
Average annual mileage per car (km)	13 737
Average car fuel consumption per 100 km in city conditions (litres)	8
Average CO_2 emissions (g/km)	225
Total estimated fuel consumption by passenger cars in Latvia per year (thsd. litres)	812 268
CO_2 emissions total for all passenger cars (t CO_2-e/year)	2 284 499
CO_2 emissions average per 1 car (t CO_2-e/year)	3.091

Based on data from the Road Traffic Safety Directorate of Latvia [89] and the Central Statistical Bureau of Latvia [82].

The results of calculations are described in the next chapter.

6.1.2. Results and discussion

The calculation results show that cooking on an electric stove is to some extent more expensive than cooking on a gas stove, or about the same if compared with an induction stove (however, it also depends on the specific habits of people in the household). The energy savings when switching from gas to induction stove are shown in Table 6.6.

Table 6.6

Calculation of Energy Savings when Switching from Gas Stoves (Natural Gas and LPG) to Induction Stoves

	Energy savings, thsd. kWh	**CO_2 savings, t CO_2-e/year**
The consumption difference (energy savings) between a natural gas stove and an induction stove per year	0.698	0.18
The consumption difference (energy savings) between a liquefied petroleum gas stove and an induction stove per year	2.115	0.5

Table 6.7 depicts the results of the calculations of energy savings and CO_2 savings per year for various percentage ratios of the replacement of gas stoves by induction ones in the case of Latvia; different scenarios of substitution in Latvian kitchens were studied.

Table 6.7

The Scenarios of Substitution of Gas Stoves by Induction Stoves

Scenario No.	**Percentage of gas stoves substituted by induction stoves**	**Energy savings, million kWh/year**	**CO_2 savings, thsd. t CO_2-e/year**
1	100 % of LPG	349.6095	82.65
2	20 % natural gas and 20 % of LPG	103.37006	25.1556
3	40 % natural gas and 40 % of LPG	206.74012	50.3112
4	60 % natural gas and 60 % of LPG	310.11018	75.4668

Scenario No.	Percentage of gas stoves substituted by induction stoves	Energy savings, million kWh/year	CO_2 savings, thsd. t CO_2-e/year
5	80 % natural gas and 80 % of LPG	413.48024	100.6224
6	100 % natural gas and 100 % of LPG	516.8503	125.778

As the first scenario, as having the greatest impact on the level of decarbonisation, we chose 100 % replacement of LPG stoves with induction stoves. The implementation of this scenario saves 350 million kWh and 83 t CO_2-e (carbon dioxide equivalent) per year. However, it is worth considering that most of the LPG stoves are located in the rural regions of the country, and the support and/or subsidies for such a replacement by legislative acts are very desirable, since the financial capabilities of residents in this area are often limited.

Scenarios 2–6 represent possible ways to implement the electrification of the kitchens in Latvia under more or less favourable conditions. Energy and CO_2 savings increase with the number of kitchen equipment substituted and can be taken into consideration by energy policymakers when planning the energy development in a city or a region. It should also be noted here that the process will go faster when developing appropriate legislation and funding.

In its turn, Table 6.8 depicts the energy savings and CO_2 savings when substituting an ICE car with an electric vehicle, as well as different scenarios of transition from fuel cars to EVs.

Table 6.8

Calculation of Energy Savings when Switching from ICE Cars to EVs

	ICE car consumption*	EV consumption**	Energy savings, (kWh/year)	CO_2 savings, t CO_2-e/year
Energy consumption per year, kWh	9 891	2 060	**7 831**	3.091
The consumption difference (energy savings) when switching from ICE cars to EVs, per year (kWh), when the percentage of cars replaced by EVs is as follows:				
1 % (7.4 thsd. cars)	73 107	15 226	**57 881**	**22 846**
5 % (37 thsd. cars)	365 534	76 130	**289 404**	**114 232**
20 % (148 thsd. cars)	1 462 135	304 519	**1 157 616**	**456 926**
100 %	7 310 675	1 522 595	**5 788 080**	**2 284 632**

*It is assumed that 1 l of petrol corresponds to 9 kWh. **It is assumed that an EV consumes 15 kWh/100 km.

As the next step, the comparing of the costs required for kitchen electrification and electrification of passenger cars in Latvia was done, when equal levels of emission reductions were achieved. Table 6.9 shows the average costs for purchasing an electric vehicle and for purchasing and installing electric or induction cooking surfaces in Latvia. The calculations of total costs if saving 20 thsd. t CO_2-e/year by switching to EVs or to electric cooking surfaces was made.

Table 6.9

The Average Cost of EVs and Electric Stoves in Latvia

	Average cost (EUR)	Number of positions switching	Cost if saving 20 thsd. t CO_2-e/year (MEUR)
EV	40 000	6.7 thsd. cars	268
Ceramic electric stove	340	62 thsd. stoves	21.08
Induction electric stove	540	62 thsd. stoves	33.48

Other results are shown in Table 6.10, which reflects a comparison of CO_2 savings, when one million EUR is subsidised for decarbonisation purposes in Latvia.

Table 6.10

Comparison of CO_2 Savings by Replacing Cars/Stoves if 1 MEUR is subsidised for decarbonisation purposes

	ICE cars to EVs	**LPG stoves to induction stoves**	**Natural gas stoves to induction stoves**
Savings, t CO_2-e/year	77	926	333

Thereby, to achieve savings of 20 thousand tonnes CO_2-e per year, Latvian households will need to substitute 6.7 thousand passenger ICE cars with EVs, or to substitute 62 thousand gas stoves (both natural gas and LPG), which is 12 % of the total number of gas stoves, with electric/induction surfaces. At the same time, by subsidising 1 million euros for the decarbonisation of Latvian households, we will get a much greater result of reducing carbon dioxide emissions by investing these funds in the replacement of stoves.

The whole picture of energy and CO_2 savings dynamics for different electrification scenarios (percentage of replacing) when substituting cars or stoves to electric equipment are reflected in Figure 6.1.

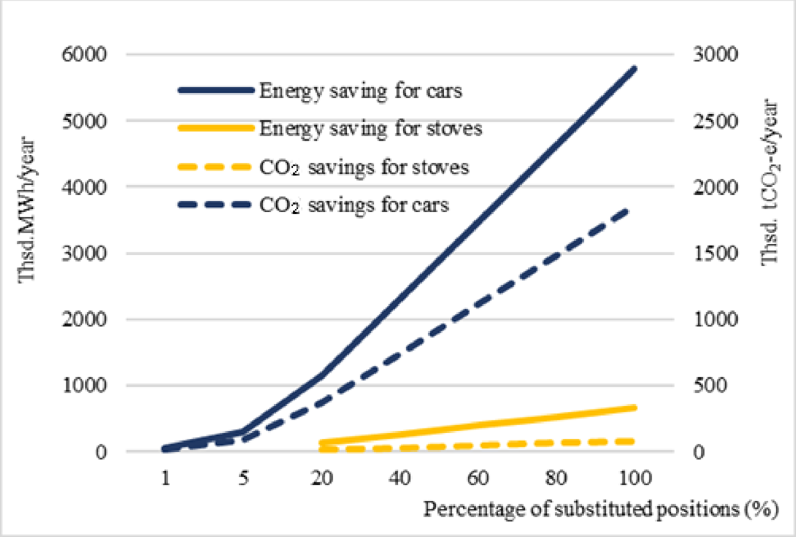


Fig. 6.1. Energy and CO_2 savings.

No doubt, replacing all passenger cars with an internal combustion engine to electric vehicles can save much more energy resources; nevertheless, replacing all stoves in Latvia with electric or induction surfaces is preferable in the first stages of electrification.

6.1.3. Chapter conclusion

It was proved that the optimal way to reduce emissions and speed up the decarbonisation process of households is to start with replacing kitchen equipment. While reducing the same amount of CO_2, it is more rational and effective to start with substituting stoves than replacing fuel-based cars with EVs. It requires much less financial expenses from dwelling owners, as well as governmental structures in terms of legislative support and subsidies to make the transformation process faster. Induction cookers are more expensive; however, we need to make a forecast for the future to choose the best solution: the energy consumption of this type of equipment is more efficient and safer for users. Therefore, the choice should be made in favour of induction surfaces.

This part of the Thesis proves that if the state is ready to invest one million euros into the decarbonisation of Latvian households, it is more efficient to start investing the available funds in replacing gas stoves, especially for stoves that use liquefied petroleum gas, with electric ones. This will reduce carbon dioxide emissions by 926 tonnes per year by replacing LPG stoves, or 333 tonnes of CO_2 per year by replacing natural gas stoves, while one million euros invested in replacing internal combustion vehicles with electric vehicles will reduce carbon dioxide emissions by only 77 tonnes per year (it can change somewhat if the EV cost drops, e.g. to 103 tonnes of CO_2 per year with the EV cost at 30 thsd. EUR). This does not repeal the decarbonisation requirements in transport, but emphasises the priorities for the efficient use of resources in Latvia.

A household decarbonisation strategy should include all options to reduce and/or eliminate the use of fossil fuels in vehicles, as well as in equipment that uses combustion fuels in households. Nevertheless, the first step, which is the most suitable course of action for the Latvian conditions, should be to reduce the amount of fossil-fuel-powered appliances in dwellings, namely, stoves that use natural gas and liquefied petroleum gas, and replacing them with electric and induction cooking surfaces.

By electrifying households, in the future, it is possible to develop on this basis easier and more convenient ways to connecting local electricity production from RES for each dwelling (turning consumers into prosumers and/or prosumagers), reducing electricity costs and emissions of harmful gases. It is an opportunity to optimise energy supply, use the lowest cost of local energy resources and reduce dependence on energy imports, improve the quality of the environment and increase people’s self-confidence.

6.2. Consumer’s energy behaviour changes modelling in dormitories

To identify the degree of influence of the energy consumption habits of residents on the indicators of the energy system in practice, within the framework of international project ITCity (An ICT platform for sustainable energy ecosystem in smart cities) a study was carried out in the dormitory buildings of the Romania’s University. The ITCity project aimed at responding to the citizens’ needs for new applications of information technologies of various energy technologies usage, integrated in an intelligent way within the platform area at city level. Within this project, five pilot setups were launched in Bucharest Polytechnical University (UPB) campus dormitories located in Bucharest, Romania. A specific consumption load curve category based on the behaviour of the occupants living in the campus dormitories is defined and is modelled in this section.

6.2.1. Methodology

In each of the five dormitories, smart meters have been set up and at the point of starting the modelling, it had been a year since data acquisition and aggregation had begun. The collected data serve as the baseline of unaltered regular dormitory consumption pattern, which is used in the modelling process. Four dormitory buildings are used for modelling purposes. A general overview of the selected dormitories is collected in Table 6.11.

Table 6.11

General Overview of Dormitories

	Number of floors	Users		Living space		Yearly energy consumption, kWh
		on the floor, number	*in the room, number*	*floor, m²*	*room, m²*	
Dormitory 1	5	60	5	360	30	109 440
Dormitory 2	5	80	2	480	12	253 635
Dormitory 3	5	80	2	480	12	246 097
Dormitory 4	5	80	2	480	12	321 194

The following aggregated data provided the daily change information from multiple sources – surveys, smart meter measurements, and additional information.

Consumption survey and smart meter measurements

The consumption survey was conducted to assess the appliance list and the habits of their use, providing a view on the potential consumption in cases when no consumption metering equipment is available. The survey covers a 24-hour interval for weekdays and weekends with a specific 15-minute intervals, which was selected to give users the chance to sufficiently control the reported consumption (see Fig. 6.2).

This survey was made in order to assess the appliances used and the overall user habits as well as to determine user consumption in non-smart meter areas.

#	Device	Average Power [W]	0:00	0:15	0:30	0:45	1:00	1:15	1:30	1:45	2:00	2:15	2:30	2:45	3:00	3:15	3:30	3:45	4:00	4:15	4:30	4:45	5:00	5:15	5:30	5:45	6:00	6:15	6:30	6:45	7:00	7:15
01	Stereo	60																														
02	Air conditioning up to 7,500	1200																														
03	Air conditioning of 10,000 BT	1600																														
04	Air conditioning of 12,000 BT	1760																														
05	Air conditioning of 18,000 BT	2590																														
06	Hot tub	180																														
07	Food mixer	60																														
08	Gas Boiler	30																														
09	Boiler up to 80 liters	1500																														
10	Boiler from 100 up to 150 liter	2500																														
11	Water pump up to 3/4 HP	1159																														
12	1 HP Water Pump	1398																														
13	Electric coffee maker	1000																														
14	Centrifuge for juices	100																														
15	Air circulator	80																														
16	Computer	250	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	2
17	Foam wrapper	65																														
18	Fax	100																														
19	Clothes iron	1000																														
20	Electric oven	2500																														
21	Microwave oven	2000																														
22	Freezer	100																														
23	Refrigerator	40	1			1			1			1			1			1			1			1			1			1		
24	Grill	500																														
25	Blender	100																														
26	Lawn mower	250																														
27	Sewing machine	50																														
28	Washing machine dishes	1500																														
29	Washing machine	1500																														
30	Mixer	100																														
31	Hair dryer	800																													1	1
32	Clothes dryer	600																														
33	Sauna up to 5,000 W	5000																														

Fig. 6.2. Consumption survey snapshot.

Smart meters have been deployed in the UPB student dormitories. The measurements provided by the smart meters are used to compare data accuracy and to address subtle changes in consumption. Two types of data are used from the smart meters:

- A continuous weekly consumption sample – a fragment of an actual uninterrupted consumption from the winter and summer seasons. This information is used to compare the model's simulated behaviour with the actual behaviour, in search of similar situations to label the model's degree of accuracy.

- Yearly energy consumption – this value is given for each floor and the dormitory in total; it is used to select the corresponding modelled student consumers, which would more accurately represent the situation measured by the smart meter.

In order to simulate a natural lighting situation, information of the natural lighting in Bucharest was taken from an online source [90].

Model development

Two categories of models were considered – auxiliary (time series analysis) and conclusive ones. Auxiliary models simulate specific details related to user consumption. This category includes models – user behaviour, daylight and appliance models. On the other hand, the conclusive models link the information produced by the auxiliary models to produce the total simulated user consumption and to simulate user awareness by reduced consumption benefits.

Auxiliary models

The results produced by the auxiliary models address basic impacting factors, which affect the individual user consumption behaviours. The data produced serve as a reference array providing the conclusive model with the base knowledge of the user. The auxiliary model section contains a user behaviour model, a daylight model, and an appliance model.

A. User behaviour model

The user behaviour model creates a necessary reference for daily user activity. This reference includes a sleep period, outdoor and home activity. Activity labelled "outside" refers to any activity the user is engaged in outside his living space. On the other hand, activity labelled with "home" indicates the user's availability at home and the potential contribution to the overall consumption.

In user behaviour creation, the first type of information taken into account is the individual study schedule, which serves as an outside activity on working days [91]. One of the 48 collected student schedules is used for each user, providing study for every working day of the academic year.

The use of study schedule provides an occupancy picture in working days, addressing outside activities on weekends; a randomised algorithm has been added. The algorithm is in charge of producing unique activities for the weekend. Every activity is simulated by randomised selection of an activity's starting moment and its length, which can be from one to ten hours. Similarly, as for other outside activities, up to one hour of additional travel time is used, before and after a certain activity.

In the modelling process, it has been assumed that the user sleeps six to nine hours, which is selected based on a randomised algorithm selection. Additionally, it is assumed that users have at least one hour before going to sleep and before they leave for their outside activities. In Fig. 6.3, an example of a potential daily period division can be seen; it can be noted that a "sleep" period following an "evening" period is generated by the information of the following day, meaning that a user might have an "evening" period extending beyond midnight if the selected "sleep" period allows it.

In Table 6.12, an hourly example of user behaviour is shown. User behaviour is divided by 15-minute increments, but to show a greater range, the sample table is converted to hours. Outside and home activities and sleep are depicted with a certain colour and number.

Table 6.12

Hourly Activity Sample

9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00
0	1	2	2	2	2	2	2	2	1	1	1	1	0

B. Daylight model

The daylight model is used to organise the data collected from the online weather source. Daylight is used as the alternative lighting solution to artificial lighting. In the modelling process, we assume that student users, along with the increase in their energy use awareness, will likely choose to efficiently use natural lighting when possible. The daylight model is made by generating a data array with values representing every day of the year with two values, the start and the end of the daylight period.

C. Appliance model

All the appliances used by the student users have been assessed and modelled individually, 24 appliances in total. The appliance models, although unique and different from one another, share similar operation and control bases due to a preformed survey time step scale limitation. This means that the modelled appliance consumption is created more generalised and less detailed with the use of the 15-minute time step.

The appliance models use two operation time periods – morning and evening, shown in Fig. 6.3 with an example case presented. These two operation areas are concrete for some appliances that require user interaction such as TV, PC, etc., but can also be flexible for appliances that require user interaction, but operate beyond the areas, such as washing machine, telephone charger, etc. These areas are irrelevant for appliances actively operating 24/7.

Fig. 6.3. The division of the day into periods.

The control setting of each individual appliance is made unique based on the following parameters (the settings are available for all appliances, except the appliances that operate 24/7): appliance consumption, minimum operation time, maximum operation time, appliance use chance, window of operation, use period preference.

Conclusive models

Conclusive models use the outcome of auxiliary models to simulate the individual consumption pattern, implement changes, and test solution feasibility.

The user consumption model designs the individual user consumption behaviour by generating the user consumption pattern, taking the information of the user behaviour model and the appliance model, which is set up based on specific user appliance preferences.

To simulate every user, the user consumption model uses a modular template, which includes the information on user behaviour, a list of 24 appliance models, and user preferences for appliance use. Using this model, 48 unique user consumption patterns are produced by using a single consumption survey and 48 different study schedules. This simulates 48 individuals with similar preferences but unique consumption patterns. The difference between modelled user consumptions is simulated through different appliances and user preferences for using different appliances. The creation of unique outcomes from a single data source is done with randomised values. Each appliance has a minimum and maximum operation time, which is selected randomly each time the appliance is used. Lastly, each appliance has a randomly selected moment when the user starts to use it.

Through user consumption model, over 3000 unique user consumption patterns have been simulated. The simulated patterns are exclusive, since each generated pattern uses one of a kind combination of user behaviour and appliance preferences. This results in a large array of total consumption fluctuation. This diversity is necessary to provide a greater variety of consumption, which will be used to represent the actual consumer group.

After simulating a large variety of consumers, depending on the dormitory size per floor, 60 or 80 random consumers are selected from the concluded simulations and compared with the real smart meter measurements to find the best-simulated user group that reflects the real measurements most accurately. This is continued until all floors of each of the four dormitories are filled with simulated consumers. These concluded consumers are selected as the potential real student consumer depicters and are used for the test cases addressing consumption changes.

The appliance consumption reduction model addresses the task of exploring user awareness changes through simulation of energy use awareness increase in the form of three types of consumption reduction algorithm for selected appliances: for appliances that are used 24/7, but should not be used in such an extended period of time; as a result of increased user awareness, the user will try to use certain appliances less; and for lighting solutions, combining daylight model and artificial lighting use. All the algorithms work with the same user awareness principles and explore the impact of user awareness on energy use by a gradual increase in awareness from 0 to 100 % of the users involved. The gradual awareness increase is examined with a 5 % step, giving the opportunity to see how each % of population impacted would provide benefit, because a 5 % increase in awareness does not directly mean 5 % reduction in consumption because of user activities, meaning that in one situation awareness might produce a larger reduction than in another.

6.2.2. Results and discussion

The accuracy of simulated results in comparison to the measurements of real smart meters were assessed based on the peak comparison and direct value comparison analysis (see Fig. 6.4).

The similarities between “peak” and “dip” values are highlighted and it can be concluded that the real and model consumption patterns are fairly similar, with many “peak” and “dip” location areas matching between the results. The selected model consumption which best depicts the real consumption was found through both data analysis approaches and is one of many similar matches found. The depicted model consumption is deemed as the most accurate representation of the real consumption based on the accumulated approach results.

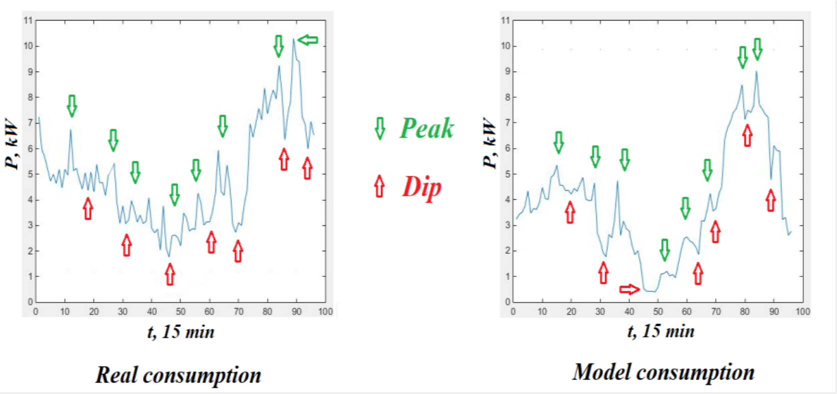


Fig. 6.4. “Dip” and “peak” comparison.

The modelled consumption accuracy has been tested using a five-day consumption sample taken from smart meter data, each representing the year’s seasons. In Fig. 6.5, a single day in autumn has been used to show an example of the match found.

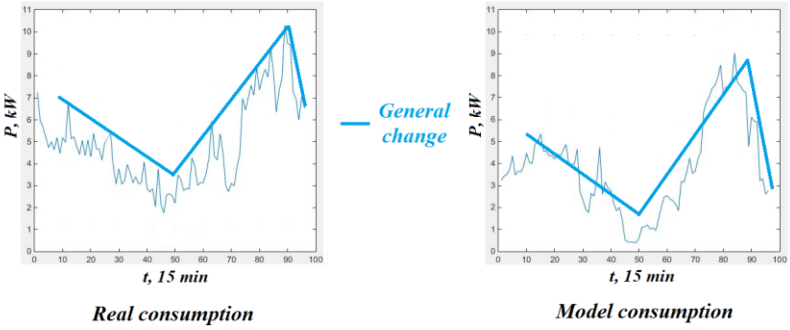


Fig. 6.5. General change in consumption.

The accuracy assessment has been performed for all sampled days, achieving an accuracy estimate of around 80 %. It can be concluded that the modelled consumption is able to produce situations that are fairly similar to the real measurement, deeming the produced consumption accuracy to be adequate and assumed as the depiction of a potentially real situation.

Pilot evaluation. User awareness analysis.

The evaluation of the UPB student dormitories was done by using the developed models, which base their operation on information acquired from real measurements and surveys. In Table 6.13, the assessment of measures regarding user awareness are collected; this assessment has been selected based on appliance use frequency and preferences, as well as the ability to affect consumption without loss of comfort.

Table 6.13

Assessment of Measures Influenced by User Awareness

	Definition
Daylight fluorescent	Maximum utilisation of natural lighting by the user to substitute fluorescent electrical lighting solutions. Action impacted by user awareness increase in efficient energy use.
Daylight LED	Maximum utilisation of natural lighting by the user to substitute LED electrical lighting solutions. Action impacted by user awareness increase in efficient energy use.
Fluorescent to LED conversion	Improvement of efficiency through using a more efficient electrical lighting solution. Action impacted by user awareness increase in efficient energy use.
PC sleep mode	Continuous unoccupied operation of a PC creates a large increase in consumption when the user does not use the PC directly. Increases in user awareness motivate users to switch to automatic sleep mode when the PC is unoccupied.
PC use reduction	PC load can contribute to a large part of users' total consumption. Increases in user awareness regarding energy use may lead to a reduction in appliance use by prioritisation of other activities or sleep mode utilisation while the PC is not directly used.
TV use reduction	TV load can contribute to a large part of users' total consumption. Increases in user awareness regarding energy use may lead to a reduction in appliance use by prioritisation of other activities or appliance shutdown while the TV is not directly used.
Kettle use reduced to own needs	A kettle as a high-power appliance can be efficient when all or most of the water boiled is efficiently used. This parameter tackles potential energy savings by appropriate water amount affected by increases in user awareness.

In the results of the user awareness test, each pre-selected appliance that was determined to have the potential to be impacted by changes in user awareness has been addressed. In Table 6.14, the results of awareness increase of Dormitory 3 users is assessed and represented for each appliance individually. The test result values for each appliance are shown in percentage of the total annual energy consumption.

Table 6.14

User Consumption Optimisation Possibilities in Dormitory 3

Equipment	**Fluo. 25W to nat.light**	**LED 10W to nat.light**	**Fluo. to LED**	**PC sleep mode**	**PC red. 20 %**	**TV red. 20 %**	**Kettle red. 30 %**
User awareness, %							
0 %	15.00 %	6.00 %	15.00 %	28.10 %	28.10 %	14.60 %	3.80 %
50 %	10.70 %	4.30 %	10.50 %	26.00 %	25.30 %	13.20 %	3.30 %
100 %	6.50 %	2.60 %	6.00 %	23.20 %	22.50 %	11.70 %	2.70 %

To reliably see the impact of user awareness, each test was conducted with a 5 % increase in user awareness. The 5 % value represented a group of four users. The results examine the changes from 0 % to 100 % of user awareness, but it was assumed that the achievement of 50 % is the plausible average value, whereas a 100 % user awareness is the potential theoretical maximum.

6.2.3. Chapter conclusion

An examination of appliance efficiency impact at 50 % user awareness was done. Five of the seven simulated cases are listed by their overall consumption impact strength:

- Lighting solutions – across all the test cases, these provide the largest reduction in consumption. The largest reduction can be achieved (3.6–7.9 % for the four simulated dormitories) by converting to more efficient LED solutions, followed by the second largest reduction (3.4–7.6 %) through increased utilisation of natural lighting.
- PC solutions – PCs are widely used nowadays, and this is especially true for university students. Out of the two tested cases, the most efficient PC consumption reduction was the third best overall reduction (1.9–3.3 %) – reduced PC overall use by up to 20 %. A slightly lesser consumption reduction (0–3 %) was provided by utilising the PC sleep mode, yet this solution rates fourth among the overall reduction rates.
- The TV solution – many of the conducted surveys indicated users having not only PCs as a frequently used appliance, but also TV sets. The reduced consumption for this appliance ranked last (fifth) in the overall consumption reduction, yet provided an optimal reduction of about 1.5 %.

7. OVERALL CONCLUSIONS

1. A multi-dimensional assessment of end users' contribution to the energy transformation process towards the decarbonisation goal was conducted. The hypothesis of the significant contribution of end users to increasing the efficiency and flexibility of the overall energy system was proved. A change in end-user energy behaviour produces a significant achievement towards the overall decarbonisation goals.

2. The tasks set were investigated and successfully solved: the impact and the role of the smart urban environment was studied and the potential influence of the energy behaviour of the end consumers was assessed. The developed methodological decision-making approach made it possible to identify a weak point in the city for sustainable, decarbonised development towards smart urban environment. This methodology allows implementing the general scheme of the energy development of a city, totally using its potential and identifying shortcomings and gaps, in order to make it possible to treat them correctly. Such a reliable model, along with a qualitative assessment using the multifunctional criteria proposed, can satisfy the needs of residents and other participants of the urban infrastructure at any request and affordability levels, and the positive experience can be disseminated and replicated to other cities and areas.

3. A survey of energy end users was conducted, and weaknesses were identified in their perception of the process of transition towards decarbonisation and smart environment, the use of new technologies, smart consumption, and becoming energy prosumers. The data obtained allow concluding that the potential of end users is used only partially, some end consumers' beliefs and energy behaviours hinder the development process. With the help of the survey it became possible to understand the direction of further development for the implementation of missed opportunities. The survey can also be used for any other region in order to find out the patterns of the energy behaviour of end users, which differ in different countries, as the survey showed.

4. A number of scenarios were developed for the Baltic countries, modelling the possible contribution of end users actively involved in the process of production and consumption

of energy, with active use of local heat pumps and solar panels. Security, flexibility, and sustainability remain the main important parameters of the energy system when adding renewable energy capacities. The scenarios created can be easily replicated for other countries as well, with the introduction of appropriate conditions and restrictions into the system.

5. Intensive renovation of existing buildings was calculated and modelled, which allows saving energy by identifying ways to accelerate the decarbonisation of the energy system with a combination of various parameters. By modelling the building sector using the *Baltic Backbone* tool and the extensive database collected, it is possible to further model various conditions of energy scenarios, taking into account the rapidly changing geopolitical situation, the rising energy prices, and the introduction of new technologies.

6. An analysis of the possibilities for the decarbonisation of Latvian kitchens was carried out; six scenarios for transition to decarbonised energy consumption were developed. A comparative analysis has been made for Latvia of the substitution of gas stoves with electrical equipment, as well as the substitution of cars with an internal combustion engine by electric vehicles. The results suggest that the most beneficial option is to start decarbonisation from kitchens. The results of this study will be useful for application in regions where there is a significant number of households using gas for cooking.

7. The research on the impact of energy behaviour in energy communities was modelled on the example of dormitories. The results obtained make it possible to direct attention to the most effective measures for saving energy resources and can be useful for development in all kinds of energy communities, such as dormitories, hostels, scheme housing, etc.

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