RIGA TECHNICAL UNIVERSITY

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

Doctoral Thesis

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ABSTRACT

Nowadays, the issue of efficient use of energy, the flexibility of switching on renewable sources of energy is as acute as acute can be. The replacement of fossil fuels with renewable energy resources and, in the future, the transition to carbon-free energy, increasing the efficiency of energy consumption, ensuring the reliability and flexibility of the energy system as a whole is prescribed in the national climate plans of European countries as a priority.

One of the most effective and fastest ways to achieve the set climate and energy goals is to change the energy behaviour of end consumers. Despite the large number of studies devoted to this issue, the multilevel nature and complexity of solving this problem are not taken into account. This Thesis considers a multi-approach structure for assessing and modelling the contribution and potential of end users to the overall change in the energy system for implementation of national plans.

To better understand the opportunities for decarbonisation, energy development in combination with smart city infrastructure and developed criteria was considered in this Thesis. Such a view, together with the decision-making approach proposed in this study, allows energy policymakers to deeply understand and solve the problems of energy supply of urban infrastructure in a clearer way, planning the impact of end consumers on national goals and correctly stimulating consumer activity towards becoming prosumers.

Among other things, scenarios were modelled to assess the contribution of end users to the overall development of the energy sector in the Baltic States; also it was researched, assessed and modelled the contribution of individual consumers (Survey) and their groups (energy communities) towards achieving the EU’s decarbonisation goals. In addition, unaccounted-for household decarbonisation opportunities specific to the Baltic countries were identified and scenarios for the transformation to a carbon-free economy were calculated.

ANOTĀCIJA

Mūsdienās jautājums par efektīvu enerģijas izmantošanu, elastīgumu atjaunojamo energoresursu izmantošanā paliek arvien svarīgāks. Fosilā kurināmā aizstāšana ar atjaunojamiem avotiem (un perspektīvā pilnīga pāreja uz bezoglekļa enerģētiku), paaugstinot enerģijas patēriņa efektivitāti, nodrošinot energosistēmas drošību un elastību kopumā, ir noteikta Eiropas Savienības un nacionālajos enerģētikas un klimata plānos kā prioritāte.

Viens no efektīvākajiem un ātrākajiem veidiem, kā sasniegt izvirzītos klimata mērķus, ir mainīt galapatērētāju enerģētikas paradumus. Un, neskatoties uz lielo šim jautājumam veltīto pētījumu skaitu, šīs problēmas risināšanas daudzlīmeņu raksturs un sarežģītība pārsvarā netiek ņemta vērā. Šajā promocijas darbā aplūkota daudzlīmeņu struktūra, kas ļauj novērtēt un modelēt galalietotāju ieguldījumu un potenciālu kopējās enerģētikas sistēmas pārmaiņās enerģētikas nacionālo plānu īstenošanā.

Lai labāk izprastu dekarbonizācijas iespējas, promocijas darbā tika aplūkota enerģētikas sistēmas attīstība viedo pilsētu infrastruktūras un izstrādāto kritēriju kontekstā. Šāds skatījums kopā ar darbā piedāvāto lēmumu pieņemšanas pieeju ļauj enerģētikas politikas veidotājiem padziļināti izprast un skaidrāk risināt pilsētas infrastruktūras energoapgādes problēmas, plānojot galapatērētāju ietekmi uz nacionālajiem mērķiem un pareizi stimulējot patērētāju aktivitātes ceļā uz enerģijas pašražotājiem.

Cita starpā tika modelēti scenāriji, lai novērtētu galalietotāju ieguldījumu kopējā enerģētikas sektora attīstībā Baltijas valstīs; kā arī tika pētīts, novērtēts un modelēts individuālo patērētāju (aptauja) un to grupu (enerģētikas kopienu) ieguldījums dekarbonizācijas mērķu sasniegšanā. Papildus tika novērtētas Baltijas valstīm raksturīgās neizpētītās un neizmantotās mājsaimniecību dekarbonizācijas iespējas un aprēķināti scenāriji pārejai uz bezoglekļa ekonomiku.

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1. INTRODUCTION

Background and topicality of the research

The world has now reached a critical point after which technology and consumption habits can lead us to irreversible climate change. In this regard, the political documents of the world's countries are becoming more stringent and restrictive, recognising and supporting the importance of switching to climate-neutral technologies, minimising greenhouse gas emissions into the atmosphere and introducing new, conscious habits of consumption of natural resources. The governments of cities and countries, striving to be smart and forward-thinking in choosing the right leadership policy, are taking further actions in pursuit of climate neutrality.

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.

Latvia, as part of the EU, has involved in the implementation of the above targets. These emission reductions would continue a trend that started when Latvia regained independence in the 1990s. Furthermore, based on the national energy and climate plan (NECP) [5] and [6], Latvia has developed a strategy to increase the use of renewable energy sources (RES) instead of fossil fuels. The main goal of the plan — Latvia's climate neutrality in 2050 — envisages reduction of GHG emissions in all sectors of the economy, achieving the target in three phases (decades). At the national level, general sustainable development based on decarbonised energy assets used is also included in Latvia's sustainable development strategy until 2030 [3].

One of the indicators used in the strategy is the intensity of GHG emissions in relation to the total primary energy consumption (t CO_2-e / total energy consumption). Taking into account that Latvia has a relatively developed service sector (it generates almost 65% of the total value added) but a less developed manufacturing sector, this indicator is more related to production processes and energy consumption. The above indicator covers energy consumption in the production of heat and electricity (the transformation sector) and final consumption, which in turn covers all the sectors of Latvia's economy (industry, construction, transport, agriculture, forestry), as well as household consumption, which accounts for 28% of the final energy consumption of the country in 2020 [7].

Energy is the largest source of GHG emissions in Latvia and accounted for 34% of the total emissions in 2017 [8]. In the energy sector, emissions from combustion processes in all the sectors of the economy are accounted. Most of the emissions come from the energy sector (public electricity and heat generation — 40%), followed by the commercial, institutional, household, agricultural, forestry and fisheries sectors (39%). Thus, the replacement of fossil energy in these sectors through technologies and innovations based on green energy, including electricity, seems efficient and promising in terms of implementing the national strategy.

The 2030 Climate and Energy Framework [9] 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% [10], 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** [11]: 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 account the source of electricity generation and gradually switch to clean electricity, which significantly increases the efficiency and speed of decarbonisation. Each of these three main areas carries significant potential, but it is their interaction that explains their maximum effectiveness. Massive electrification should be combined with decarburised electricity, which produces clean electricity, which in turn improves efficiency and is a way to reduce the burden on the electricity sector.

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. Therefore, special emphasis is placed on ensuring that consumers in the EU have the best choice among energy suppliers, that they can actively transform from only being consumers to becoming energy prosumers and have access to effective tools for comparing energy prices. 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) report [12] stresses the role of behavioural changes in end users in achieving the ambitious Zero Carbon Emission goal by 2050 (see Fig. 1.1).

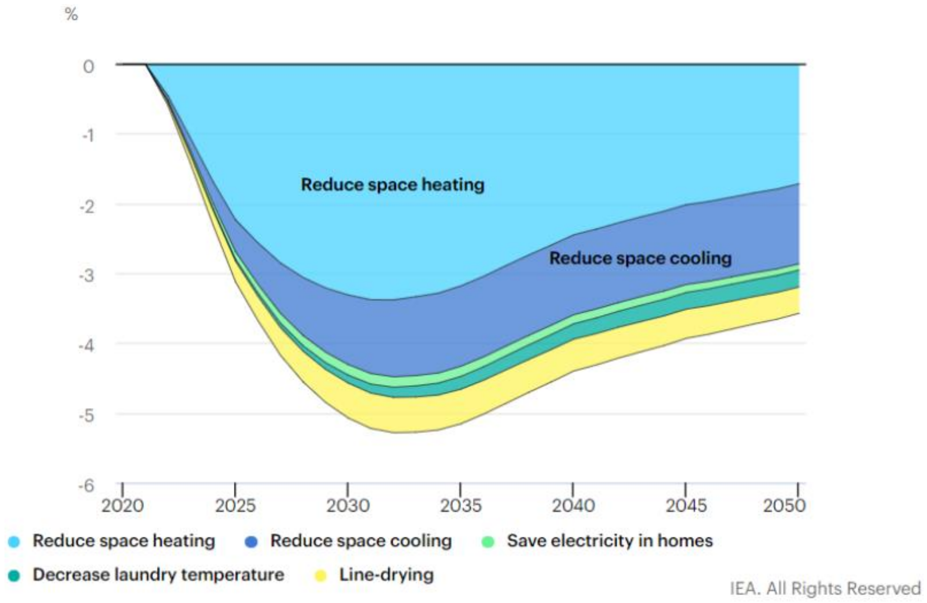


Fig. 1.1. Impacts of behavioural changes on energy consumption in buildings in the Net Zero Scenario, 2020–2050 [12].

The three-decade forecast made by the IEA includes reduction of space heating and cooling, as well as more rational consumption of electricity in homes as a significant contribution to the implementation of climate and energy goals. Only introducing technical solutions and innovations does not go far enough. As the IEA points out, achieving zero emissions by 2050 needs the active support of people. In addition to such obvious impacts as the purchase of an electric car or the installation of green technologies by consumers, other possible measures include a change in the consumption of electricity, a change in travelling habits towards public transport, cycling or walking, the application of the principles of a circular economy, the long-term use of materials. The IEA argues 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 [13], 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.2.8). Large-scale modelling is presented by the Baltic countries — Estonia, Latvia and Lithuania — both annual and hourly operation of the power system sustainable and flexible work simulation. Baltics are facing new tighter 2030 emission reduction targets proposed by the EU from a unique position. Till 2025, the Baltic countries are looking to desynchronise from Russia’s electricity grid and join the synchronous grid of Continental Europe while phasing out a substantial share of power generation from fossil fuels. Until recently, Estonia has been a net exporter of electricity due to its large-scale oil shale industry, while Lithuania has been a major electricity importer since the shutdown of their nuclear power station some ten years ago. The Baltic countries look to renewable power generation — especially wind and PV — as well as electrification of transport and heating to transform their energy system while maintaining security and cost-efficiency.

In this Thesis, the Baltic region framework was modelled by the open-source energy system dataset to investigate the above-mentioned energy system changes and the forecast of the impact of end users under new circumstances. Thereby, this Doctoral Thesis provides a set of measures aimed at researching 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 is 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 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 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. The **survey** was used for studying the present energy consumption habits in various countries and specific conditions for developing smart cities which make it possible to citizens to become more active and aware of energy efficiency, be more energy-saving and to 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 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 on the required terms.
3. A unique survey of end users was compiled and conducted, which explores in detail the energy behaviour of residents and identify 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 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 work on the Thesis 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 this Doctoral Thesis, the author participated in several international projects. The decision-making approach for urban energy environment development was produced by the author in 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 Prof. 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 Assoc. Prof. D. Zalostiba, VTT representatives T. Lindroos, N. Putkonen, LEI (Lithuania) and TalTech (Estonia). The author contributed in all parts of the research, especially in input database information gathering 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 Prof. 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 the consumer's energy behaviour changes in dormitories was conducted together with Prof. A. Mutule, 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 this Doctoral Thesis were presented at the following scientific conferences:

1. The XI INTERNATIONAL SYMPOSIUM ON ADVANCED TOPICS IN ELECTRICAL ENGINEERING, March 28–30, 2019, Bucharest, Romania.
2. The 2020 IEEE 61th 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 following results included in this Thesis have been published in scientific publications indexed in Scopus or Web of Science:

1. Mutule, A., **Teremranova, J.**, Antoskovs, N. "Smart City Through a Flexible Approach to Smart Energy". Rīga: 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. THE XI INTERNATIONAL SYMPOSIUM ON ADVANCED TOPICS IN ELECTRICAL ENGINEERING, 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: 2020 IEEE 61th 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” (presented at the 2022 IEEE 7th International Energy Conference (ENERGYCON’2022) in Riga, Latvia, May 9–12, 2022). Doi: 10.1109/ENERGYCON53164.2022.9830169.

The following 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 this 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 199 references.

The Thesis contains 59 figures, 23 tables and 3 appendices. The volume of the Thesis is 148 pages.

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 transmission 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 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 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

2.1. End users in the energy balance

In the energy balance of any country, the main positions are primary and final energy consumption, which provides an overview of the energy flows and status of the country in the energy market. While primary energy consumption refers to the total domestic demand for energy, which is made up of the production and import of the required energy resources, final energy consumption refers to consumption by the end users, without accounting for the auxiliary consumption or losses of the transformation sector.

According to [14], an end user is "the person who actually uses a particular product". In the same manner, **energy end users** are those who use all kind of energy resources for their needs, and end users' demands are summarised in the energy balance as final energy consumption. By the term **end-use energy**, we mean energy that is actually consumed by the user, while primary energy is produced directly from the country's natural resources or imported. Final energy consumption is the amount of available energy delivered to consumers for end consumption.

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

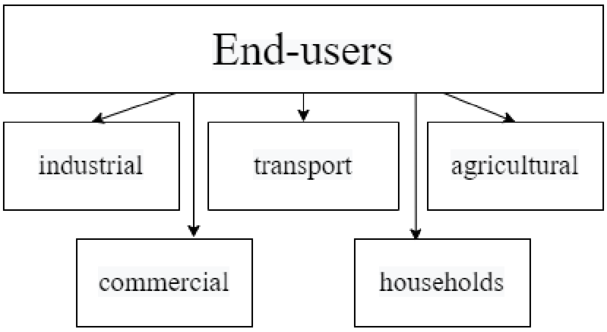


Fig. 2.1. The structure of end users.

The industrial, transport, agricultural, residential and commercial sectors are the main end-users of energy. 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.

2.2. Policies and regulations

On November 30, 2016, the European Commission published a Winter Package of eight proposals for a successful transition to a clean energy economy and for a reform of the European Union's electricity market [15]. The new energy market design will facilitate changes in the technical characteristics of electricity generation and enable electricity consumers to make conscious choices and receive real benefits from new technologies, facilitate the introduction of investments, contribute to the successful promotion of renewable energy sources and the decarbonisation process, and also improve the security of the entire EU energy system by active participation in the energy market.

At the forefront of this package 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.

The installation of smart devices with visualisation of energy production and consumption provides new opportunities for each end user to change their behaviour and the way they use energy resources towards becoming more effective, green, secure and flexible [16]. A new type of energy consumer, namely, prosumer, who not only consumes but also produces and can also store the produced energy and share it with other users, is appearing in the electricity market [17]. The participation of single consumers as well as energy communities (groups of active energy consumers and/or prosumers) in the energy market is considered as an important and necessary contribution to the sustainable and efficient energy distribution process. Despite a growing number of proposals for green technologies to move towards the goal of carbon neutrality in 2050, the adoption of green energy is slower than necessary. There are several factors needed to incentivise consumer choice for cleaner energy [18] explored more as a theoretical approach than as a practical one. Some researches focus on how end-user participation can contribute to the achievement of decarbonisation goals and energy policies [19] through establishing focus groups. Greater public involvement can influence the adoption of more credible energy policies and climate targets. Creating focus groups of active consumers also significantly improves their knowledge about the production of various types of electricity and influences the choice of consumed energy sources [20]. In addition, the location of end users contributes to the perception of sources of energy production. The goals of reducing greenhouse gas emissions for urban infrastructure require transforming the city and changing the lifestyle of its inhabitants. This requires a more involved and active public participation in the life of the city. One of the ways to achieve the goal is dialogues with the participants of the city infrastructure [21], where the level of interaction between the participants, the competence of the participants and the degree of their capabilities in solving the problems of the city's energy and urban climate become the key development points. In general, the perceptions of citizens about modern forms of energy and its consumption have an impact on the speed and quality of the transition to sustainable energy [22]. It should be taken into account that different socio-economic groups prefer different ways of transition to smart energy management and the use of VRES (variable renewable energy sources), and their diversity and consistency affects the quality of the transition as a whole.

Thus, in order to achieve Europe's climate goals of carbon neutrality by 2050, as well as the transition of the energy system to a new efficiency level using renewable resources and green technologies, the participation of end users is not only useful, but also necessary. 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 how large the role that end-users play in an energy transition towards sustainability in Latvia and Baltics can be, and how deeply end-users can support their country in energy and climate challenges.

2.3. Household energy consumption

The household sector energy consumption has reached 23% of the final energy use in the EU countries and is continuing to grow (see Fig. 2.2). 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.

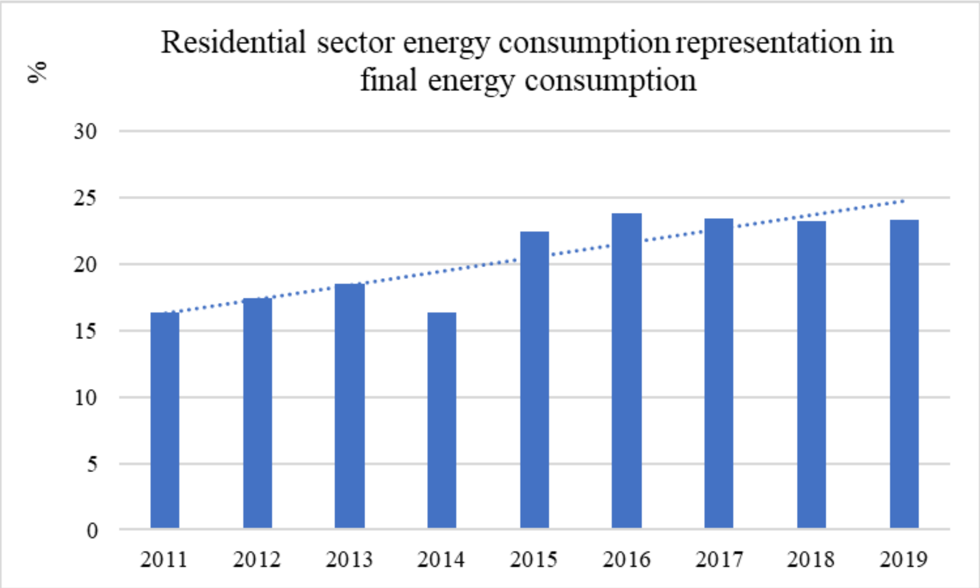


Fig. 2.2. Household energy consumption rate in total final energy consumption of EU countries. Based on Eurostat data [23].

During the years 2000–2019, the amount of fossil fuels used in the residential sector of the EU decreased by 20% and by 8% in district heating (DH), while the use of electricity and renewables increased by 16% and 65%, respectively [24], in the beginning showing a good speed in the transition to green fuels. However, in 2015–2020, the changes were not so sharp: fossil fuel use decreased only by 2%, and the increase in the use of electricity, district heating and renewables was 2%, 1% and 5%, respectively. Natural gas accounts for 32% of the final energy consumption in the residential sector, renewable energy sources (including waste) — for 20%, whereas coal and petroleum products — for 15% (see Fig. 2.3).

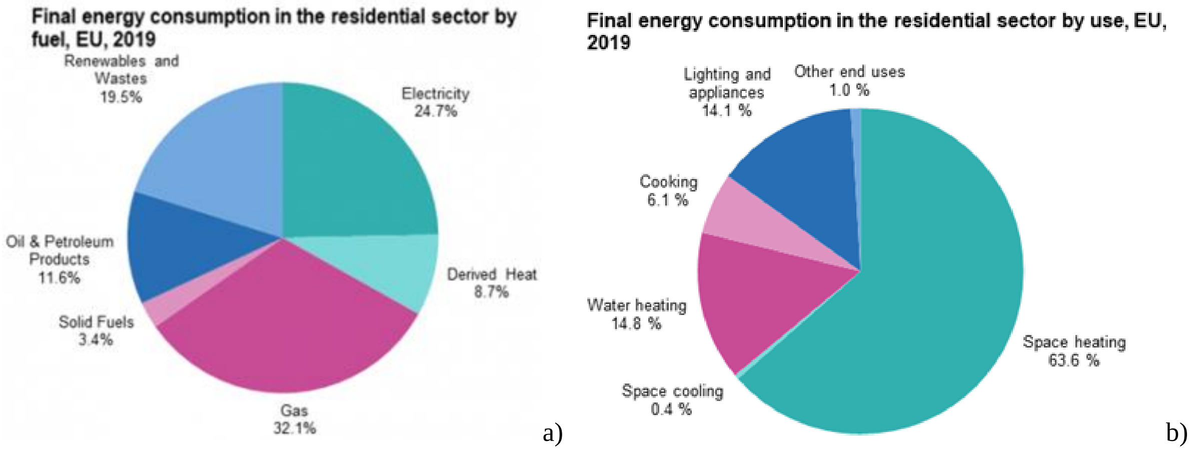


Fig. 2.3. Final energy consumption in residential sector by fuel (a) and by use (b), 2019. Source: Eurostat (nrg_bal_c) [23].

One of the most significant consumption sectors in households is heating. In the EU, 64% of the final energy consumption was used for residential heating. 15 % was used for water heating and 14% — for lighting and appliances, 6% — for cooking. These figures make it clear that the end users and their energy consumption patterns and habits can contribute significantly to the country's overall energy consumption framework.

According to Eurostat's data [24], 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. Among the EU countries, Portugal, Croatia, Bulgaria, Slovenia, Romania and Latvia are the countries with the largest share of renewable resource consumption for space heating, while the Netherlands, Italy and Hungary mainly use natural gas for this purpose, and Cyprus, Ireland and Greece — oil products. To prepare hot water, mostly derived heat is used, as well as gas and oil products. Only four EU countries use mainly renewable energy sources for water heating. For cooking, electricity and gas are used most often. All of the above facts open additional opportunities for decarbonisation and the introduction of green energy resources and innovations in the end-user sector.

Latvia

The total energy consumption in Latvia in 2020 was 184 petajoules (PJ) (see Fig. 2.4) [7]. The share of RES in the total consumption has continued to increase in recent years, while the share of fossil fuels has been declining. The share of RES consumption in the total consumption has increased by 14.8 percentage points over ten years and in 2020, it was 42.4%.

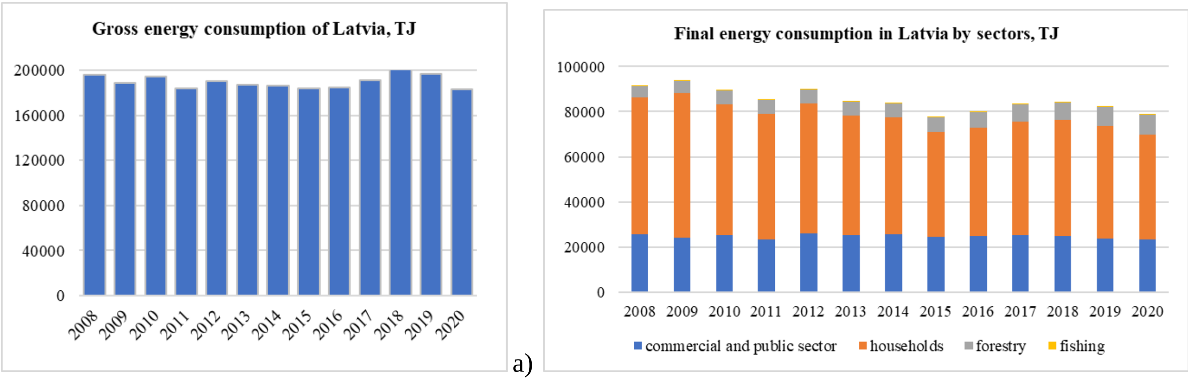


Fig. 2.4. Gross (a) and final (b) energy consumption in Latvia (based on the data of the Central Statistical Bureau of Latvia [7]).

Wood products and distributed heat are the biggest sectors in residential energy consumption (39 and 31 per cent), followed by electricity, natural gas and coal (13, 10 and 5 per cent, respectively) (see Fig. 2.5.). At the same time, the percentage of wood products used for heating is even higher — almost 54% together with waste, while derived heat accounts for 34%. The share of gas and oil products, 10.5% of total fuels used for space heating, represent the potential for decarbonisation.

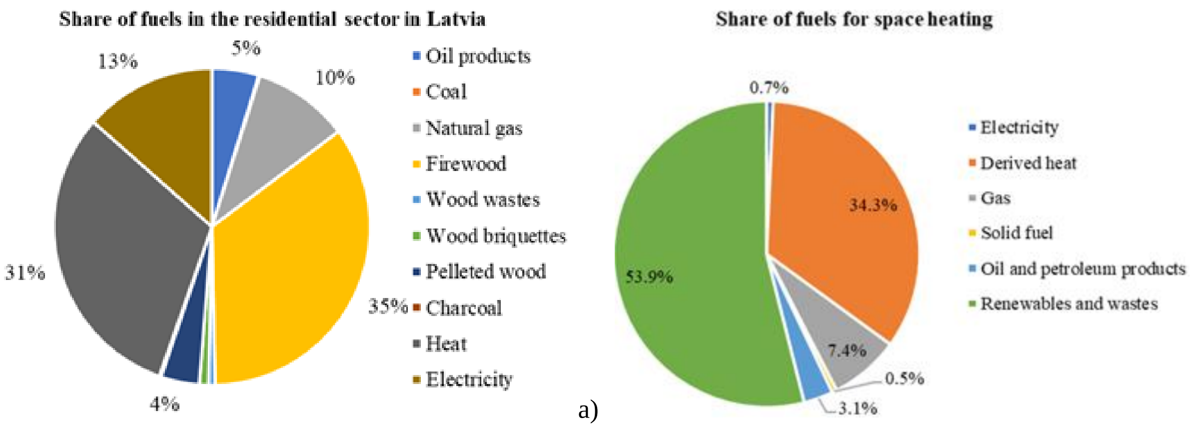


Fig. 2.5. Share of fuels in the final energy consumption in the residential sector in Latvia total (2020) (a) and for space heating (2019) (b). Sources: Official statistical portal of Latvia, Energy Balance in 2020 [7] and Eurostat [23].

In general, we see a slow positive trend towards reducing heat consumption for space heating (see Fig. 2.6), 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 when changing technologies and consumption habits.

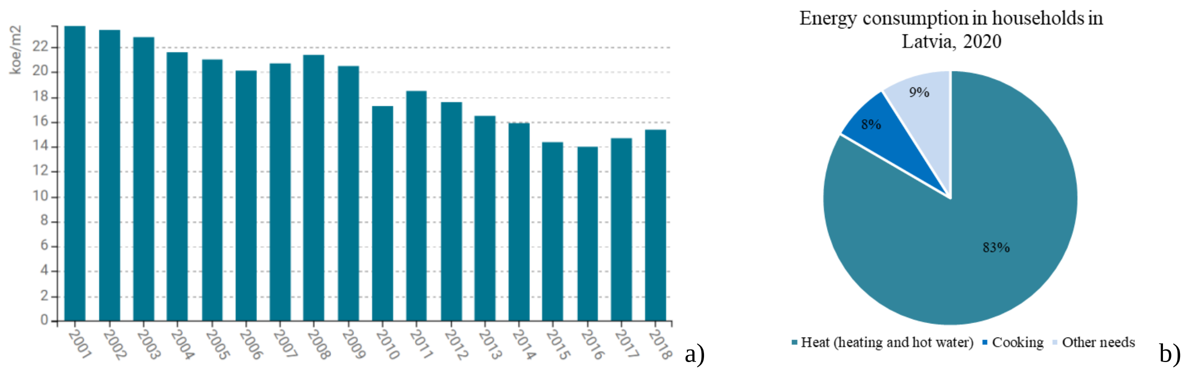


Fig. 2.6. Energy consumption of space heating per m^2 (normal climate) and Types of energy resource consumption in Latvian households (%). Source: ODYSSEE [25] and Central Statistical Bureau of Latvia [7].

To sum up, there are several main driving forces that affect the increase or decrease of energy consumption used by households as main end users (see Fig. 2.7). On one side of the balance we find a reduction in fuel consumption per dwelling, the introduction of technologies that have allowed more efficient use of fuel and a change in behaviour; on the other hand, an increase in the number of electrical and other appliances, as well as an increase in the common household area followed by an increased heated area. To achieve the goals of a climate-neutral Europe, there may be pressure to change both sides of the balance. However, reducing consumption and increasing efficiency through technology and changing habits seems to be the most preferable option, as it maintains the comfort required by the end users.

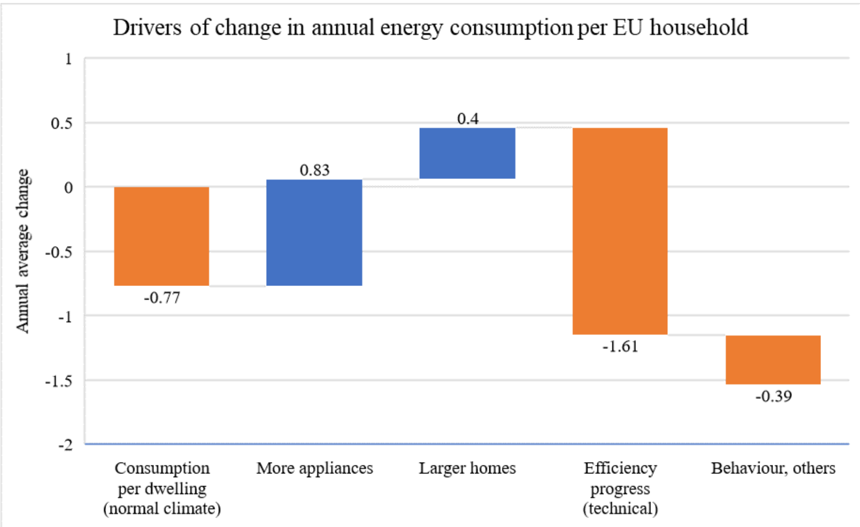


Fig. 2.7. Drivers of change in annual energy consumption per EU household. Based on the data of ODYSSEE [25].

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.

2.3. The tasks faced when introducing a consumer-centric, urban-focused, multi-level approach

Urbanisation (the concentration of the population and the resources necessary for their life in cities) is an important factor that determines both the amount and type of the energy resources used by a country. In general, urbanisation is accompanied by higher income levels and higher energy consumption by households.

Since most of the world's inhabitants live in cities and by 2050, may reach 80% of the total population, the way city life is organised and the attitude to energy consumption and energy saving on the part of its inhabitants significantly affects the overall level of development, flexibility and long-term prospects of the existing energy system. The Thesis will focus on the largest part of end consumers — the residential and commercial sector, which is concentrated mostly in cities and has a tendency to increase. Therefore, 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:

- 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;

– 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;

- to consider the possibilities of decarbonisation of single sectors where the consumers' impact can be the most influential;

- 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 other words, **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. 2.8), allowing to find the gaps and their solutions at various layers, which contributes to a much more complete coverage of the problem and decision findings.

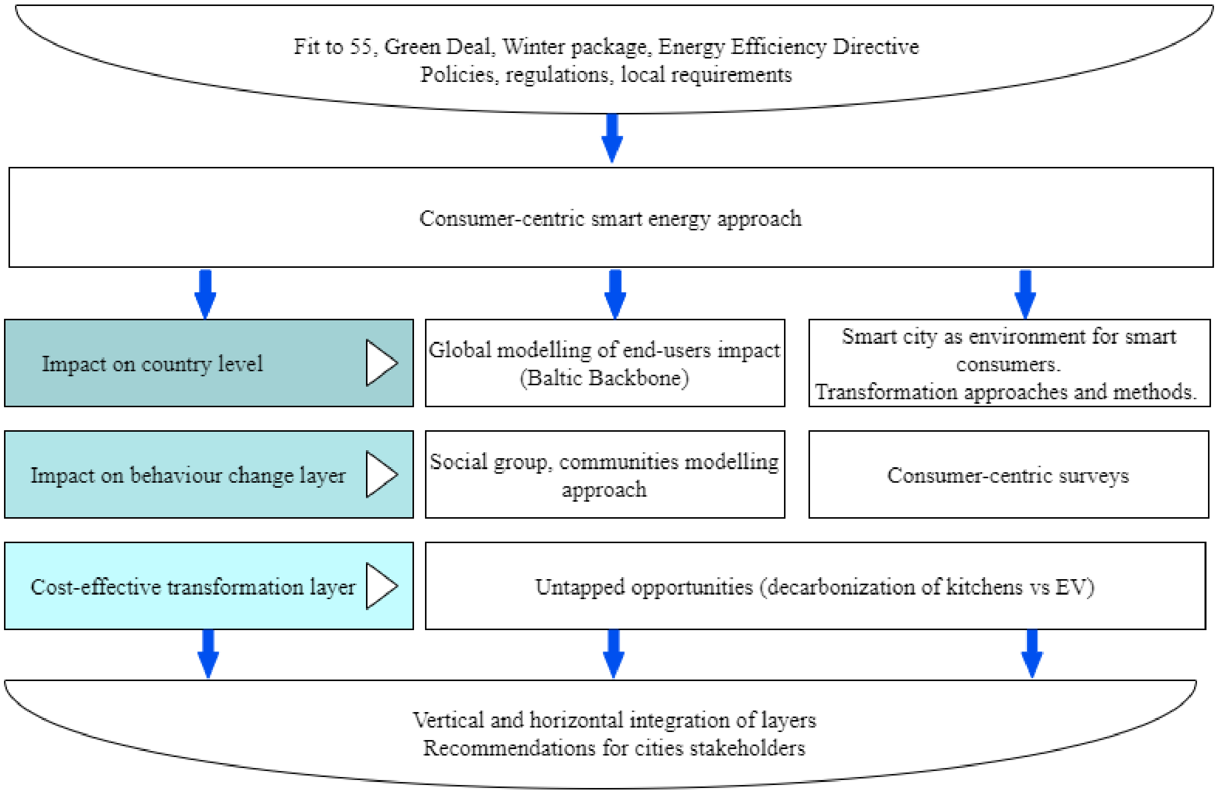


Fig. 2.8. Consumer-centric multi-level structure for the study of the contribution of end users to the overall decarbonisation goal.

A country-level impact assessment will allow modelling solution scenarios for end users in general; studying and modelling the behaviour of energy consumers in an energy community or other social groups reveals trends in energy use in specific groups of a given society and ways to overcome undesirable energy habits; while a study at the level of the individual end user will identify the most feasible and cost-effective ways to decarbonise at the level of an individual household.

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. Impacts can be positive, negative or neutral and can be regarded as pertaining to e.g. energy, environment, mobility, business etc. The whole population of the city create a large impact on multiple city aspects; thereby the affecting of the end users may provide a large benefit.

The subject of end-user energy behaviour has an overarching role, therefore, multiple studies need to be conducted to analyse citizens' impact on energy efficiency and various assessments from different points of view need to be made. 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.

3.1. Motivation for the research

In recent decades, cities around the world have been experiencing, in a very active form, the process of transformation of the urban environment, they have been forced to solve large-scale tasks and face serious challenges. In this process, a central place is taken by the innovative development of urban infrastructure — energy, transport and communications. Scientific and technological progress in recent decades has revealed several fundamentally new opportunities for improving the quality of life in megacities, including the growth of population mobility, the reduction of environmental pollution, the transformation of urban space (for example, the introduction of intelligent street lighting systems, smart water or electricity metering, introduction of "green" technologies such as heat pumps and solar panels, etc.). An especially strong progress is observed in green energy technologies: smart energy systems and VRES, which can radically change the urban environment of large and small cities in the future.

To solve the problem related to the exhaustion of energy resources, smart management of energy supply, infrastructure and energy flows is necessary. Among other systems and elements of the future, economists, environmentalists, energy researchers and engineers identify the following energy elements or components: smart household appliances, home energy management systems, building energy management systems, the consumer/ prosumer, energy storage, electric vehicles, and microgrids.

However, 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 of 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.

Based on the above-mentioned considerations, the following definition of a smart, or intelligent, city can be given: a city whose all resources are spent most effectively on the basis of the analysis of the information received from all structures, organisations and inhabitants of this city. For the holistic and effective management of urban energy development towards the goals of the country's National Energy and Climate Plan, an analysis of approaches to energy management and planning in cities, their strengths and weaknesses needs to be conducted.

3.2. The role of energy in urban environment

Moving towards intelligent, carbon-neutral cities and improving the quality of life in cities, we need to understand clearly what we are speaking about. We need to keep in mind the whole concept of a smart city, its separate aspects and vectors of development. A smart city is an urban development that unites the needs of the citizens in a sustainable and secure way along six main vectors (see Fig. 3.1).

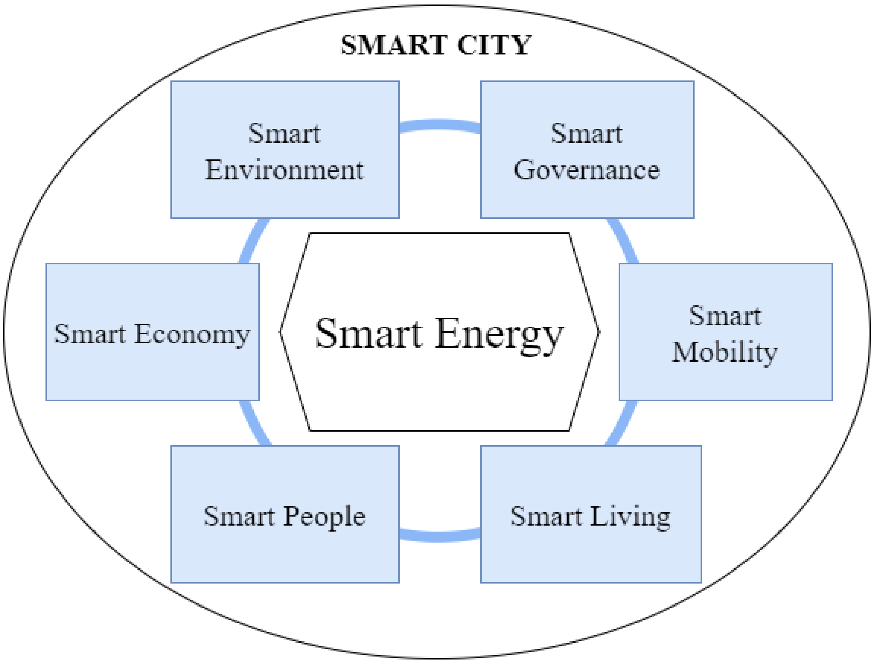


Fig. 3.1. Smart city and smart energy interaction model.

These six vectors are:

1. Smart Governance: public and private organisations, transparency of city management and its infrastructures, open data.

2. Smart Economy: on this basis, there are the processes that support the sustainable growth of the city, its individual parts and infrastructures.

3. Smart People: people who contribute to creativity, have critical thinking and are able to apply innovative ICT technologies to their everyday life.

4. Smart Mobility: integrated transport and logistic systems, innovative transport solutions.

5. Smart Living: healthy and safe living through smart technologies and applications that enable responsible lifestyles, behaviour and consumption.

6. Smart Environment: sustainable increasing of renewable energy sources and green energy managed by ICT control and monitoring, waste and pollution control and smart management.

Despite the fact that the term “energy” in the above concept is hidden, energy is the key to the sustainable development of the smart, carbon-neutral city, as is shown in Fig. 3.1.

All six vectors need energy in its different forms and ways, which requires the development of its intelligent, efficient production, transformation, storage, distribution and consumption in all the areas of the smart city. Therefore, it is necessary to find a way of effective interaction between the dimensions of a smart city and the energy which participates and interacts with each of the areas of development.

Whereas energy has the greatest influence on other vectors for the development of a smart city and its fundamental base, an important factor is the understanding of the clear and successful methodology for the development of smart energy in the city. To streamline the approach to understanding smart energy in the city, the concept of a “Smart Energy City” (SEC) has been created, which makes it possible to be aware of the need for an integrated approach to energy in a smart city.

In addition, since initiatives aimed at the effective implementation of renewable energy sources (RES) have an advantage in the development of cities, the issue of the ecological introduction and use of smart energy is more acute than ever in all spheres of city life. As stressed in [26], the transition to renewables happens all across the entire urban energy landscape from buildings to transport, industry and power. Renewables can bring tremendous benefits to cities, including cleaner air, modern services, and improved living spaces. At the same time, cities are crucial to the world’s transition to a low-carbon economy, accounting for 65 % of global energy use and 70 % of man-made carbon emissions. The intermittency of renewable sources, the increasing demand, and the necessity for energy-efficient transport systems, among other things, represent important energy challenges that are better addressed jointly rather than separately, as is usually the case [27].

As a brief summary of the main points, it is necessary to mention that the concept of a smart city, including the six development vectors, covers all the major interconnected areas of the city. This city model is appropriate to use for a general overview of trends, overall development planning and identifying areas required for transformation. On the other hand, the concept of a smart energy city implies a more professional, more focused approach to selecting and adopting solutions that are necessary for city development, based on an integrated approach to energy issues as the most influential factor in the sustainable development of a smart city. Cities’ energy requirements are complex and abundant. In consequence, modern cities should improve present systems and implement new solutions in a coordinated way and through an optimal approach, by profiting from the synergies between all these energy solutions. The complexity of the approach to a smart energy city is illustrated in Fig. 3.2.

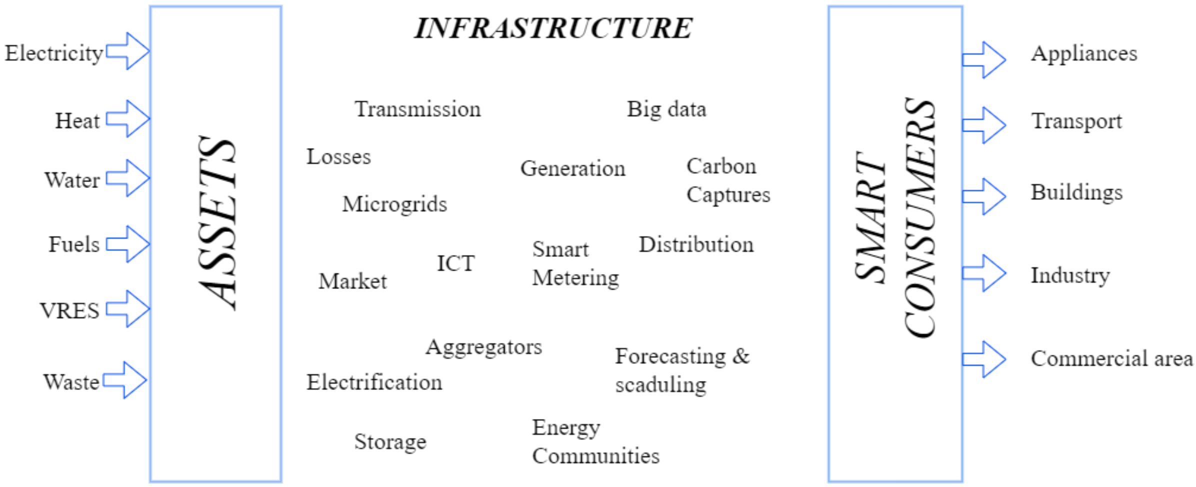


Fig. 3.2. Smart energy structure.

Between the energy sources and their final smart consumers, there is an infrastructure that includes a variety of different positions, from production and conversion of energy to the use of ICT solutions, microgrids, and other elements that make energy consumption smart, economical, sustainable, meeting the needs of the environment and raising awareness in consumers and prosumers.

A review of approaches to a smart city

The concept of a smart city implies the active involvement of end consumers in its development, as well as the joint achievement of the climate and energy goals described above, while maintaining the comfort and sustainability of energy consumption. Smart cities strive to become low-carbon urban energy systems with flexible and efficient approach that realise the goal of carbon neutrality and energy efficiency. Such urban energy systems use various renewable energy sources, promote the emergence and development of energy communities, and are interested in the wide participation of end users in the production and flexible consumption of resources. Therefore, a study was undertaken to investigate questions involved in transforming cities into smart energy cities, which is a highly complex, interdisciplinary, transnational issue [28]. In Table 3.1, different methods of the smart city development were 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 the 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 indicators (KPI) sets, standardisation and innovative IT-based approaches are used to create a suitable solution.	[29]; [30]; [31]
Smartainability	This approach uses qualitative and quantitative indicators of technology assessment for intelligent	[32]; [33]; [34]

Smart city approach	*Description*	*Sources*
	solutions that are designed to improve energy efficiency and environmental sustainability in the city; is more focused on integrated intelligent mobile platforms.	
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.	[35]; [36]
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.	[37]; [38]
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.	[39]; [40]; [41]; [42]
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.	[43]; [44]; [45]; [46]; [47]; [48]; [49]
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.	[50], [51]; [52]; [53]; [54]; [55]; [56]; [57]; [58]; [59]; [60], [61]
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.	[62], [63]
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 clarify the procedure for monitoring and managing	[64], [65]; [66]; [67], [68]; [69]; [70]; [71]; [72]; [73]; [74]

Smart city approach	*Description*	*Sources*
	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.	[75], [76], [77], [78], [79]

A large group of methods and approaches concentrate on making a study, planning and development of the infrastructure of cities in a gradual, step-by-step, improvement of each specific city sphere, moving towards smartness. The article [27] considers energy-intervention areas within the city and their relations, as well as compares different currently available energy models, energy-efficient facilities, control systems, and demand-response schemes. In its turn, source [30] explores the relations existing among urban and territorial networks, actors and participants, functions and activities, suggesting a way to integrate various aspects of a smart city. However, the end-user sector here is considered only from a general standpoint, as an opportunity to save resources, without individualisation and differentiation in influence.

An approach called Smartainability, with the help of qualitative and quantitative indicators, assesses the extent to which enabling technologies for intellectual solutions contribute to improving energy efficiency and environmental sustainability in the city [32]–[34]. Thus, the presented group of studies offers options for moving towards a smart city, starting with the selection of a separate area of development, for example, an increase in the efficiency of electricity use in smart buildings, or a decision to cut traffic congestions in the city, etc., to planning simultaneous implementation of effective solutions in various areas. It is also proposed to use indicators, standards, comparison of development indicators and the rating of cities to determine the areas with the greatest need for improvement. However, when aiming to improve the citizens' quality of life, there is a gap in feedback from the city residents, focusing mainly on ICT decisions in mobility and other trends.

Another group of intelligent city decision studies argue that the most optimal solution is the planning of separate regions, districts or even a whole city in advance by including in the plan all the necessary infrastructure and possibilities for smart building and using smart technologies of a smart city. It is claimed that cities generally have no clear idea as to their precise future smart city requirements at the present time and specify a few models in order to effectively meet potential future requirements and give guidance on what is needed to plan for any new development to support the smart city plans for a chosen area [35]. The problem follows that that kind of solutions is accessible only for a small number of city participants, exacerbating the problem of accessibility of efficiency improvements to all classes of the population and making national climate plans difficult to implement.

An example of considering a city as a multi-dimensional system and an approach to modelling solutions through the construction of a model for each layer is presented in a smart city infrastructure architecture model (SCIAM) [37], [38]. Again, end users are seen here as a homogenous group of consumers, which need to have common goals, ambitions and preferences, however, this model allows to investigate in certain questions to be solved and take into account some specifics of end users in more detail.

Some researchers have focused on the issues of smart cities through the prism of smart energy, believing that energy management is the most influential means of developing smart cities. The way to develop the sustainable smart energy city is considered by [39], providing the definition for a SEC as well as giving a set of practical solutions and technologies for smart energy, considering interconnections between such concepts as smart city, smart energy, sustainability and its management and stressing that the interaction between these basic areas is not delineated clearly enough. A more holistic SEC definition is provided by [40]: “The Smart Energy City is highly energy and resource efficient and is increasingly powered by renewable energy sources; it relies on integrated and resilient resource systems, as well as insight-driven and innovative approaches to strategic planning. The application of information, communication and technology (ICT) is commonly a means to meet these objectives. The Smart Energy City, as a core to the concept of the Smart City, provides its users with a liveable, affordable, climate-friendly and engaging environment that supports the needs and interests of its users and is based on a sustainable economy.” Such approaches to smart energy are really diversified and make the whole picture of the smart city and the role of smart energy in it clear enough. The overall approach [41] describes the Sustainable Urban Regeneration Model, stressing that cities need to become ‘smarter’ with respect to energy optimisation. The added value of the proposed methodology lies in the combination of energy efficiency and energy management using multidisciplinary data sources. However, in those concepts, end users appear only as a theoretical object for setting energy goals, appealing to the convenience and comfort of users, without a clear understanding of their priorities and choices.

Another area of consideration of smart urban environment, which has become very relevant in the past few years, is the use of energy centers (energy hubs) for the optimisation and efficient management of energy flows throughout the city. The use of various models, including energy hubs, as well as the possibility of their use for different conditions and needs of the city, its flexibility and management is considered in [43] and [44]. In [45], the idea is discussed that a smart city can be considered to be an open complex giant system, from which consensus emergence can be demonstrated and handled by a meta-synthesis method and clarify the differences between smart city management and traditional city management. On the other hand, the model did not pay attention to residential or end-user sector as having the ability to influence the increase in the flexibility of the entire energy system and reduce resource consumption, and does not consider the possibility of interacting with end users.

In recent years, one more approach has become increasingly popular and topical – the so-called blockchain technology – a continuous sequential chain of blocks, containing information built according to certain rules. Most often, copies of blockchains are stored independently of each other on a variety of different computers. The technology of blockchains can be extended to any interconnected information blocks. Applicable to the smart city, the blockchain is the right network to succeed in the delivery of codes (policies, planning, regulations and standards) since it is universal and decentralised, allowing for a bottom-up delivery of codes owned and implemented by the citizen and not by a central authority. The source [51] expresses assurance that the blockchain networks will disrupt the urban context as well, similarly to what is happening with the earlier application domains, and puts forward the Future Living Framework as the meta-use case of a wide research called Blockchain4Cities. The benefits of using blockchain in the urban field are shown. “Blockchain is here to take on and be the next network for cities.” A model for service of prosumers using blockchain technology [52] allows connecting different sources of energy to different users and manufacturers. Analysing the energy picture of users, the authors argue that this technology leads to increased energy efficiency. Blockchain technology and energy issues are combined to integrate the power and information infrastructure. Blockchain is well suited for organising the end users in the cities by creating effective communication in an urban environment using the blockchain technology [54], and applying the blockchain technology and smart meters to help prosumers in energy production and consumption management [56]. In this case, it is also necessary to take into account possible negative aspects of this technology that may be encountered [61].

In the forefront of city development, there are multidisciplinary methods and innovative decisions of production, transmission, accumulation and consumption of energy resources, with the purpose to optimise the already-existing technologies and equipment, and there are approaches to flexible switching to new modes, such as mini-generators, microgrids and the use of the energy of wind, sun, hydrogen and renewables [43], available for use by prosumers, with the so-called hubs — energy centres. By means of hubs, it is suggested to solve the problem of delivery and consumption of energy resources, such as electricity, gas, water, district heat, etc. Nowadays, the policy of decarbonisation is on top, as well as implementation of production and electricity consumption from small generation from renewable energy sources. Therefore, the need to shift supply of energy resources and their consumption, e.g., by means of energy accumulation, or a pre-discretion of additional power sources, is gaining in relevance. Energy centres (hubs), depending on the needs of a network and load consumption, can have a variety of inputs/outputs and conversion stages, along with the storage of different energy types. Relevant optimisation problems can be used to compute the optimal energy mix for the hub to minimise operational costs or to optimize the operation of an interconnected system of energy hubs. The principal advantage of such a system is in flexible prosumer activity and in the flexible operation process; it is trouble-free in deliveries taking into consideration the possibilities of energy producers and consumer demands for different types of energy. However, the model offers more opportunities specifically for active energy prosumers/consumers, ignoring the possibilities of other groups of end users.

The picture of approaches used in urban environment is not complete without citizens or local residents, who are supposed to participate in the innovation process through platforms. Platformisation is also a relatively new trend in the development of the infrastructure and the city as a whole. Since all the advantages of smart cities with new technologies, devices and approaches to solving problems arising in cities are associated with people living in them, with their awareness and willingness to promote city development, efficiency and care for the environment, special attention should be paid to creating the opportunity for citizens to directly participate in the life of the city, managing its processes and actively influencing all structures. The studies [64], [67], [68] raise problems related to the effectiveness of the development of any city through the creation of a common infrastructure through open data in the form of a platform where multiple sources of information from all over the city, its most important functions and objects are collected. This approach to the development of the city, based on the human resource, raising the awareness of citizens, the perspective of transforming consumers into prosumers, deserves close attention in the prospective and current trends in energy, transport, ICT and other areas.

The Frugal Social Smart City concept [62], [63] has been designed to reduce the level of energy poverty, and, despite the financial availability, it relies more on the social contacts of people, to a certain extent rejecting the introduction of new technologies.

Platformisation means the unification of disparate sources of information, for example, in the case of energy, the production, distribution and sale of electricity and heat, the supply of gas, hot water, the weather forecast, the price of energy services offered by various sellers, the forecast of the cost of electricity on the exchange, the data concerning customers' consumption of electricity, and much more, gathered under one umbrella — on the basis of a common platform, where data from each information source are collected and constantly updated, e.g. [67] (Estonia), [68] (Denmark), [69] (Norway), [70] (Austria). Unlike solutions based on the introduction of more and more advanced technologies to enhance the city's intelligence, the publication [64] proposes a way to achieve an intelligent and sustainable city by combining existing infrastructure, i.e. open government data and data from large energy companies and sensory networks deployed in cities, by providing a mechanism for sharing the heterogeneous data sources offered by the city, which reduces the complexity of access to city data while bringing citizens closer to the role of prosumers and allowing for integration of data into the city's ecosystem. Platformisation is an excellent supportive technology to increase the influence of end consumers in the energy life of the city; however, it cannot serve as an independent issue for development, but only in combination with other approaches in urban environment.

Open data allows expanding the management and development of smart cities, including, among others, the possibilities of navigating open data sources, transparency and accountability, performance management, transportation and infrastructure, resilient city planning, IoT of smart cities, civic engagement, etc. The combination of platformisation with a citizen-centric approach [76]–[79], where the end consumers, recognised as one of the main participants in the energy market, can bring significant changes to the energy structure, bringing flexibility, multivariance in VRES consumption and transparency, which in turn will increase the activity of consumers/prosumers, decentralisation and an increase in efficiency. To be effective, cities must not only provide advanced services, but also ensure that they are used by consumers who have the opportunity to choose and manage the way they consume or produce, consumers who are participants in the process of the introduction of certain technologies and innovations and understand their essence and benefits [65], [75], [80]. It should be added that the opportunities provided to citizens in the form of a unified data platform do not explore their desire and willingness to actively participate and use these progressive technologies.

According to the above considerations, there are many approaches to consider cities as smart urban energy environment development, which have been classified above.

Systematisation and evaluation of criteria

To promote an understanding of the strengths and weaknesses of the approaches, a variety of criteria has been proposed in this Thesis that allows for a comprehensive assessment of each of the approaches. An evaluation is provided to 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 different models of smart city development according to the criteria selected

Evaluation criteria	***Model***								
	Single sector optimization	***New city planning***	***Smart energy city (SEC)***	***Energy hubs, multi-energy systems***	***Smart city infrastructure architecture model (SCIAM)***	***Blockchains***	***Platformization***	***Frugal Social Smart City***	***Citizen-centric***
Flexible response to changing needs	possible	pronounced	possible	pronounced	possible	pronounced	pronounced	possible	pronounced
Transparency	possible	possible	possible	possible	possible	possible	pronounced	possible	pronounced
Economic affordability of the model for implementation	pronounced	unexpressed	possible	possible	possible	possible	pronounced	pronounced	possible
Attraction of citizens in active participation in city's life	possible	possible	possible	possible	possible	pronounced	pronounced	pronounced	pronounced
Unification and standardization is available	pronounced	possible	possible	possible	possible	unexpressed	possible	possible	possible
Application of information and communication technologies	pronounced	pronounced	pronounced	pronounced	pronounced	pronounced	pronounced	possible	pronounced
Top-bottom approach	pronounced	pronounced	pronounced	pronounced	pronounced	possible	pronounced	possible	possible
Bottom-top approach	unexpressed	unexpressed	unexpressed	unexpressed	unexpressed	pronounced	unexpressed	possible	possible
Opportunities for further development after the implementation of the model	possible	pronounced	possible	pronounced	possible	possible	pronounced	possible	possible
Environmental-frendly	possible	pronounced	possible	possible	possible	possible	pronounced	possible	possible

Legend: pronounced criterion; is possible (average value); unexpressed criterion

Flexibility as one of the main parameters that meets the modern requirements of a city, according to the literature review provided in Table I, manifests itself heterogeneously in the selected approaches, prevailing as much as possible in new city planning, energy hubs, blockchains, platformisation and a citizen-centric smart urban approach. A vast majority of sources indicate the presence of flexibility in the mentioned approaches, while in the description of single-sector optimisation, smart energy city and SCIAM, the flexibility in responding to changes in needs is mentioned to a lesser extent, although it is present in these tools.

Transparency, as a tool of data openness, accessibility and data-based operations, is part of a city system and is presented moderately among the selected sources. Platformisation-based and citizen-centric approaches differ in the role of transparency that is put at the forefront, being one of the cornerstones of these methods.

The economic affordability of the selected model ranges from low (with significant financial investments requiring a long payback time) in new city planning to high (requiring relatively low costs) at a separately selected optimisation point, as well as in platformisation and the frugal social smart city, which originally incorporated the idea of low financial investments.

Attracting end users to active participation is becoming an increasingly valuable and necessary resource for the effective operation of a smart city. Many authors of publications point out the need for the active participation of citizens in urban management, and the headings occupying the last four columns in Table II gained the maximum number of references about the possibility and desirability of the participation of citizens in the formation of the urban environment.

Accessibility of standardisation and unification has been mentioned in the literature as a significant and necessary criterion for the quality and sustainable development of the city.

The use of ICT has firmly entered the concept of urban environment development, and without it, the progress of a city is impossible. In most models, the readiness and necessity of transformations is noted taking into account innovative information technologies used by all city stakeholders. Only the frugal social smart city model, due to its specificity and its initially set goal, focuses to a great extent on the human resources and to a lesser extent on computerisation and technology, which can mentioned rather as a shortcoming in the modern conditions of urban development.

The top-bottom and bottom-top criteria in the context of the approach to solving smart city issues can be considered in relation to the specific tasks set for the city, and can serve as an additional support for clarifying the choice of the model. To a great extent, it depends on the institution initiating the transformation in the city: utilities, government, municipalities, electricity generation or distribution companies, energy efficiency projects and initiatives, etc. Consideration of these criteria also becomes important when applying some innovative technologies (e.g., blockchain, which involves the foundations of interaction based on partnership, an equal contribution of the resources of the participants of the chain to the process).

To coordinate urban changes with the requirements of the EU, UN and others, for example, on energy efficiency or reducing GHG emissions in the atmosphere, many issues highlight an environment-friendly criterion. Its application will allow the city to successfully claim for high positions in the ranking of smart cities in the future. To evaluate the approach from the perspective of further development, it is worth taking into account the criterion "Opportunities for further development after the implementation of the model" (e.g. when planning a smart city, prospects for development are already considered in advance, as well as opportunities are envisaged for embedding the latest technologies that may appear after the implementation of the project of the new smart city).

A general analysis of the evaluation criteria of the approaches demonstrates that platformisation has a strong position in the majority of criteria, which means that this approach can be highly recommended for the implementation of almost any activity within the framework of the development of a smart city. Platformisation will allow naturally integrating the additional data, as well as the requirements for new methods of processing and presenting information into the existing structure.

The blockchain approach also confidently leads in the number of functions shown, being a progressive and promising factor in the successful development of the city, where standardisation and unification will follow the technology as it develops. Economic affordability (availability of the necessary financial resources) of the model for implementation certainly does not come last in the list of criteria; without this, it is impossible to reasonably and responsibly plan changes in the urban infrastructure. Although the planning of a new city (or district) with the latest technologies and opportunities for environment-friendly and active participation of residents is very attractive, the economic factor is the strongest negative factor against the wide implementation of this approach. In contrast, single-sector optimisation, platformisation and the frugal social smart city are examples of cost-effective spending, which are suitable for almost all cities, irrespective of the initial conditions and the amount of resources.

Some of the approaches to city development considered above pay more attention to end users and their contribution to the overall energy consumption and the climate goals. Blockchain and platformisation, combined with the city-centric approach, are key positions in the city energy system transformation, however, they cannot be used by themselves to fully influence the efficiency, flexibility and sustainability of energy production/consumption by end users and can only strengthen the overall model.

Much more individualisation of end users, considering their needs, capabilities, energy consumption habits, beliefs and their willingness to interact with new technologies is needed, as well as grouping them for further research, in order to find an approach to each group and then combine these into a common approach to the development of a smart city. Currently untapped opportunities must be found to reduce energy consumption, increase flexibility and efficiency in various consumer groups, producing the overall effect of decarbonisation for the country and the community as a whole.

3.3. Decision-making algorithm development

Coordination of interests of all the stakeholders of the city will contribute to the concretisation of the necessary requirements, constraints and confidence that all opinions are considered to the maximum extent in an integrated approach. By city stakeholders in the case of this Thesis, the author means energy generation, transmission and distribution companies, energy utility services, citizens (household members, who use and/or produce energy resources and behave in their own way), government, policymakers, administrations, funds, businesses, experts, energy communities, researchers, and other energy end-users.

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. 3.3).

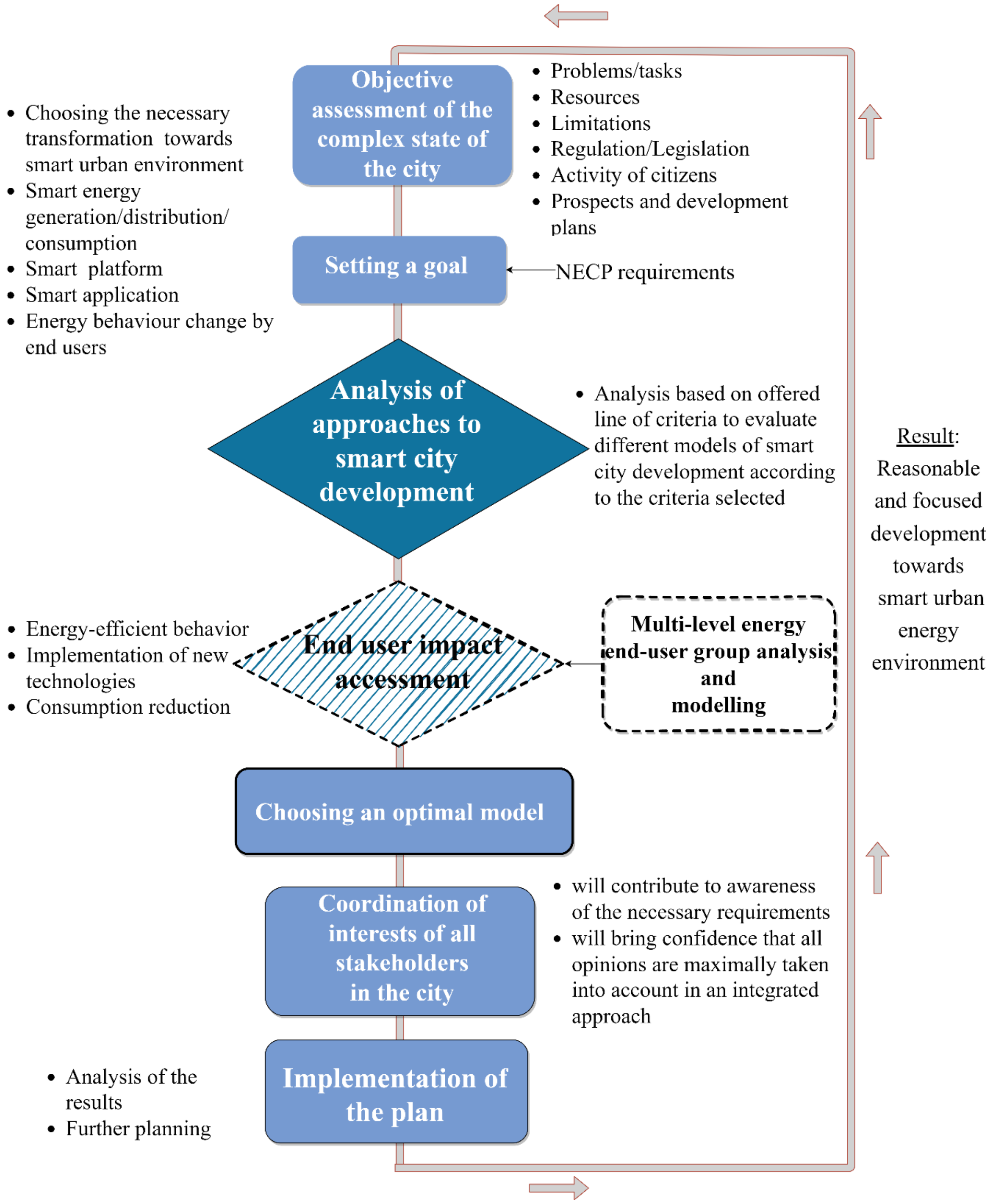


Fig. 3.3. Decision-making algorithm for choosing the development methodology in a smart city.

Based on the analysis of evaluation criteria of approaches to the development of a smart city (see Table 3.2) and the decision-making algorithm developed (see Fig. 3.3), the author of the Thesis concludes that the block-integrated approach, combining platformisation, blockchain, specific local approach (energy, transport, healthcare, economics, etc.) with end users centric focus can have the greatest potential for flexible, sustainable and stable development and will enable the greatest possible quantum leap towards the development of an urban environment (see Fig. 3.4).

Such a development method presupposes the necessary transformation of the energy sector (using specific knowledge gained, indices and standards, inviting high-level professionals), enables accessibility, convenience and transparency for the data approach through an open platform, and allows implementing plans with the help of modern reliable and fast blockchain technology as an effective platform for transactions within the network combining equal partners. The citizen-centric approach contributes with acceptance of technologies used for fast and feasible transformation. Successful experience of introducing the blockchain technology into the energy sector can be illustrated by initiatives in Chile on governmental level [81], as well as in France, Italy, Germany, Japan and other countries where large energy companies or government organisations are already transferring energy data to the blockchain, and are interested in developing this concept from the level of an idea to the practical result, sharing the view of many world-class experts which has it that blockchain is the advanced technology of the past decade and can become part of everyday life in the next few years. Potential options for using blockchain in the energy sector, supported by the citizen-centric idea, include not only the possibility of improving security, but also the use of peer-to-peer (P2P) distribution networks, customer billing (tracking of paid work and costs, billing and payment control) and the use of renewable energy certificates.

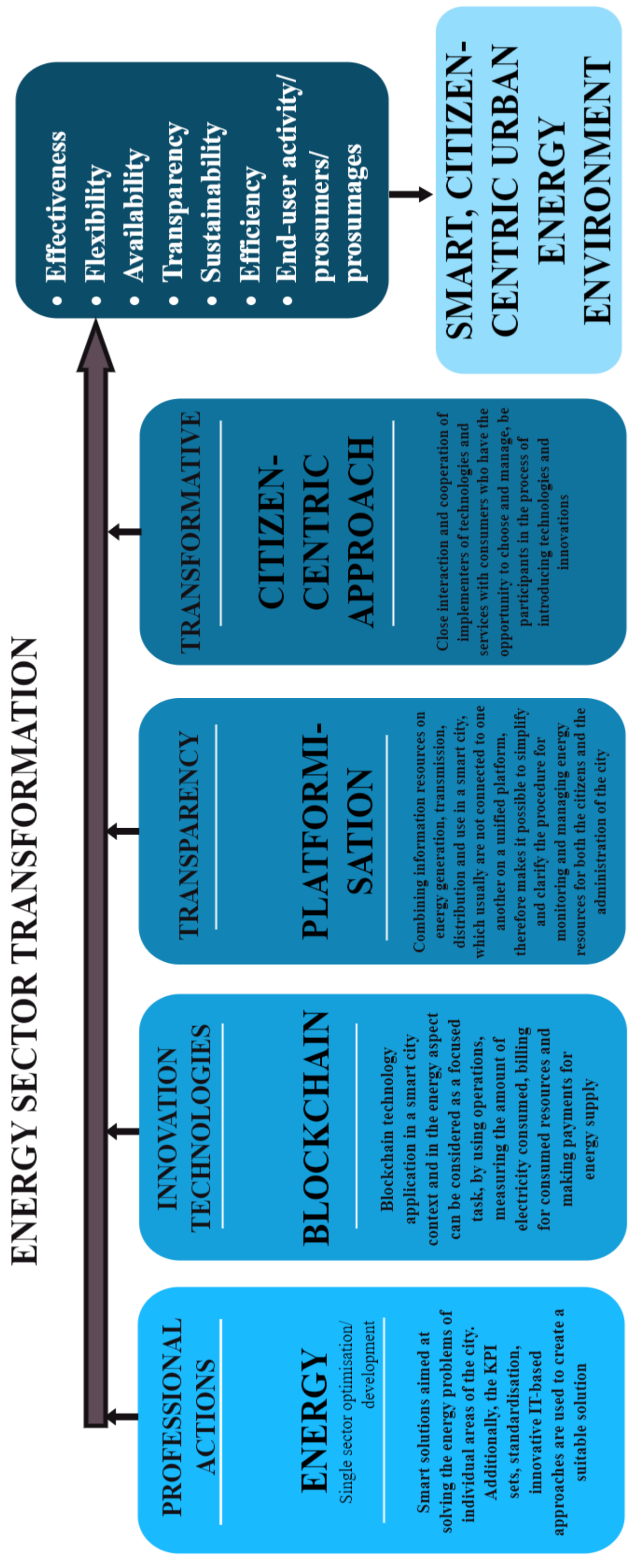


Fig. 3.4. Block-integrated approach to the development methodology of a smart, citizen-centric urban environment.

However, it should be noted that the weakest link of this algorithm at the moment is close interaction with end users, the comprehensive assessment of their contribution to the energy transformation process within the country or region. Despite the increasing attention paid to this issue in the last couple of years, awareness of the relevance and coverage of the problem in the scientific community and the applied policy of development and planning is still weak. In the energy sector, there has been activity by separate companies to collect data for their own marketing needs to identify consumer preferences; also, there have been an increasing number of webinars and advertising activities from government administration to motivate consumers to become prosumers and use the capabilities of end consumers to produce and consume their own energy. However, assessment of the impact of various groups of society on consumption habits and energy microgeneration, finding gaps in searching opportunities for energy efficiency increase by end consumers, assessment and modelling of their contribution to the achievement of common goals remains minimal.

3.4. Chapter conclusions

Small and large cities collect a huge amount of information about what is happening to them. Much of this information has been collected over the years, and some of it is available for public review. Nevertheless, to work effectively, we need more than some separate resources that we can find on the Internet, for a fee or free of charge to get acquainted with certain information, for example, on energy consumption, or the possibility of using different tariff plans for electricity consumption, etc. By unlocking data and making them open with the help of a common data platform, as well as by modelling the impact of energy consumer groups, we can achieve much greater efficiency in managing resources, changing citizens' energy behaviour towards near-zero carbon emission level, and ultimately accelerating the development of each city and region towards sustainability and intelligence.

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 will 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 account 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

4.1. Motivation for the research

The need for an innovative approach, structuring and new management of the processes taking place in the urbanised society is quite natural; it follows from continuous changes occurring in the society. Electrical power engineering as one of the base branches of development of any country constantly requires a new view of the processes taking place in it. Reduction of CO_2 emissions, integration of VRES with the entire flow of produced energy, optimal distribution of resources, saving resources such as electricity and heat as well as introduction of new technologies enabling transition to a qualitatively new level of development, exemplify only part of the tasks citizens and city administration are facing. This primarily applies to smart cities because it is the cities that have the highest development rates; so, problem solving tools and techniques have to be diverse, effective and validated.

The question then arises: what is one of the major factors that affects and enables launching successful implementation of the aforementioned tasks? More and more often, an expert opinion [82], [83], [84], [85] can be heard that the motivation of citizens is a crucial factor to the success of introducing new technologies and achieving national energy goals. Regular habits, ingrained and “safe” behaviour do not correspond to a dynamic development environment any more. However, many progressive ideas remain neglected and new technologies are carving their way with great difficulty. Furthermore, efforts aimed at promoting energy saving technologies meet with citizens’ indifference and mistrust. Therefore, it is important to find out what motivation techniques would be necessary and sufficient to change the situation. Another significant issue is discovering whether such techniques would be common for different countries and regions and whether it would be possible to apply the same techniques to improve the situation. The author has also studied the factors on which end user energy behaviour depends and how to make the citizens more active, open to innovations in the field of energy, and ready to be not only consumers but also producers as well as participate in the life of their city fully.

What kind of specific conditions for developing smart cities will make it possible to the citizens to become more active and aware of energy efficiency, and be more inclined towards energy saving and towards introducing new progressive technologies? Do they differ from country to country? Can the experience be easily replicated? To answer these questions, a comparison of the experience of different countries within the international project ITCity (“An ICT platform for Sustainable Energy ecosystem in Smart Cities”), conducted in 2017–2019, under the ERANet-LAC 2nd Joint Call on Research and Innovation for Latin America, Caribbean and European Union Countries was performed by the author; the cities of Riga (Latvia), Bucharest (Romania), Concepcion (Chile) and Sao Paulo (Brazil) were taken as examples. Conditions of legislation development in the field of energy, as well as the current situation in each country were analysed and discussed within the project. A survey was conducted and factors were analyzed that affected the making of decisions by citizens in Europe and Latin America (LA) as to embracing or declining innovative suggestions in the field of energy efficiency.

4.2. Introduction of smart technologies in smart cities

A successful model of a smart energy city can be based on the balanced long-term strategy of electric engineering development or an activity plan aimed at stable electric engineering for a smart city, which also is, in essence, the starting point for future initiatives as an integrated tool for infrastructure development. Actually, the way to a smart city starts with a clear plan that includes ambitious goals, a concept of the necessary legislative amendments and, of course, indicators for measuring progress [86], [87].

Modern programmes and plans of development and implementation of solutions for a smart city are focused primarily on the interests and needs of end users. Substantial attention should be paid to decisions that have an impact on the daily life of users and allow people to determine for themselves whether they want to use them.

According to a wide-ranging study of McKinsey Global Institute (MGI) [88], which was carried out on examples of cities of three types, differing both in the design of existing infrastructure systems and the initial level of development, about sixty modern solutions for a smart city and how they affect various aspects of the quality of life were analysed. The use of these new tools provides a number of positive results: in particular, they can reduce mortality by 8–10%, increase the efficiency of emergency response by 20–35%, reduce the average time spent at work and travelling to and from work by 15–20%, reduce incidence on road by 8–15%, and reduce greenhouse gas emissions by 10–15%.

MGI analysis of the development of 50 cities in different countries showed that in cities with a higher standard of living, transformations usually go faster, although the level of awareness among the population regarding smart solutions and their use is sometimes quite low. In the cities where there are many young people who are familiar with digital technology, transformations are proceeding much faster and easier. Cities vary greatly in the implementation of decision groups, the vector of transformations and the resources available, but all of them are paying a lot of attention to energy issues, transport systems, devices used in households, environmental issues and network security.

All of the above issues point to the need for changes in the implementation of smart technologies in smart cities, which will allow cities to develop according to their long-term plans and make the most of the available resources to become smart.

Within the framework of the International ITCity project, it was decided to conduct a study of the impact of energy policy development on energy end users in different cities, their attitude to new technologies and thus to assess their contribution to the development of a smart, carbon-neutral city.

Development of legislation

The development of the electricity market in Europe and LA countries has experienced significant changes over the years. Currently, while maintaining the tendency to increasing energy efficiency and introducing innovations in that field, to a greater or lesser extent in individual countries, this process is aimed at developing a stable model of generation, transmission and distribution of resources using up-to-date technologies and building interaction with the most important part of this process, customers who are consumers but can potentially become prosumers who both consume and produce electricity.

A. Development of European legislation in the field of electric power industry

Starting from 1998, Europe has been following a policy of shaping a competitive internal energy market for electricity and gas [89]. For that purpose, several directives have been issued, each of which has been reflected in the legislation of certain EU countries. The last legislative initiative was the European Union's Third Energy Package [90]. One of the goals of the Third Energy Package is to strengthen consumer protection mechanisms including the right to change their gas or electricity supplier without any additional charge at three weeks' notice.

In November 2016, The European Commission presented a package of documents entitled "Clean Energy for All Europeans"- Winter package [15]. The package foresees further measures aimed at the EU's transition to clean energy. The documents laid down consumer right and necessity to be active and central players on the energy markets of the future, to have a better choice of energy supply, access to reliable energy tools for energy price comparison, as well as to have a possibility of producing and selling their own electricity. In addition, the Commission set a task that by 2020 at least 80% of consumers have to be equipped with smart meters.

Major difficulties that the reform of the electric power industry in Europe faced were the shortage and non-optimal allocation of network infrastructure, the national but not transnational character of energy generation, information asymmetry regarding actual indices of electric power systems, the lack of transparency in trading electricity as well as several tasks related to the need to introduce a wide-scale training of consumers aimed at mastering new approaches and technologies in the field.

B. Development of energy legislation in Latin American countries

Brazil

In 1995, Brazil commenced liberalisation of the branch and separation of the energy generation, transmission and distribution activities [89]. To supervise the functioning of the new system, ANEEL (Agência Nacional de Energia Elétrica) was established (Law No. 9427/1996), as well as a system operator (ONS) and a wholesale energy market (Law No. 9648/1998), which started operating in 2001 after the corresponding standards and functioning rules had been defined. Currently, there are two environments in Brazil for making contracts for purchase/sale of electricity: *Ambiente de Contratação Regulado* (ACR) — for making regulated contracts (for one year ahead, for three and five years ahead) at the prices set by ANEEL, and *Ambiente de Contratação Livre* (ACL) for making unregulated contracts for end users whose consumption exceeds 500 kW.

In Brazil, the electricity tariffs for customers are usually different depending on the utility, government taxes, level of demand, client income, type of customer (rural, public service, residential, commercial), and time of day (usually, three classes). The tariffs cover the costs involved in the generation, transmission and distribution of electricity, in addition to the sector charges. In 2015, energy bills brought a novelty: the Tariff Flag System, which has the following modalities: green, yellow and red (the colours of traffic lights) to indicate whether or not there will be an increase in the value of the energy to be passed on to the final consumer, depending on the conditions of electricity generation. The modalities have the following characteristics: - Green flag: favourable conditions of power generation. The tariff does not suffer any increase; - Yellow flag: less favourable generation conditions. The tariff is increased by R $ 0.010 for each kilowatt-hour consumed; - Red flag - Level 1: costlier generation conditions. The tariff is increased by R $ 0.030 for every kilowatt-hour consumed. - Red Flag - Level 2: even more costly conditions of generation. The tariff is increased by R $ 0.050 for every kilowatt-hour consumed. The Tariff Flag System will invoice all captive consumers of distributors with the exception of those supplied by isolated systems.

Chile

In Chile, there is a regulatory framework in terms of infrastructure for both the transmission and distribution systems. In both cases, the aim is to provide security to people and facilities, and minimise energy prices. The new distribution law (currently under discussion) obliges energy distribution companies to incorporate technologies in their areas in order to optimise the continuity of the electricity supply, facilitating the integration of smart meters into the network.

The electricity market in Chile has been open since 1982. Chile was the first country in the world to open the electricity market. In electricity, there is a competitive open market, with well-established regulations for generation, transmission and distribution. Contracts offered to regulated clients last one year. In Chile, there are twenty-five contract options for regulated customers; therefore, it is very important to know the load profile in order to select the best contract alternative and obtain savings in billing. On their part, free customers have an option to directly negotiate contracts with an energy supplier. You can negotiate technical conditions (security, continuity of supply, etc.), economic conditions (variable, fixed prices, etc.) and duration (typically four years).

Differing tendencies and rates of development of the electric power industry in the considered countries of Europe and Latin America as well as legislation details in the field, as we'll see later, affect both the current state of things in the field of generation, transmission and distribution of resources and the peculiarities of consumer perception and habits regarding management and control of energy resources.

State programs oriented towards the development of citizens' energy behavior change

Chile is one of the leaders of Latin America in promoting the principles of smart energy. Thus, for example, the government is carrying out a wide-ranging strategic programme of participation and dialogue with citizens within the fundamental plan "Energy Route 2018–2022: Leading the modernization with citizen seal" [91]. This initiative is intended to best solve the tasks Chile is facing in the field of energy so as to achieve a stable level of development for all Chileans [92]. It helps to focus attention on the improvement of the quality of people's life, create networks for working with participants from the sector, region or society, and reach the maximum possible consensus among administration and the citizens of the country. In the Citizen Attention Portal, citizens can enter queries, suggestions, complaints or congratulations, as well as access applications online and follow up on the processes of the different programmes and initiatives of the Ministry. Furthermore, the development of the electric power industry in Chile actively incorporates multiple innovative techniques; among them, the blockchain technology can be mentioned.

When forming its energy policy, **Latvia** pays great attention to this sector in the development of the country as a whole. The emphasis is placed on the introduction of energy-efficient and innovative technologies, integration of renewable energy sources into the entire power generation and distribution network, as well as modernisation of heat and electricity generating equipment, renovation of buildings, development of transport, etc. At the same time, at the state level, there is a lack of implementation of programs in the field of energy, focused on large-scale education of the population and obtaining effective feedback. The only exceptions in the last couple of years have been European packages of programmes with partial financing for the renovation of houses and the purchase of electric cars. Private initiatives cover local interests of certain producers of innovative products in the field. Besides, large-scale studies of citizens' motivation (or the lack of it) to use energy efficiently and to make use of the proposed technologies and options, e.g. dynamics tariffs for electricity, have not been conducted. Furthermore, the reasons of the conservative attitude of the citizens to energy saving techniques for managing the consumption of their energy resources have not been analysed yet.

A similar situation is observed in **Romania**. The European Parliament and Council Directive on energy efficiency has been transposed into the national legislation on energy efficiency; a National Action Plan on energy efficiency has been created. Still, these initiatives contain measures for the big sectors (e.g., Energy Efficiency in Buildings, Industry, Transport, Heating and Cooling Services, etc.). After the measurements are implemented by the big sectors, the legislation requires that all the utilities (gas, water and electricity) should inform the consumers about the measures that could lead to energy savings. However, for now, there are no special state programs for citizen education as regards energy saving, only local initiatives.

4.3. Smart technologies vs awareness of end users

Many studies on the subject of smart cities are primarily devoted to technological aspects [93]–[95]. Indeed, the investment and efforts of urban administrations remain important factors in the successful implementation of technologies, but many of these technologies have only an indirect, and sometimes invisible, impact on the lives and behaviour of citizens. For example, an ordinary city dweller often does not notice any influence of smart grids or video surveillance systems on their life, since these technologies are used in processes that do not involve public participation. Recent studies [96] show that to know about new technologies does not necessarily mean to use them. This, however, does not diminish the importance of such solutions for a smart city since they allow all the concerned participants to be maximally involved in the management of energy resources through flexible and timely response to changes in the energy market. Direct and active participation of consumers in the process of energy consumption could benefit the field in terms of efficiency and flexibility.

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.

4.3.1. Smart City Survey

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 did they trust 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. The full Smart City Questionnaire created by the author can be seen in Annex 1. 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 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, yet 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", whereas respondents from Brazil and Latvia were more pragmatic, marking "vividly presented savings of energy and money" first

4.3.2. Results and discussions

The survey showed (see Fig. 4.1) 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 and Fig. 4.2). 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.

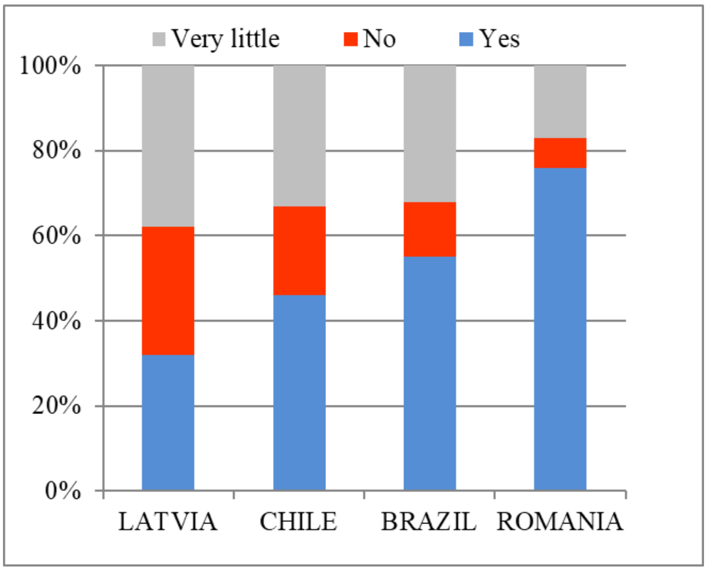


Fig. 4.1. Citizens' awareness about smart initiatives in their cities.

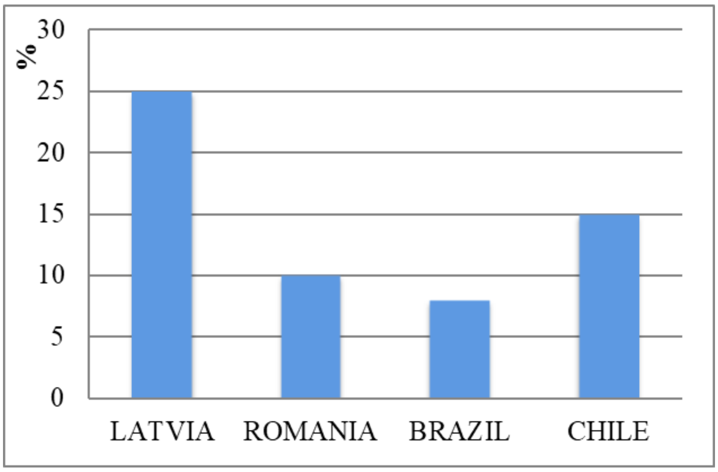


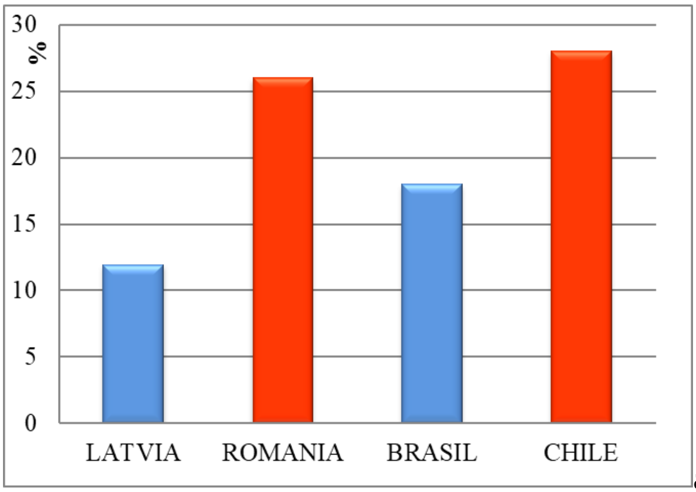
Fig. 4.2. Citizens' awareness about energy-saving options available in their country: the percentage of citizens who know nothing about the possibility of changing their energy consumption mode to a more efficient one.

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.

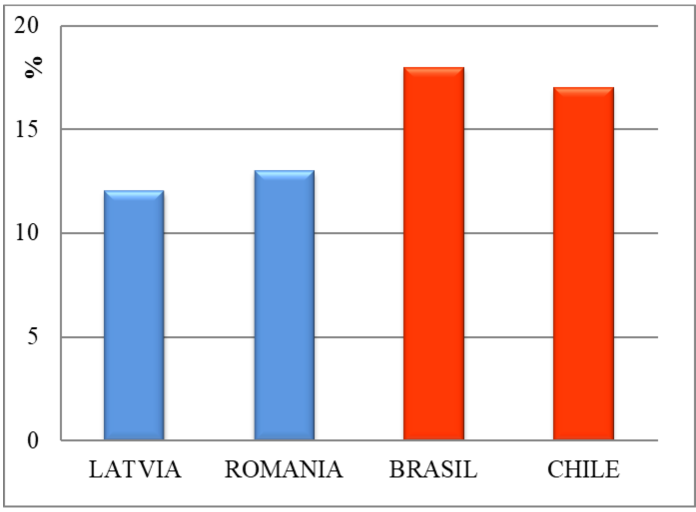
This does not necessarily imply that there is no or little information about such opportunities in Latvia. Rather, the reason is citizens' excessive conservatism and distrust, as well as the choice of appropriate communication channels through which information about energy-saving technologies will reach people and interest (motivate) them; here, the method of such information dissemination is of crucial importance.

As was pointed out before, 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 Figure 4.3 where Chileans have shown 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 their turn, in Latvia and Brazil citizens are more concerned about their electricity bills, and as a consequence, the possible ways to lower them.



a)



b)

Fig. 4.3. 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 account.

Besides the above, the motivation of consumers to change their behaviour concerning energy saving is highly influenced by the terms used, e.g., “saving money,” “better pricing options,” “dependable service” and “energy efficiency” make a positive impact on consumers during their decision making, whereas other terms like “informed”,” “choice,” “control”, “flexibility” do not cause any interest [97]. This kind of research has to be conducted in every country based on preliminary studies already completed and the experience of other countries. This kind of research would provide a more precise evaluation of the state-of-the-art situation and thus will provide most suitable schemes of involving and training end consumers.

4.4. Energy saving principles in Latvia

4.4.1. Current state

To understand more deeply the current situation of the end users behaviour of Latvian citizens in the field of state-of-the-art energy-saving technologies, the Smart Energy Survey was analysed in detail to reveal the attitude of the residents of Latvia to new technologies and their readiness to follow the development trends of a smart city. Based on the results, an analysis can be conducted and recommendations for improving the efficiency of introducing new energy-saving and energy-efficient technologies into every household can be presented in order to create the most favourable conditions for the implementation of long-term plans for the development of smart cities in Latvia.

According to the data of the Central Statistical Bureau (CSB) of Latvia [7], [98] (see Fig. 4.4), electric energy consumption in households (in percentage) increases every year.

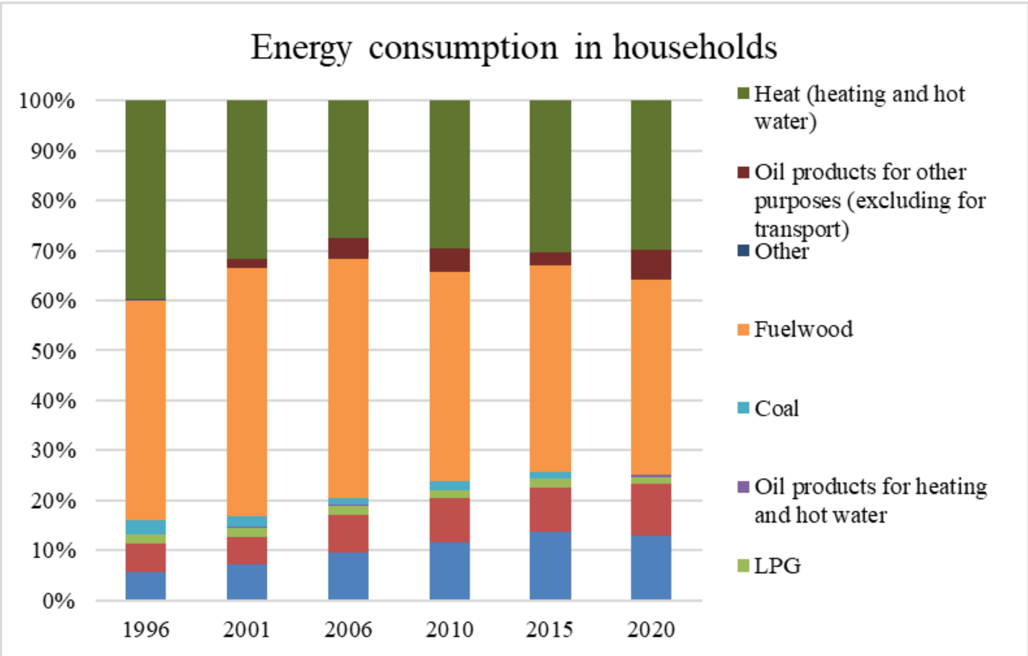


Fig. 4.4. Changes in the structure of energy consumption in households in Latvia, by CSB [98].

In 2020, energy consumption in households constituted 13 % of total energy consumption, excluding transport, while total household expenditure on energy consumed (see Fig. 4.5) was 40 % of the cost of total energy consumed in households. Since 1996, the average price of electricity for households has multiplied and is continuing to grow.

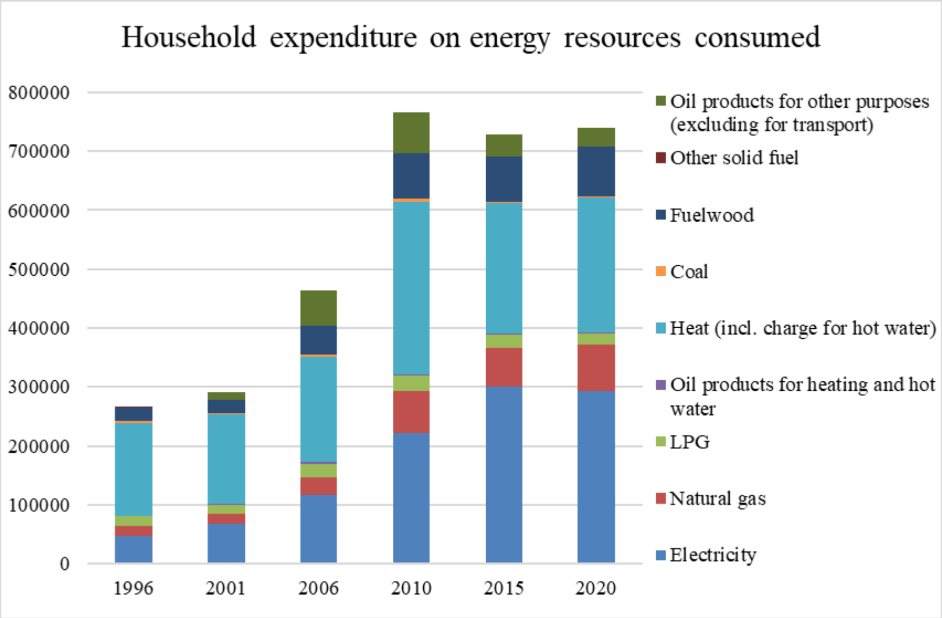


Fig. 4.5. Total household expenditure on energy consumed (in thousands of euros), by CSB [98].

While the total indicator of the final consumption of energy in Latvia has a tendency to decrease, energy consumption in households grows every year. In 2020, it constituted 28 % of the final energy consumption in Latvia.

According to CSB data, the average consumption of electricity per household has not changed much: the figure was 2008 kWh/year in 2010, 2185 kWh/year in 2015 and 2098 kWh/year in 2020, which can serve as an indicator that under the continued growth of electric appliances and equipment that consume energy in households, efficient energy use is an important and necessary condition for the inhabitants of Latvia.

Consumers can sufficiently contribute to achieving flexibility in energy systems by changing the amount and way of energy consumption, which can promote growth of stability of the whole energy system and bring about a decrease of the system load in peak hours [99]. For that purpose, understanding and use of the technologies available in the market is crucially important, as well as understanding of one's contribution to promoting the growth of the share of renewables and ensuring a more flexible energy system. According to the market research conducted by *Lattelecom* [100], 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 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 [101], 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.

The problem is compounded by the fact that a huge number of new technologies are entering the market, including on-line programs to control the power consumption rate and load, new equipment and information systems, web portals, calculators and software for comparing and controlling energy consumption. All of the above requires customer attention, willingness to study and master new technologies, and readiness to use them to control their own resources. 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.

As experience shows, the most frequent and informative communication with customers takes place either personally or by phone or, most frequently, in electronic form using automatic messages and replies, as well as using the internet, web tools, social networks, TV and other tools used for advertising. Often, several communication methods are required to establish successful interaction. Teaching and incorporating new clients have to be performed on a regular basis. The author has studied issues of the Latvian population's flexibility and adaptivity to initiatives of energy-efficient use of resources, and has also examined the causes and ways to influence awareness and acceptance of new initiatives by the end users.

4.4.2. Analysis of the needs and awareness of electricity customers in Latvia

To clarify the picture of the attitude and awareness of the inhabitants of Latvia in the field of the innovations and possibilities of a smart city, as well as to study the existing beliefs and habits in the sphere of energy resource management that promote or impede the use of new intelligent potentialities of a smart city, the above-mentioned survey was used. The survey included topics such as sufficiency of information on the specified subject, confidence in the information gained from different sources, issues of personal values and priorities, issues of finance as a motivator, as well as studying what else can serve as a motivator for changes, and the presence of possible limitations on changing the behaviour to an environment-friendly, stable and energy-saving one.

In the course of the survey, the following trends have been discovered that are fundamental for understanding customer response to possible changes:

• A third of the respondents in Latvia have no idea about the notion of a smart city and have never heard about the initiatives aimed at supporting a smart city (Fig. 4.6, (a));

• More than half of respondents have admitted that they have no idea about any projects oriented towards "smart" energy resource consumption in their city (Fig. 4.6, (b)).

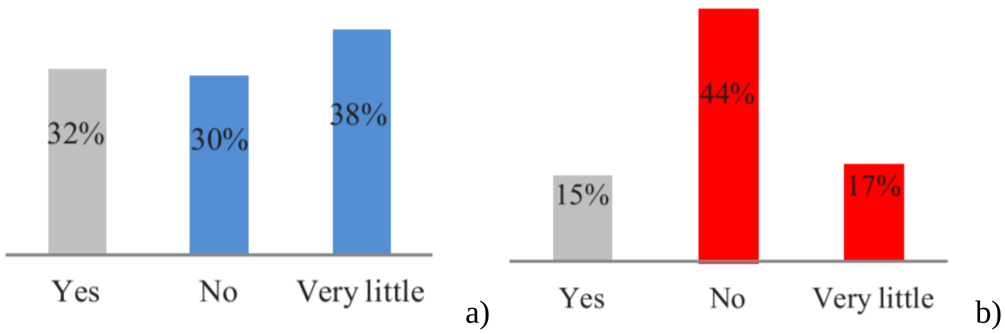


Fig. 4.6. Answers to questions about a smart city: (a) “Do you have an idea about the notion of a smart city?” (b) “Do you have heard about the initiatives aimed at supporting a smart energy city?”.

The data obtained reflect an insufficient level of informedness on the part of the inhabitants of Latvia as regards initiatives implemented in the sphere of a smart city. This is the gap that should be filled first of all by solving the issue about information sources that the inhabitants of Latvia use and trust.

The above consideration is supplemented by the fact that 4/5 of the respondents have positively answered the question “Are you interested in saving energy?” This is a very good dynamic for promoting projects and initiatives aimed at raising the intellectuality of the Latvian cities and saving energy in case of delivery of appropriate materials and provision of information. Moreover, 80% of inhabitants consider it important to have up-to-date technologies at home, whereas 20% do not care about it.

To promote the training and informing of the end users about the latest achievements in the field of electric engineering and energy resource saving, we have first of all to find out what the current state of affairs is and what issues are important and necessary not only from the point of view of the government, administration and legislative references, but also from the point of view of ordinary people, each of which is an energy consumer. It is also essential to search out which topics motivate their willingness to accept the novelties and develop by following modern technologies and trends, and which ones cause non-acceptance, as well as to find out the reason for such behaviour. These circumstances could be different within different countries, and may even differ from city to city within a country. This is a detailed study of the circumstances that can promote further successful organisation and development of a city wishing to be “smart”.

Respondents were also asked a question: What is your attitude to energy-saving technologies? Their replies show the level of awareness existing in Latvia nowadays (see Fig. 4.7):

• The most numerous group of respondents (about 60 %) responded that they knew about energy-saving technologies and use them to a small extent;

• 2 0% of the respondents stated that they were aware of energy-saving technologies but did not use them. While 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.

• Only a very small group of people (about 3%) have responded that they neither know about such technologies nor wish to know about them. Actually, this can only demonstrate that a special approach is required to contact this kind of people and to awaken their interest in energy saving issues.

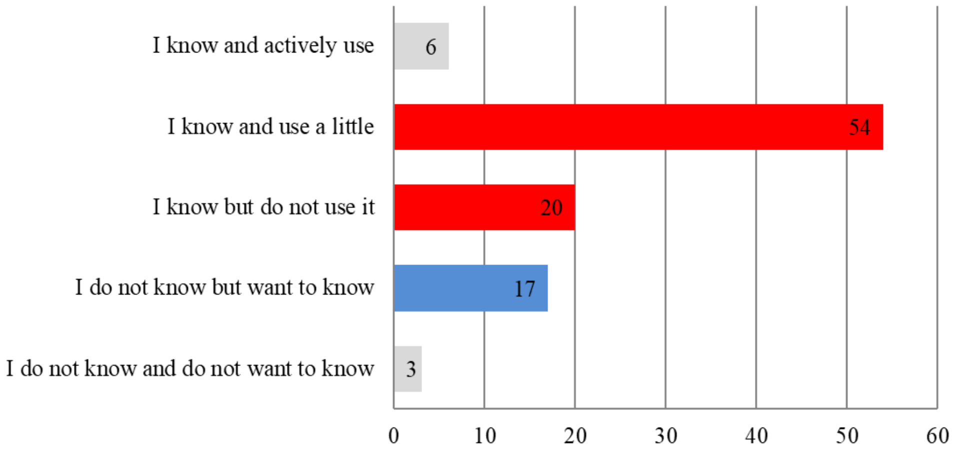


Fig. 4.7. Respondent attitude to energy saving technologies in Latvia.

In Fig. 4.7, two groups of people marked can be considered, correspondingly, those marked in red and blue. Respondents in the red group do know about new technologies but due to some reasons do not use them or use them very little. Therefore, simply by distributing information about new projects and innovations in the field of energy saving, it is impossible to solve the issue of informed use of the above technologies by inhabitants. Additional studies are required to more precisely define the reasons as well as the motivation that will work just in the specified group of people. Here, the research discussed in [99] should be mentioned whose authors have conducted considerable research aimed at clearing up what information sources customers trust, as well as what the form is in which information not only can be taken into consideration but also starts to be used in households.

On the other hand, respondents who belong to the “blue” group, i.e., those who wish to know but know nothing about smart energy and smart consumption, are, due to some reasons, uninformed about energy saving and introduction of new technologies despite all advertising handled and existing within the initiatives of a smart city. Most probably, this gives evidence that training information has to find new channels of reaching clients. Again, this is a topic of thorough study regarding such a group of customers; specifically, it is important to find out who belongs to the group, what the age-related characteristics are, what information sources they are accustomed to use and where they would be ready to obtain and take into consideration information, offers and initiatives on energy-saving technologies.

It should also be noted that despite the fact that an absolute majority of the respondents are interested in saving energy resources, their vision as to how to implement it differs: three-fourths of the inhabitants prefer to use at home a new energy saving technology that will itself care about smart consumption of resources after adjustment, whereas one-fourth of the inhabitants prefer manual everyday correction of equipment that consumes energy resources in order to diminish their consumption.

The topic of Latvian citizens' motivation to use energy-saving technologies (see Fig. 4.8) is quite interesting and important (the respondents could tick off several techniques that are close and motivating for them). The question: "What would make you to more frequently use energy saving technologies?" was answered as follows:

• 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, awareness that they will promote preservation of nature and earth resources for their offspring is important;

• 34 % of the respondents have chosen to mimic the example of their neighbours/friends/acquaintances;

• 32 % of inhabitants stand for public companies that would explain the advantages of new technologies;

• 13 % of respondents would be motivated by an example of state public figures.

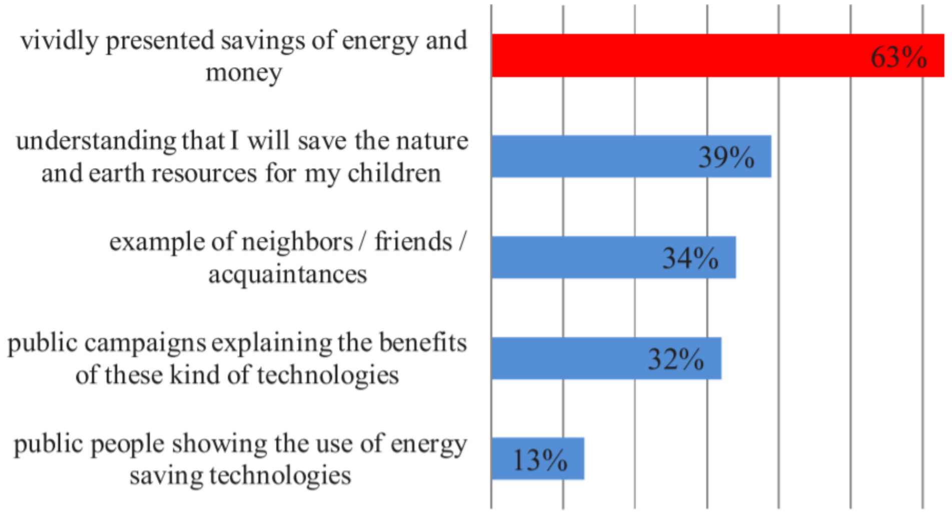


Fig. 4.8. Motivation to use energy-saving technologies.

All the aforementioned topics that motivate the inhabitants of Latvia to save resources as well as their distribution percentage deserve further attention and study with a view to organise effective introduction of new energy-saving technologies in our life. As pointed out in [102], a majority of approaches to reaching stable energetic behaviour consider people in the context of their wish to acquire and enlarge their wealth and property. Although the social context plays a great role in the way how people think and behave, they do not realise it frequently. We are members of different social groups and societies, which can affect our behaviour and persuasion in using innovative technologies and energy efficiency attitudes.

The financial issue definitely also contributes to the influence of the Latvian inhabitants' choice on the use of innovative energy-saving technologies (see Fig. 4.9):

• 46% of the respondents would be ready to use the new technologies provided they would pay off within 1–2 years;

• 39% would be ready to wait for a payback period of 3–4 years;

• 12% have made investments in new technologies or will be ready to do so if the payoff period is within 5–10 years.

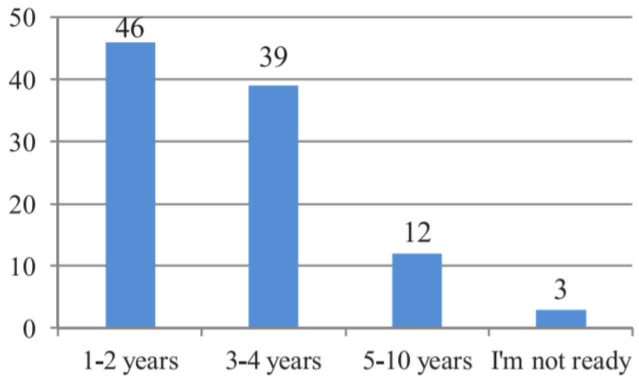


Fig. 4.9. Residents' readiness to pay for new technologies: "I am ready to use the new technology if it pays off".

Another vector of research has been directed towards finding out how much money a person is ready to pay for new technologies every month knowing that they help one save energy and lead to the enhancement of the ecological situation in the country. As a result, the following has been found (see Fig. 4.10):

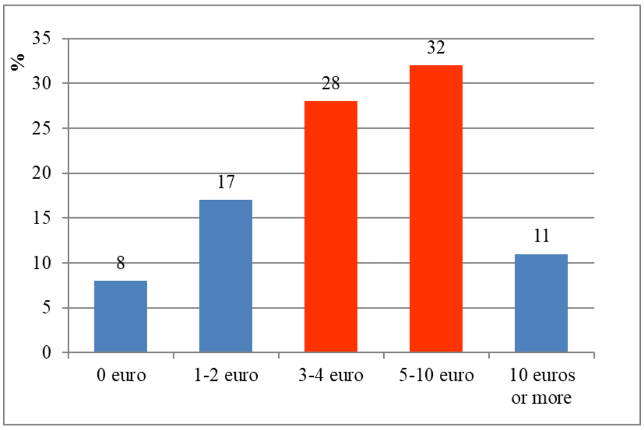


Fig. 4.10. The amount of money a person is ready to pay for new technologies every month. "How much money would you agree to pay monthly for new technologies in your home, knowing that they will help to save energy and improve the environment?"

• 17% are ready to pay € 1–2 per month;

• 28% – € 3–4 per month;

• 36% – € 5–10 per month;

• 11% – more than € 10 per month;

• 8% are not ready at all to invest money in new technologies.

In other words, it can be argued that 92% of people in Latvia are ready to pay for new technologies.

Basically, the inhabitants of Latvia are ready to invest in new technologies € 3 – € 10 monthly, provided they are sure that the investment would ensure savings of energy, and consequently, financial savings (48% of all the respondents).

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. 4.11).

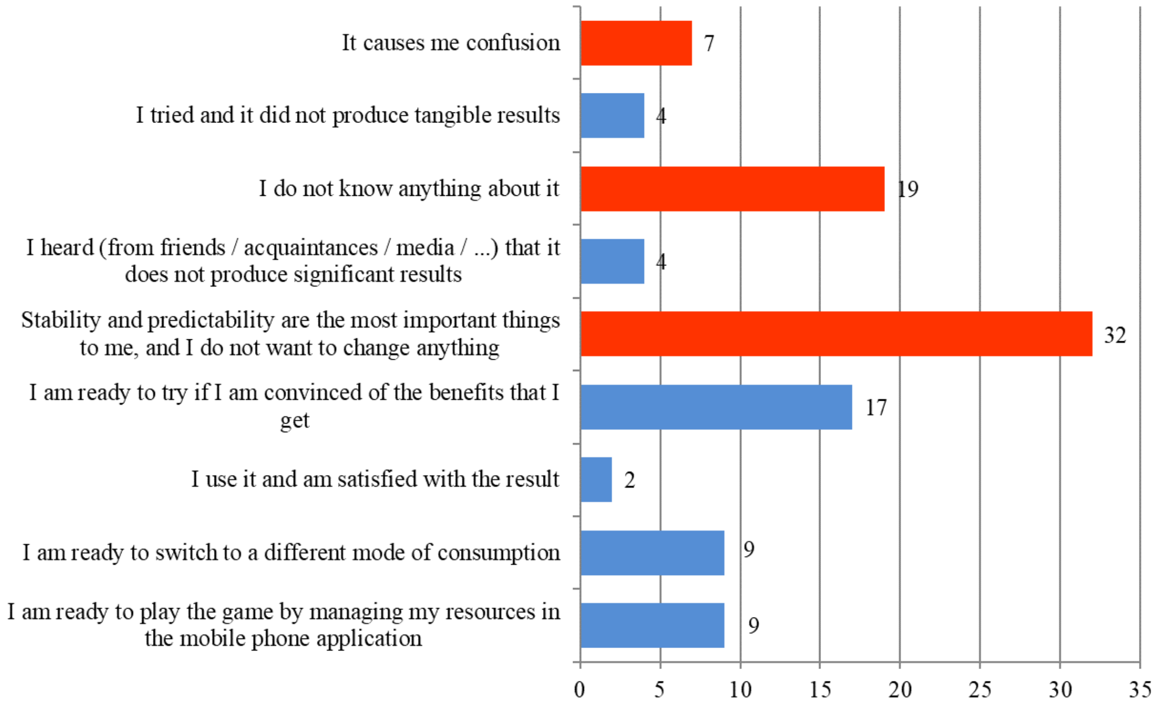


Fig. 4.11. Readiness to choose a different electricity consumption mode: "What do you think about choosing a different electricity consumption mode for saving resources and money?"

In the survey, respondents could point out several choices that were closest to their situation. The results of the survey are summarised below.

• For one-third of the respondents, stability and predictability are the key factors and they do not wish to change anything. This is a serious claim for long-term and gradual work with this kind of customers aimed at having an opportunity to change the habits of these people in the direction of new technologies and new possibilities. It is evident that the percentage of mature aged people in this group is high, and here, one effective way to convince somebody to try something new, bringing mutual benefit both to the customer and the trader as well as the ecology of the country in general, is through personal contact;

• 4% of the respondents have experienced a negative result in their attempt to switch to a new mode of electricity consumption;

• A large group of respondents (19 %) are not aware of the new potentialities in the sphere of energy resource management and saving;

• 17% are ready to try something new if they are convinced of the benefits to be gained from it;

• A relatively small percentage of respondents (9 %) are ready to take part in the modelling of their expenditures and energy consumption management through mobile game applications.

There was quite a large group of respondents who knew nothing about new possibilities in the field of energy management and saving or wished to change nothing or felt confused or uncertain (the group of replies marked in orange). Here, further research could be oriented towards finding the reasons for such unawareness and non-acceptance. One possible reason could be using insufficient information sources except for widely used types such as TV, radio and the internet. If this is the case, new information dissemination channels should be searched for, say, in public transport, at the cash desk in a shop, as advertisement in mobile games etc.

4.5. Chapter conclusions

The research conducted in 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 (by use, the author means at least one-time use of smart solutions).

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 then 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.

Effective interaction with customers is essential for electricity suppliers installing smart meters and systems; they are encouraged to use various modes of energy consumption, including real-time mode.

It is necessary to understand and use the intellectual technologies and opportunities offered in the market, together with the understanding of consumers' contribution to a more flexible energy system and the smart city as a whole.

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.

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. Plenty of useful, up to-date energy saving technologies and equipment could be available in the Latvian market, but the lack of interest and willingness to use them would reduce all the possible economic effects of such innovations.

Furthermore, in the modern world, multidisciplinary studies are becoming increasingly called for, ones that combine knowledge and competences from the spheres that are traditionally considered different. Electric engineering and smart consumption of energy resources, on the one hand, and awareness of end users and their active participation in consumption management, on the other hand, if combined together, would further promote the most rapid and confident progress in a stable development of a smart city in general and smart management of the resources of every inhabitant of the country or region. The issue of personal values and priorities of each end-consumer is one of the major issues in the successful strategy of city development, which contains possibilities and challenges to change habits and persuasions to more energy efficient, active and conscious ones.

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

5.1. Motivation for the research

The transition of energy system to a decarbonised , flexible and using various renewable energy resources requires a carefully selected modelling system that takes into account all the necessary features and specifics of the transition in the region. The modelling approaches [103]–[107] includes a wide range of parameters and can be categorised into the following main groups (see Fig. 5.1).

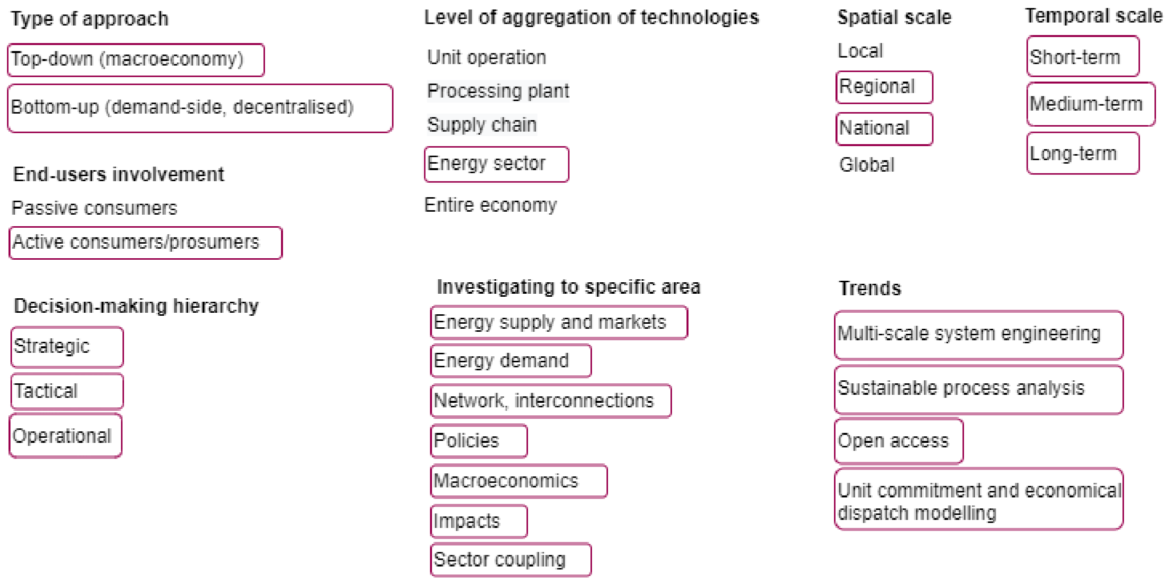


Fig. 5.1. Categorisation and trends of energy system modelling.

There is a basic division of energy models into top-down and bottom-up approaches. Bottom-up models, also referred to as the engineering approach, are based on the study of a detailed technological process and the operation of an energy system, using a demand-side management and decentralisation approach. Conversely, top-down energy models explore a macroeconomic approach and long-term processes, interconnections and trends of all the sectors of the economy, which cannot be predicted by bottom-up modelling. The level of aggregation of the model can change from the unit or plant operation, or exploration of the energy supply chain, to studying the energy sector or entire economy tasks. Energy models can also be categorised by the spatial and temporal scale: from local to global and from short-term (seconds and minutes) to long-term (years and decades). The important part of the model can be the role given to end users — whether they are modelled only as passive consumers of the energy, or as active contributors to the generation and consumption process. By the decision-making role the models can be categorised as strategic (e.g., for decision on the energy policy making level), operational (the optimisation of energy system operation) and tactical (modelling the right time and place for a determined activity). Finally, the area of investigation can differ according to the set goals and can include energy supply and markets, energy demand tasks, exploration of the interconnections between units or sectors, network optimisation, impacts of new technologies or policies, the issue of sector coupling and other issues.

Besides the above, the following current issues and trends are seen in state-of-the-art energy system modelling approaches. First of all, it is the necessity for multi-level system engineering, because the decarbonisation and the use of VRES necessitates optimisation of the energy system in various sectors and levels for flexible, safe and sustainable work. Analysis of sustainable process is a consequence of the above processes and requirements. Open access has become another necessity for a modelling approach, allowing data to be open and transparent for all stakeholders. The unit commitment provides the process of deciding at what time and which units should be started and stopped at each of the power plants, as well as whether economical dispatch involves the process of deciding on the output capacity of each of the scheduled generating units, at any point in time. Unit commitment and economical dispatch modelling is a very difficult complex optimisation problem due to the sheer number of possible combinations of generating units that are on and off in a power system at all times, reinforced by the process of replacing fossil fuels with various renewable energy sources.

For the modelling end-user impact on the overall energy system, it becomes clear that a modelling system has to include the aggregation of the modelling approaches from the various groups from mentioned above. It means that a multisectoral, flexible, multilevel approach needs to be chosen for the required task. The desired parameters for our modelling research in Fig. 5.1 have been framed.

Usually, to perform trustable, detailed, justified modelling, energy scenarios are used. Energy scenarios usually fulfil two basic needs: exploring the current situation in an energy system or its part; and planning/forecasting future technical and economic parameters, taking into account the uncertain forecasts, the requirements of legislative documents and the vision of the possible technical, economic and political development of the energy sector. The different scenarios can then be compared by using indicators suitable for the chosen purposes.

Modelling tools

From the most widely used models/modelling tools for system energy modelling, which can be suitable for the modelling of Baltic system end user detailed energy use, the MARKAL and TIMES family of models [108]–[110] can be mentioned first. They are an example of the bottom-up approach and are well suited for planning long-term development scenarios, having a high level of detail regarding technological aspects. However, these models do not provide open access; moreover, they have a rough temporal resolution, which does not allow considering in detail the optimisation of the necessary technological changes. MESSAGE (a modelling framework designed for medium- and long-term energy system planning, energy policy analysis and scenario development) [111] is another power system modelling tool with possibilities for annual, weekly or hourly scheduling for long-term planning. MESSAGE-Access is an offshoot of MESSAGE and is suited for residential energy modelling. This family of approaches makes the model very adaptive yet not flexible enough to assess the dynamics of renewable resource fluctuations. Open-source energy planning tool OSeMOSYS [112] copes with this task, however, it does not provide for the possibility of solving the unit commitment task. HOMER (Hybrid Optimization of Multiple Energy Resources) [113] is a micro-power optimisation tool for off-grid and grid-connected systems. It is a very powerful tool designed to find the least cost combination of components with specified electrical and thermal loads. However, it is only well suited for a small number of variables and does not adequately reflect the flexibility and variability of renewable energy sources and is not intended for district heating and thermal storage modelling [114].

There are also several modelling approaches investigated specifically to the transformation of the Baltic energy system, including the residential and commercial sectors. A dynamic model with a 2050 horizon evaluates changes in the Baltic energy system with a high penetration of wind and solar energy [115]. However, this model did not include cross-border electricity trading, balancing needs and demand-side flexibility. [116] explored a case study with significant RES growth and disconnection of fossil fuel modelling in the overall Baltic energy system with a 2050 horizon. Still, the presented results do not consider the electrification of the building sector, which is an important focus of interest of the present Thesis. The authors of [117] created the model of the long-term development of the Lithuanian energy sector, using the MESSAGE optimisation tool, considering that all the possible fuels can be used as alternative ones, still concentrating mostly on electricity supply analysis. However, only seasonal, weekly and daily variations were accounted for in this model. All energy sectors were analysed by scenario-based analysis of the Baltic energy system [118], applying the Balmorel and TIMES modelling approaches. Increased RES share, secure and efficient energy supply and demand, increase of the domestic electricity and heat generation tasks were studied in detail for the three Baltic countries. The building sector was also presented in the scenarios, but the potential of modern heat pump technology applying to the end user sector was not explored; moreover, the temporal resolution of model was low. Also, the study on deep decarbonisation in the Nordic-Baltic region (using the Balmorel model) [119] describes scenario analysis with energy sector coupling, implementation of heat and electricity storage, an increased share of VRES and policy measures for net-zero requirements to be fulfilled by 2050 in this region. Still, the model focused on the energy systems, not including full chronology in time series; moreover, the results concerning the Baltic States were not described in detail. Most of the considered studies analyse scenarios by the year 2050, not focusing on immediate decisions and policy choices to achieve mid-term targets.

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.

Backbone represents a simulation approach with a highly adaptive power system simulation that combines sector interconnection, simulation of any number of renewable energy sources, reserves, accumulation technologies, power-to-X technologies, power transmission, unit commitment and economic dispatch tasks solving. *Backbone* allows both modelling large-scale systems with many parameters and constraints and detailed study of medium or small-sized systems and their specific aspects. This tool is also well suited for exploring the contribution of end users to the overall process of transformation towards a decarbonised energy system. It is possible to analyse the inclusion of a variety of new progressive technologies in the end-user sector, to study the interconnections of sectors and the impact on changing the cost of the system as a whole. In addition, the ability to include time series and apply hourly resolution allows finding flexible, optimal solutions in terms of costs and resources used. The open-source modelling framework gives *Backbone* an advantage over commercial models.

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 targets set by the National Climate and Energy plans and the EU Climate and Energy Framework.

5.2. Methodology

5.2.1. Modelling the Baltic energy system transformation

5.2.1.1. Overview of the Baltic energy system

The year 2030 is an important intermediate point (also set by the National Climate and Energy plans) for achieving the above goals of decarbonisation of the housing stock as well as a necessary transition period, on the correct implementation of which the fulfilment of the final energy efficiency goals depends.

For all the Baltic countries — Latvia, Lithuania, and Estonia — the overall dependence on fossil fuel sources and electricity imports is high, and both the EU and the Baltic countries are striving to change this [120]. First, the aim is to join the synchronous grid of continental Europe by 2025 to diminish or even eliminate the dependence on Russian electricity. Despite building new high-voltage cross-border connections both with Nordic and continental Europe, this would reduce the cross-border capacity of the Baltic countries by 1.5 GW [117], [119], [121].

Second major change is the phase-out of oil shale capacity in Estonia [117], [122]. The high CO_2 content of oil shale, emission reduction targets, and recent increase in CO_2 prices have already reduced annual use and Estonia is planning to phase out 1.5 GW of oil shale capacity by 2030. While Baltic CO_2 emissions have declined, the Baltic countries have become increasingly dependent on electricity imports. This will be further escalated by the planned decommissioning of combined heat and power (CHP) units in Lithuania.

The third planned major change is a sharp increase in variable renewable electricity (VRE) capacity. In total, Baltic countries are planning to increase their wind power capacity from 0.9 GW to 4.2 GW and solar PV capacity from 0.08 GW to 1.4 GW from 2017 to 2030 [123]–[125]. Each of these three changes is very large compared to the average electricity demand, which was 2.8 GW in 2017, and the peak demand, which was 4.3 GW at the same time [126].

In additional, the refusal of Russian gas due to geopolitical issues may call for additional capacities, speed and flexibility in the Baltic energy transition.

In general, the above transformation process covers all sectors of energy production and consumption, including the residential and commercial sectors. About 40 % of the final energy consumption takes place in buildings, and accordingly 36 % of CO_2 emissions are accounted for by all buildings in Europe, making them the largest energy consumer, the effect of which can reduce emissions and significantly increase consumption efficiency. Along with the *Fit for 55* package, the Energy Performance of Buildings Directive 2010/31/EU [127] and the Energy Efficiency Directive 2012/27/EU [128] set the package of goals concerning energy consumption in the building sector: (1) to achieve an energy-efficient and decarbonised housing stock by 2050, (2) to create a favourable environment for investment, (3) to create an opportunity for consumers to make more informed and confident choices in favour of saving energy and money. To fulfil the energy efficiency targets and accelerate decarbonisation of buildings, a boost of the renovation of the existing building stock and implementation of green, cost-effective and energy-saving technologies are required.

It should be noted that to facilitate reduction of emissions in the building and transport sectors, a separate stand-alone emission trading system (ETS) for fuel distribution for road transport and buildings will be introduced (from 2025) [9]. This will take place along with the electrification of these sectors and implementation of sector-coupling technologies.

The residential sector consumes about a third of the energy sector in Latvia [23], therefore, there is a great potential for achieving climate goals and improving energy efficiency by regulating (reducing) energy consumption in buildings. Since the building stock in Latvia has a significant percentage of houses built more than fifty years ago [129], the energy consumption of such buildings is remarkably high, and the heat supply is ineffective, with high heat losses. The construction of new buildings is proceeding slowly, and the population’s ability to buy new apartments is low. Therefore, to improve the energy efficiency of previously constructed buildings, among others, gradual renovation is required. The Latvian NECP in 2030 provides for a reduction in the average consumption of thermal energy by buildings for heating by at least 30% from 2020 and energy-efficient renovation of at least 2,000 apartment buildings and at least 5,000 private houses, as well as the continuation of the renovation of state and municipal buildings. Lithuania and Estonia are also monitoring the implementation of the accepted building renovation programmes.

5.2.1.2. The Baltic Backbone model

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

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

where

$p_{f,t}^{prob}$ — 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 lines (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, 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 [130].

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 [131].

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.

Figure 5.2 presents a diagram of the *Baltic Backbone* model where three modules have been developed: system, buildings and transport. The structure built allows running the system module separately, or all three modules can be optimised simultaneously.

A. The *system module* includes electricity and district heating systems. It also comprises electricity reserves, transmission, storages, and conversions between grids, such as large heat pumps. The system module was used to study the impacts of new generation capacity, sources of flexibility, the role of interconnections to the overall Baltic energy system.
B. The *buildings module* represents the residential, commercial, and public building sectors. This module was chosen to study the impacts of improved energy efficiency, electrification, and flexibility in buildings.
C. The *transport module* includes the energy consumption of personal vehicles in each country to investigate transport electrification, charging patterns, flexibility options, and their impacts on the system.

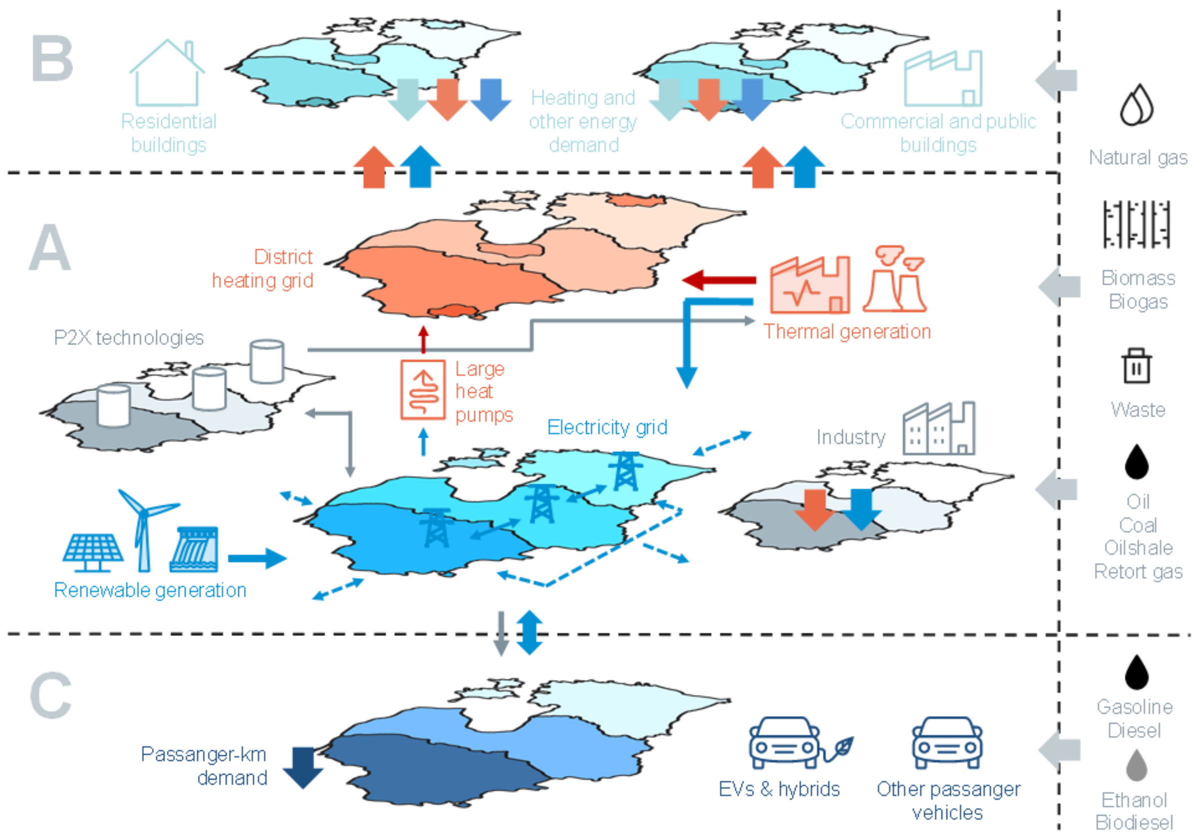


Fig. 5.2. Illustration of the Baltic energy system model in Backbone [132].

The model consists of an electricity grid, district heat grids, energy conversions (Module A); energy use by buildings (Module B); and personal vehicles (Module C). All are modelled with hourly time resolution in full interaction with one another.

To simulate the scenario, it was chosen to represent 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 split between the buildings' energy demand in the capital and other regions was assumed as a proportion equal to the region's population. Transport energy use is modelled at a national level.

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 model is accompanied with automated result processing tools that can be used to summarise and compare the outputs of various model runs and statistical values as well as to draw a range of figures representing the main results.

System module (Module A)

The system module includes production, storages, and transmission of electricity, district heating and fuels. Electricity units are modelled at unit level of detail, while heat-only units are aggregated by fuel.

Tables 5.1 and 5.2 summarise the production unit data. The majority of installed electrical capacity in Estonia is concentrated in condensing oil shale (67 %) or cogenerating oil shale (8 %) power plants [133]. The oil shale units are located in the northeastern part of Estonia (Narva region). The district heating capacity is more evenly distributed between biomass, natural gas and other fossil production. The expansion of wind and solar capacities are estimated from Estonia's 2030 National Energy and Climate Plan's trajectory for reaching renewable energy targets [125]. According to the Estonian transmission system operator [134], a total of 1.7 GW_e of Narva units' electrical capacity is planned for decommissioning between 2021 and 2031, but the two most recent units are kept as backup capacity in the modelled reference scenario due to the lack of reserve capacity in 2030 according to the current plans.

Renewable energy sources comprised 61% of the total electrical capacity in Latvia in 2017, including the cascade of the three hydro power plants on the Daugava (1,5 GW_e) with 3–6 hour storage options depending on season, small hydropower, wind, biomass and biogas units as well as solar microgeneration. The remaining electricity producers are mainly gas-fired CHP plants, including two large gas-fired CHP plants in Riga (1.0 MW_e). The main part (64%) of district heating capacity is concentrated in gas-fired CHP plants and boiler houses [7]. TSO Augstsprieguma Tīkls forecasts the disconnection of the Imanta gas-fired CHP plant by 2030 and assumes an increase of wind power [135].

In Lithuania in 2017, the total installed net power plant capacity was 3.6 GW, whereof 46% in natural-gas-fired power plants. The major gas power plants are: Lithuania Power Plant (1.0 GW), Vilnius Combined Heat and Power Plant (0.4 GW), and Kaunas Combined Heat and Power Plant (0.2 GW). A significant share of the installed capacity (0.9 GW) was provided by Kruonis hydropower plant, with 11 GWh of storage. According to Litgrid, the system operator [136], it is planned to significantly increase the installed capacity in the country by 2030. This is to be achieved mainly by expanding renewables including 1.0 GW of new onshore capacity, 0.7 GW offshore wind capacity, and 0.8 GW of solar PVs. The total capacity of renewables should increase from 0.9 GW to 3.5 GW. To balance the substantial increase in variable generation, Lithuania is planning to expand the Kruonis pumped hydropower plant by a new 110 MW unit and build 200 MW of batteries.

Unit operating parameters (variable and fixed operating costs, operating constraints, etc.), are from previously mentioned national sources when available. Missing parameters are supplemented with data from Baltic Energy Technology Scenarios study [118], [137] and technology catalogue data by Danish Energy Agency [138].

Table 5.1. Summary of modelled electrical capacity by source and by country in 2017 and change to 2030

	Electrical capacity [MW_e]					
	Estonia		Latvia		Lithuania	
	2017	2030	2017	2030	2017	2030
Renewables & waste	**429**	+1312	**1798**	+945	**853**	+2608
..wind onshore	303	+397	77	+319	521	+985
..wind offshore	0	+500	0	+396	0	+700
..PV decentralised	0,1	+405	1,2	+97	82	+803
..PV centralised	0,1	+10	0,1	+10	0.1	+10
..Hydro run-of-river	8		28	+1	27	
..Hydro reservoir	0		1536	+44	101	
..Biomass	95		95	+41	66	+69
..Biogas	6		60	+31	37	
..Waste	17		0	+7	20	+41
Natural gas	96		1168	−74	1676	−52
Oil shale	1879	−1609	0		0	
Retort gas	10		0		0	
Oil	0		0		186	
Coal	0		3	−3	0	
Storages	**0**	**0**	**0**	+30	**900**	+310
..Hydro pumped	0		0		900	+110
..Batteries	0	+200	0	+30	0	+200

Table 5.2. Summary of modelled district heat capacity by source and by country in 2017 and change to 2030

	District heat capacity [MW_{DH}]					
	Estonia		Latvia		Lithuania	
	2017	2030	2017	2030	2017	2030
Renewables & waste	1493		1972	+353	1980	
..Biomass	1436		1909	+278	1866	+188
..Biogas	7		64	+32	52	
..Waste	50		0	+28	63	+185
..Solar collectors	0		0	+15	0	
Natural gas	4027		3651	−765	7730	−298
Oil shale	360	−50	0		0	
Oil	1092		17	−9	434	
Coal	0		66	−33	0	
Excess heat	0		0		390	
Heat pumps	0		0	+115	0	

Baltic countries are part of the BRELL (Energy systems of Belarus, Russia, Estonia, Latvia and Lithuania) grid where electricity is transferred from Belarus through the Baltic countries to the St Petersburg region in Russia. Because the model does not include Russia and Belarus, the net transfer capacities of interconnectors are modelled based on typical historical flows. Available capacities are estimated from the power flow data of the ENTSO-E transmission system operator [126]. Major changes are foreseen for the Baltic countries due to the planned disconnection of all transfer capacities with Russia and Belarus, and strengthening Polish and inter-Baltic connections as a part of ongoing integration with the synchronous grid of Continental Europe [67] (see Table 5.3).

Table 5.3. Summary of modelled electrical cross-border transfer capacities in 2017 (actual and modelled), and change from 2017 modelled to 2030

	Cross-border electricity transfer capacity [MW]					
	[1] → [2]			***[1] ← [2]***		
	2017, actual	***2017, modelled***	***2030***	***2017, actual***	***2017, modelled***	***2030***
[Estonia] - [Finland]	1000	1000		1000	1000	
[Estonia] - [Latvia]	800	800	**+600**	800	400	**+1000**
[Estonia] - [Russia]	600	600	**−600**	600	25	**−25**
[Latvia] - [Lithuania]	1000	1000	**+300**	1000	550	**+750**
[Latvia] - [Russia]	400	100	**−100**	400	200	**−200**
[Lithuania] - [Sweden]	700	700		700	700	
[Lithuania] - [Poland]	500	350	**+650**	500	350	**+650**
[Lithuania] - [Belarus]	1000	1000	**−1000**	500	500	**−500**
[Lithuania] - [Kaliningrad]	300	0		300	300	**−300**

The annual demand data of electricity and district heating for 2017 have been taken from national statistics [7], [133], [139]. National estimates project a 12 to 25% increase in total electricity demand and an 8 % to 19 % decrease in district heating demand in 2030 [123]–[125] (see Table 5.4.). Transmission and distribution losses (9–16% depending on the grid) are subtracted between production and consumption [7], [133], [139]. End-use electrification and economic development are estimated to increase the electricity demand while the impact is countered by population decline and efficiency improvements. District heating demand will decrease towards 2030 due to improvements in energy efficiency and investments in alternative heating technologies.

Hourly historical electricity demand data from Nordpool [140] are divided by sector according to national statistics. The sectoral development is according to national estimates [123]–[125], [134] and transport and building assumptions. District heating demand time series are calculated based on historical temperatures and demand time series.

Table 5.4. Summary of modelled electricity and district heating demands by country in 2017 and change to 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 heat	**4602**	−10 %	**7034**	−10 %	**10817**	−19 %

	Annual demand [GWh]					
	Estonia		**Latvia**		**Lithuania**	
	2017	**2030**	**2017**	**2030**	**2017**	**2030**
..Buildings	3812	**−10 %**	5986	**−10 %**	7873	**−22 %**
..Other	790	**−10 %**	1048	**−10 %**	2944	**−11 %**

The reserve requirement of the modelled power system includes aggregated primary upward reserves for each Baltic country that equal the largest producing unit or interconnector fulfilling the (N-1) condition. Thermal units are assumed to be able to provide 7 %, hydropower — 10 %, wind power — 20 %, and batteries — 90 % of their online capacity as upwards reserves. Technically, wind power could provide more reserves, but a lower value is used to avoid overestimating the option, as the model uses deterministic time series.

Variable renewable datasets from MERRA-2 [141] are combined with technology data [138] and used as deterministic time series for wind and solar generation [142]. The average capacity factor of onshore wind is estimated to increase from 0.25–0.30 in 2017 to 0.37 in 2030. The hourly variation for hydro inflow is based on previous studies [118].

Modelled fuels include biogas, biomass, waste, natural gas, coal, oil, oil shale and retort gas, modelled as commodities with annual prices [143], [144]. Natural gas supply is balanced by Latvian Inčukalns underground gas storage facility. Imported electricity is also modelled as a commodity with hourly price time series [140].

National taxes, like fuel and excise taxes, are also included in the model [145]–[147]. Power transmission and distribution costs are included for all end-use sectors, the EU emission trading system prices are estimated to increase from 5 €/tCO_2 in 2017 to 50 €/tCO_2 in 2030.

For the power and heat sector, investment costs are calculated outside the model. Investment annuities are based on technology data [138] and use 5 % as the interest rate and 20 years as the payback time. Decommissioning costs are estimated as 10 % of building costs.

Buildings module (Module B)

The buildings module was used to model the use of energy for space heating and hot water and other electricity needs in buildings (see Table 5.5). The historical energy data are built on Eurostat energy balances [23], the Eurostat Questionnaire for statistics on final energy consumption in households [148], and the national district heating statistics presented in the previous module. 2017 was taken as the base year as one without strongly pronounced extremes in energy production and consumption and with a moderate degree days.

Eurostat energy balances provide data on the total final energy use by fuel for residential and commercial sectors but they do not specify the type of end use, e.g. heating or cooking. The questionnaire for households provides data of final energy use by type of end use, but only for the residential sector. The same split is used for the commercial sector due to the lack of more detailed open data from the commercial sector. Energy use data are supplemented with heat pump data from the Eur’Observer heat pump barometer [149]. The split between the energy demand of buildings in the capital area and other regions is based on the population of these regions in each Baltic country. National district heating statistics provide the amount of DH supplied in each modelled region (capital and other) while other fuels are split between the remaining demand figures of each region.

Table 5.5. Summary of modelled energy demand of buildings by fuel, type of end use, and region in 2017

	Energy use for heating and hot water, 2017 (GWh)								***Other energy use, 2017 (GWh)***
	Coal	Oil	Natural gas	Biomass	DH	HP, ambient	HP, electricity	Electricity, direct	Electricity, other
Estonia	**24**	**101**	**1264**	**4507**	**3558**	**348**	**174**	**1008**	**3473**
…Tallinn	7	28	352	1294	1552	100	50	279	1158
…Other	17	73	912	3213	2006	248	124	730	2315
Latvia	**156**	**603**	**1754**	**6476**	**5986**	**14**	**7**	**1052**	**3363**
…Riga	27	105	304	1137	3427	3	1	181	1087
…Other	129	498	1450	5339	2559	12	6	871	2277
Lithuania	**1039**	**260**	**1978**	**5709**	**7873**	**22**	**11**	**634**	**5500**
…Vilnius	204	52	389	1134	1719	4	2	124	1139
…Other	835	208	1589	4575	6154	18	9	511	4361

National estimates and other forecasts project a 10% decrease of heating and hot water demand in buildings 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 [118].

Transport module (Module C)

The transport module models passenger vehicles and their energy use. The module includes the main fuels (gasoline, diesel) and the main alternative energy sources (electricity, biodiesel, ethanol). In addition, Lithuania and Latvia have a notable share of LPG passenger vehicles, which corresponds to 10% of the total passenger vehicle energy use [150]. The LPG vehicles are added up with gasoline vehicles. In Estonia, the share of LPG vehicles is considerably smaller with only 1% of total fuel consumption in 2017.

The transport module requires that the hourly passenger demand (vehicle-km) is fulfilled. The total national demands for vehicle-km are from Eurostat [151] and the hourly curve is from Lithuanian road traffic measurements [152]. The contribution of different vehicle types is based on the total amount of vehicles per fuel type [153] and annual fuel consumption, which allows calculating the average annual distance driven by vehicles per fuel (see Table 5.6). The total fuel demand and emissions are calculated bottom up based on previous assumptions and the average annual efficiency of each vehicle type [154]. The calculation is done for different age groups in 10-year intervals. The module is calibrated by some slight national adjustments to the distance driven and the efficiency of vehicles that both reflect national differences in car stock and typical journeys.

Renewable fuels are blended to fossil fuels. The historical values are from national energy statistics [150] and the 2030 shares are based on national legislation or targets (Estonia 6%, Latvia 2%, Lithuania 6% of ethanol in gasoline and 10% of biodiesel in diesel).

The development from 2017 to 2030 is based on national projections where the total national transport demand continues the historical growth trend leading to a larger number of vehicles. The efficiency of the future car fleet is based on the published technology catalogues [154].

Table 5.6. Summary of modelled passenger vehicle stock by country in 2017 and 2030

		2017			*2030*		
		Amount	***Avg. distance driven***	***Efficiency***	***Amount***	***Avg. distance driven***	***Efficiency***
		1000 vehicles	1000 vkm	1000 vkm / MWh	1000 vehicles	1000 vkm	1000 vkm / MWh
Estonia	Gasoline	450	9.5	1.46	573	9.75	1.61
	Diesel	275	16.2	1.55	378	14.4	1.70
	PHEV	0	-	-	12	9.25	3.09
	EV	1.2	9	4.47	25	9.25	4.72
Latvia	Gasoline	301	13.3	1.42	313	12.5	1.58
	Diesel	388	16	1.53	558	14.2	1.69
	PHEV	0.1	12.8	2.92	11	12.8	3.09
	EV	0.3	12.8	4.47	23	12.8	4.72
Lithuania	Gasoline	441	13	1.46	456	12.3	1.60
	Diesel	907	15.6	1.57	1337	14	1.70
	PHEV	9	12.3	2.92	23	12.3	3.05
	EV	0.6	12.3	4.47	47	12.3	4.72

Two types of charging technologies for PHEVs and EVs are included. For 2030, 50% of the fleet is assumed to be charged by way of fast charging throughout the day with little given flexibility in the charging pattern. The rest would be charged overnight with slower chargers and the option for the model to shift the charging during the night.

5.2.1.3. 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. More detail of the 2017 validation is provided in Annex 2.

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 5.7 are based on NECPs targets and expert opinions.

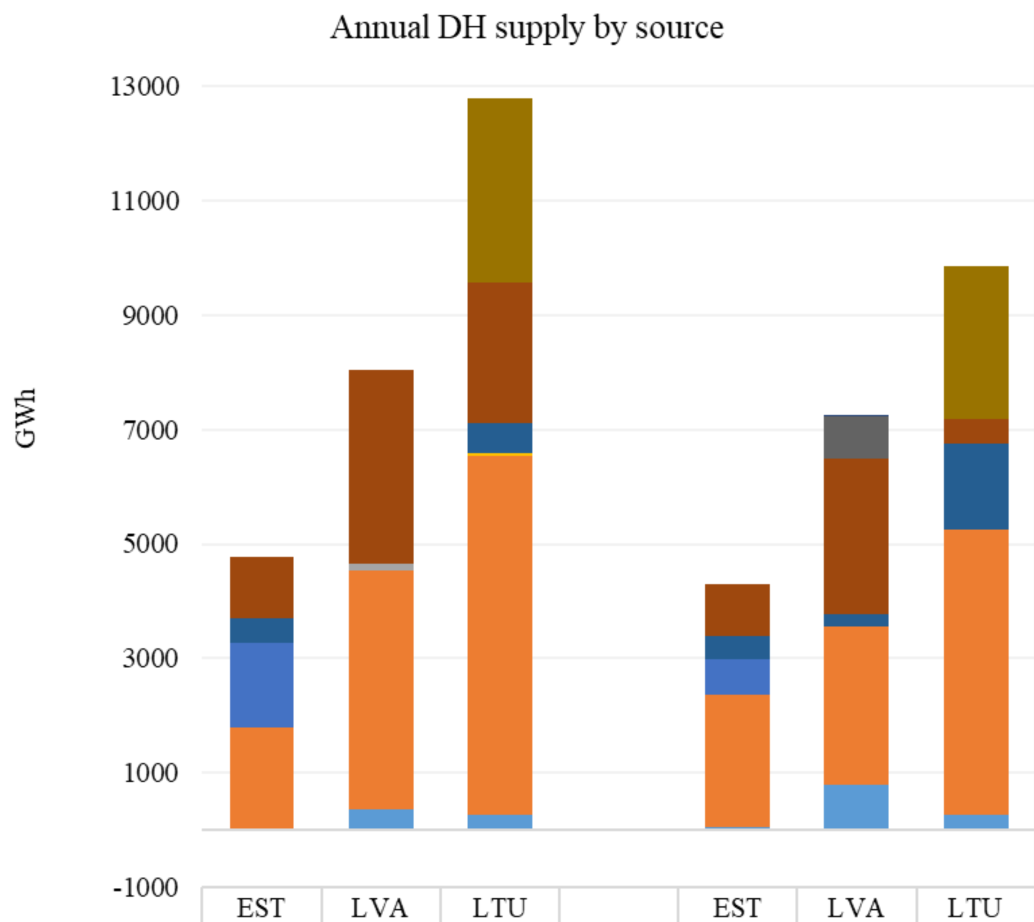
Table 5.7. Assumed main changes in energy consumption from 2017 to 2030 reference scenario

	EST	LVA	LTU
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 figures, 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.

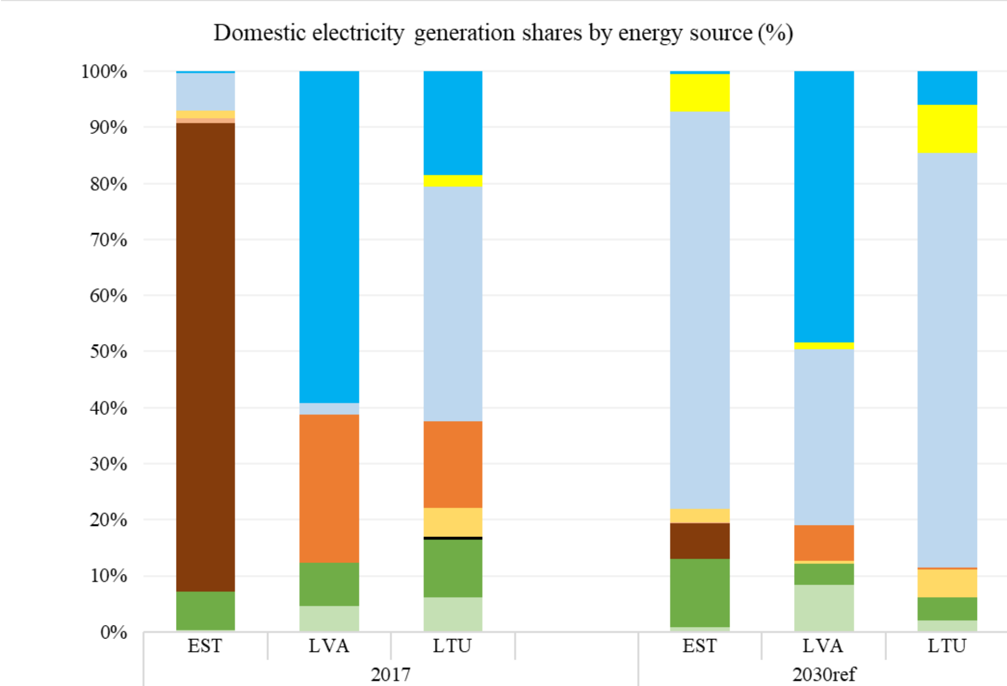
The reduction in fossil fuels used and their substitution by green energy yields a significant emission reduction in 2030 (11.011 kt of CO_2 for ETS and 61 kt of CO_2 for non-ETS sectors).

The main results of the 2030 reference scenario are depicted in Figs. 5.3–5.4; more details of 2030 validation is provided in Annex 3.



	2017 EST	2017 LVA	2017 LTU	2030ref EST	2030ref LVA	2030ref LTU
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

Fig. 5.3. Annual district heat generation by energy source.



	2017 EST	2017 LVA	2017 LTU		2030ref EST	2030ref LVA	2030ref LTU
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

Fig. 5.4. 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.

5.2.1.4. 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 5.8).

Table 5.8. 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 (compare to 2030ref) for each country
2030ref_locHP2	+500 GW of energy produced by local heat pumps (compare to 2030ref) for each country
2030_PV_Eps	no adding of new PV capacities
Additional scenario coupling	
2030_DH1_HP1	Combination of 2030ref_lowDH1 and 2030ref_locHP1 scenarios
2030_DH1_HP2	Combination of 2030ref_lowDH1 and 2030ref_locHP2 scenarios
2030_DH2_HP1	Combination of 2030ref_lowDH2 and 2030ref_locHP1 scenarios
2030_DH2_HP2	Combination of 2030ref_lowDH2 and 2030ref_locHP2 scenarios
2030_DH1_PV0	Combination of 2030ref_lowDH1 and 2030_PV_Eps scenarios
2030_DH2_PV0	Combination of 2030ref_lowDH2 and 2030_PV_Eps scenarios
2030_HP1_PV0	Combination of 2030ref_locHP1 and 2030_PV_Eps scenarios
2030_HP2_PV0	Combination of 2030ref_locHP2 and 2030_PV_Eps scenarios

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 (see Fig. 5.5).

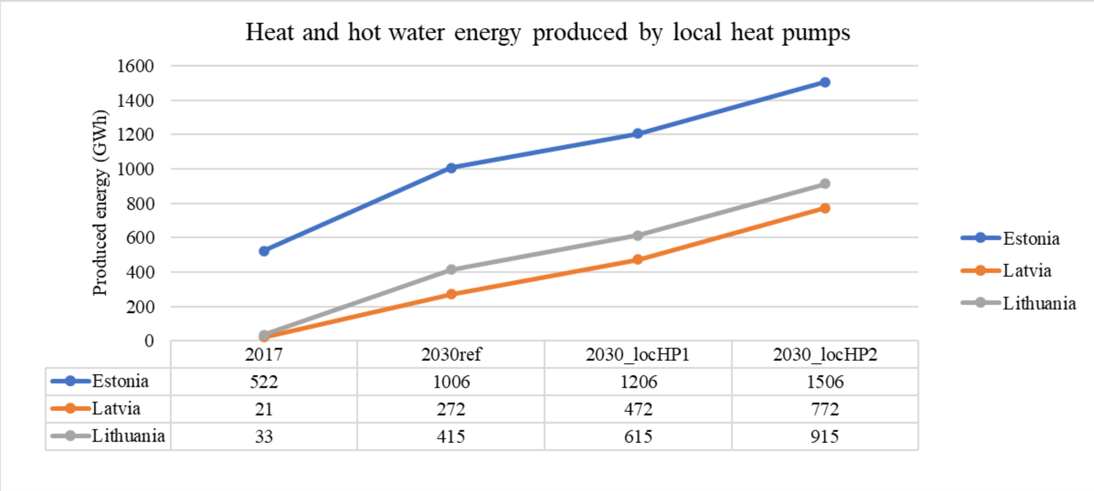


Fig. 5.5. Simulated heat and hot water energy production from HPs in the Baltics.

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 (see Table 5.9).

Table 5.9. Indicators for energy scenarios assessment

Indicators	
Decarbonization	*ETS CO_2 (ktCO2)*
	non-ETS CO_2 (ktCO2)
	RES-E (% units)
	RES-H (% units)
Energy efficiency	*Primary en. (GWh)*
	Final en. (GWh)
Energy security	*Domestic gen. (GWh)*
Costs	*System operation costs (M Eur)*

The group of indicators for decarbonisation assessment includes ETS and non-ETS CO_2 emission reduction measures in $ktCO_2$, the share of electricity production from renewable resources (RES-E) and the share of heat production from renewable energy sources (RES-H). The energy efficiency indicators consist from the amount of primary and final energy in GWh. The energy security indicator is presented by the domestic generation rate (GWh), and the cost-related group of indicators is presented by the system operational cost in MEur.

5.2.2. Modelling the impact of the building sector on decarbonisation

5.2.2.1. District heating in the Baltics

District heating in the Baltic countries has historical peculiarities. Whereas in the EU countries DH is used on average by 25% of all the end users (Fig. 5.6), in the Baltic countries a stable and extensive centralised heat supply system has been actively developing and makes up a significant part of the energy balance of the Baltic countries. About 60 % of the end consumers use centralised district heat in Estonia and Lithuania, and the figure in Latvia reaches 65% [155], [156]. The development of the DH system is also facilitated by the impressive housing stock of multi-apartment buildings in the Baltics and the relatively harsh weather conditions during the winter.

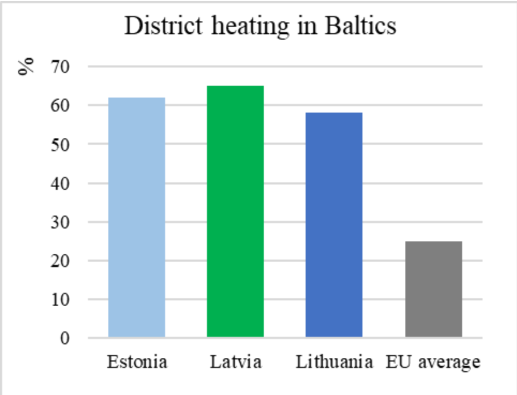


Fig. 5.6. Residential district heating in the Baltics and the EU, 2017. (Based on data from [157], [158].)

Measures to reduce DH consumption can significantly influence the main indicators of NECPs in the Baltic countries. The decrease in heat consumption by 2030 could be achieved by boosting the buildings renovation process as well as by coupling the electricity market to local heating via power-to-heat technologies.

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

During the years 2014−2020, several programmes was available in Latvia for supporting renovation activities [157], [158]. Assuming that the renovation of the building stock will maintain the same speed as before — around 1700 buildings during 2014−2020 [9], [12] —, the calculated number of renovated buildings during the reference years 2017 and 2030 can reach four thousand for Latvia.

According to [159], the average annual heat energy savings obtained as a result of the renovation of one apartment block during 2014−2020 and 2020−2030 is calculated at 156−226 MWh. Thus, the total heat energy savings of Latvia's households renovated apartment blocks by 2030 can reach 800 GWh as a minimum (Table 5.10).

Table 5.10. Forecasted saving of district heat energy of building stock renovation till 2030 in Latvia

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

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

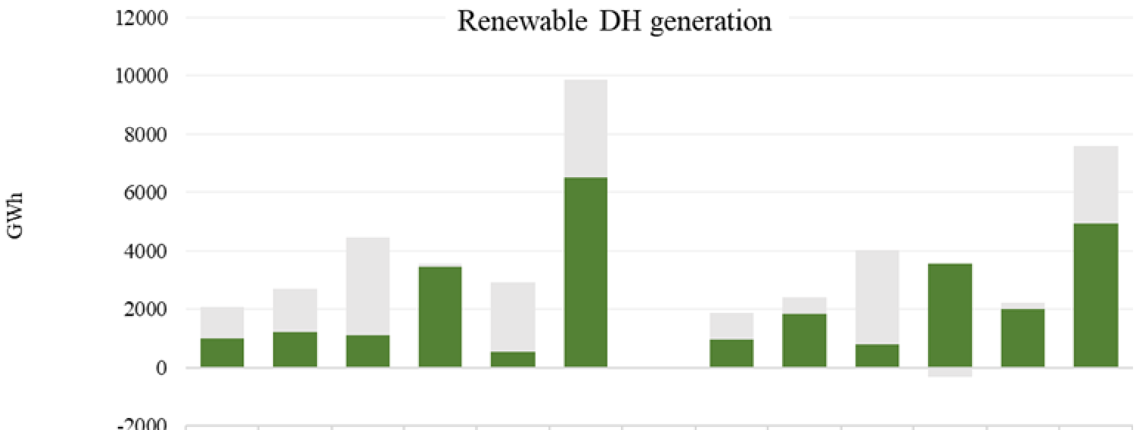
In the experts' opinion [129], by 2030 it is possible to carry out a cost-effective renovation of 70% of the total amount of buildings, as it will not be useful to renovate the remaining 30%. Towards the target of renovating 30% of apartment blocks by 2030, a total of 8,100 apartment blocks needs to 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 [129]. 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.

As mentioned before, 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 [160]. As illustrated in [12], 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.

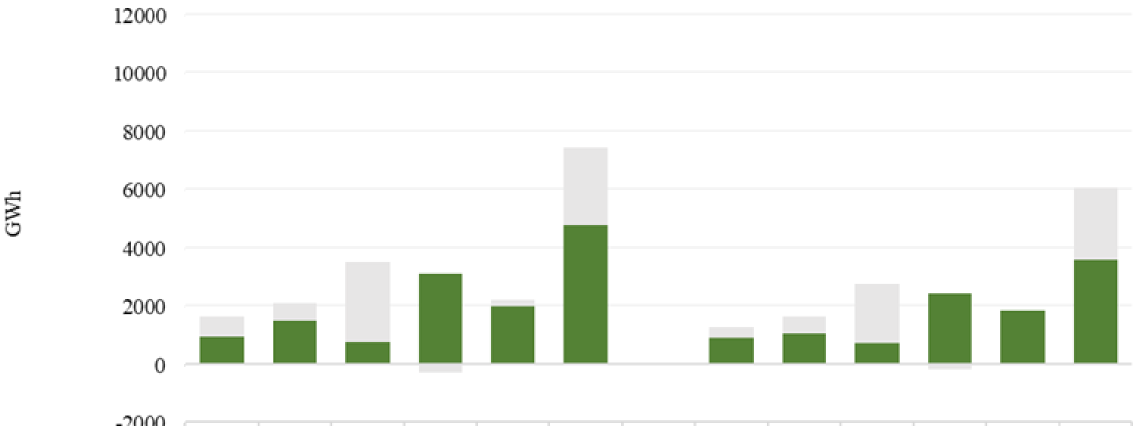
5.2.3. Case study results and discussions

5.2.3.1. Main results from the lowered DH scenarios

The scenarios with lowered DH consumption as a result of building renovation (see Figs. 5.7, 5.8) show an increase in the generation share of renewables.

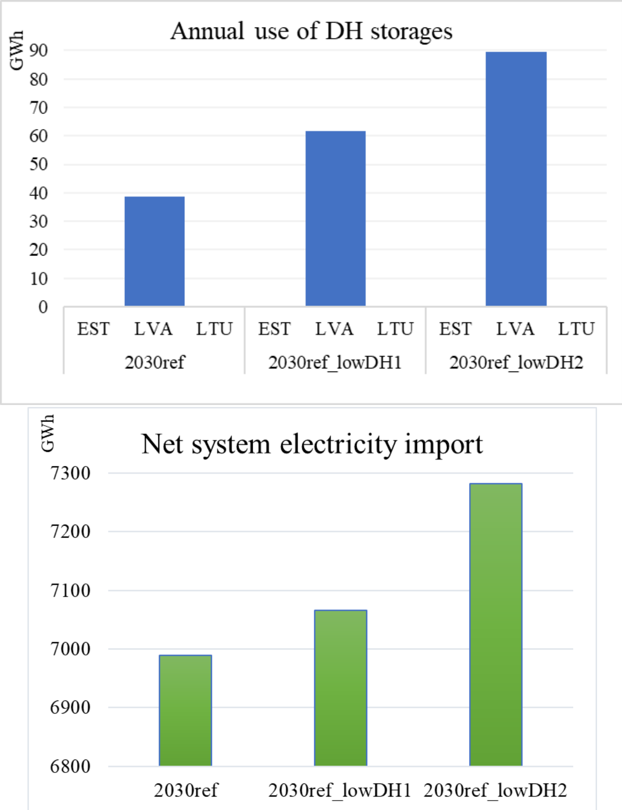


	2017 EST Tallinn	2017 EST other	2017 LVA Riga	2017 LVA other	2017 LTU Vilnius	2017 LTU other	2030ref EST Tallinn	2030ref EST other	2030ref LVA Riga	2030ref LVA other	2030ref LTU Vilnius	2030ref LTU other
RES share, incl. waste (%)	48.1 %	44.6 %	24.6 %	96.3 %	18.0 %	66.2 %	51.9 %	75.0 %	19.1 %	110.2 %	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



	2030ref_lowDH1 EST Tallinn	2030ref_lowDH1 EST other	2030ref_lowDH1 LVA Riga	2030ref_lowDH1 LVA other	2030ref_lowDH1 LTU Vilnius	2030ref_lowDH1 LTU other	2030ref_lowDH2 EST Tallinn	2030ref_lowDH2 EST other	2030ref_lowDH2 LVA Riga	2030ref_lowDH2 LVA other	2030ref_lowDH2 LTU Vilnius	2030ref_lowDH2 LTU other
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. 5.7. The share of renewables for district heating generation.



a) b)

Fig. 5.8. Use of DH storage (a) and net electricity import in the Baltics (b).

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 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. 5.9). The investment in renovation noticeably increases the overall costs of the system. However, as stressed in [16], 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.

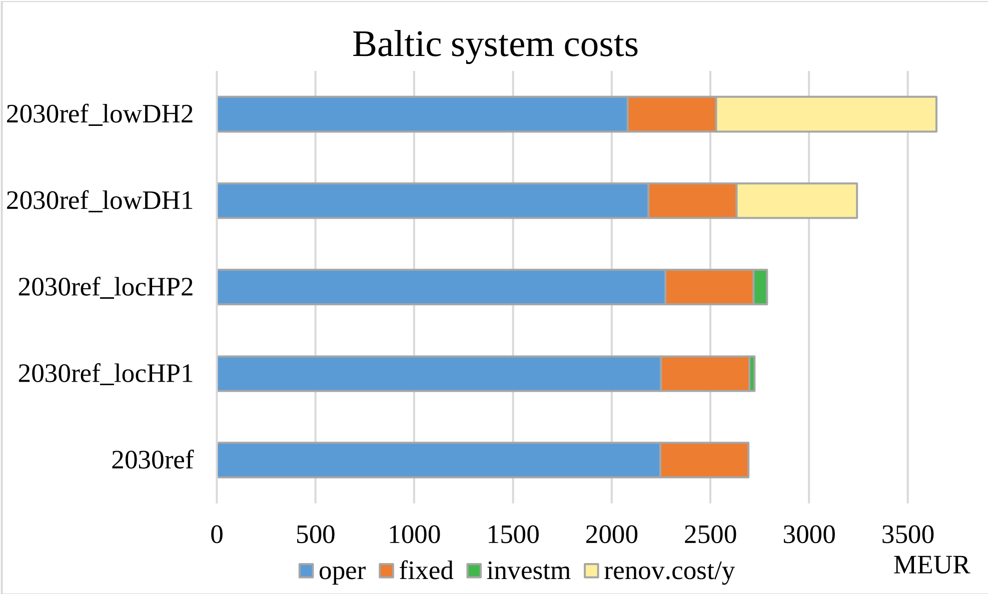


Fig. 5.9. Baltic system costs for the 2030 scenarios.

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. Fig. 5.10 shows the cutback of ETS and non-ETS CO_2 emissions.

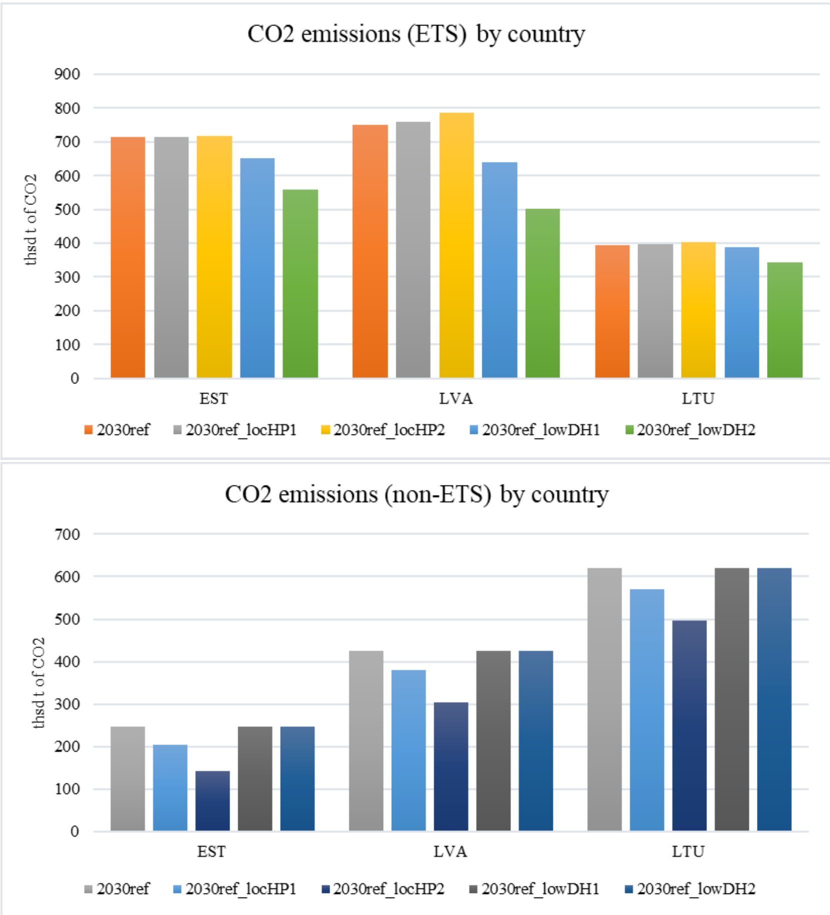


Fig. 5.10. Baltic system emissions.

The lowDH-1 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.

5.2.3.2. Main results from the local HP increase scenarios

There is no impact on the district heating production level because only local fuels are used for heat substituted by local heat pumps. The simulation results show a decrease in CO_2 emissions in both the residential and commercial sectors (see Fig. 5.11).

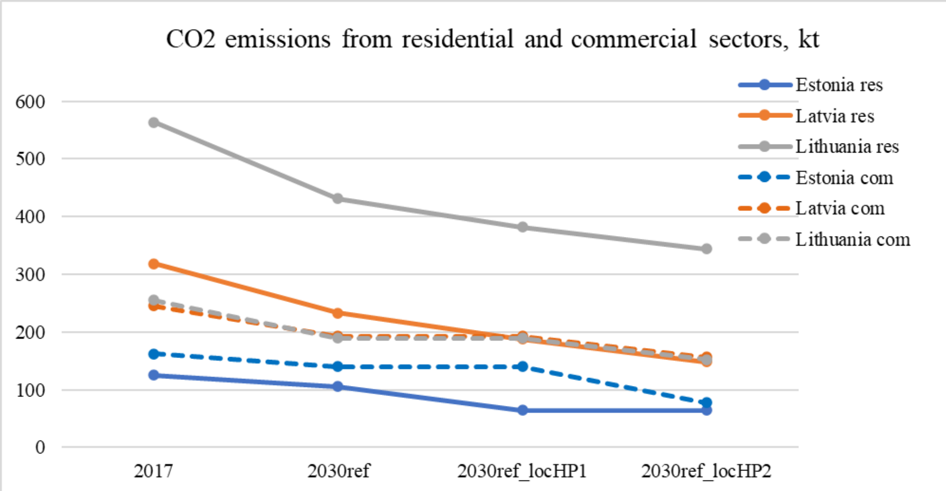


Fig. 5.11. CO_2 emissions from residential and commercial sectors.

The model noticeably increases net system electricity import to compensate for the increased demand of electricity consumed by heat pumps.

The scenarios with increased numbers of local HPs are especially cost-effective for Latvia from an electricity and heat generation point of view, peaking for non-capital regions (see Fig. 5.12).

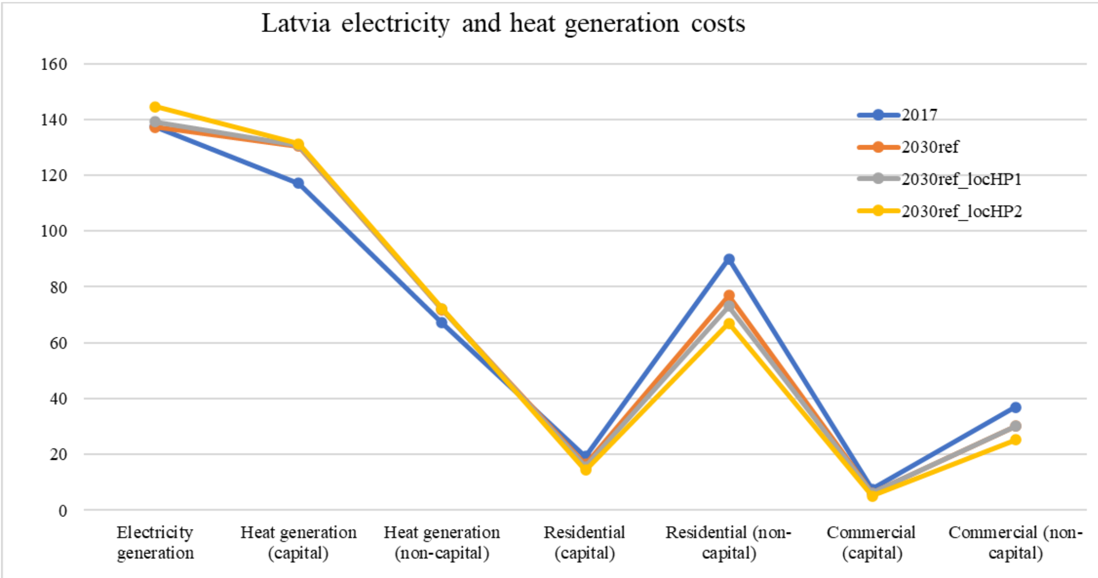


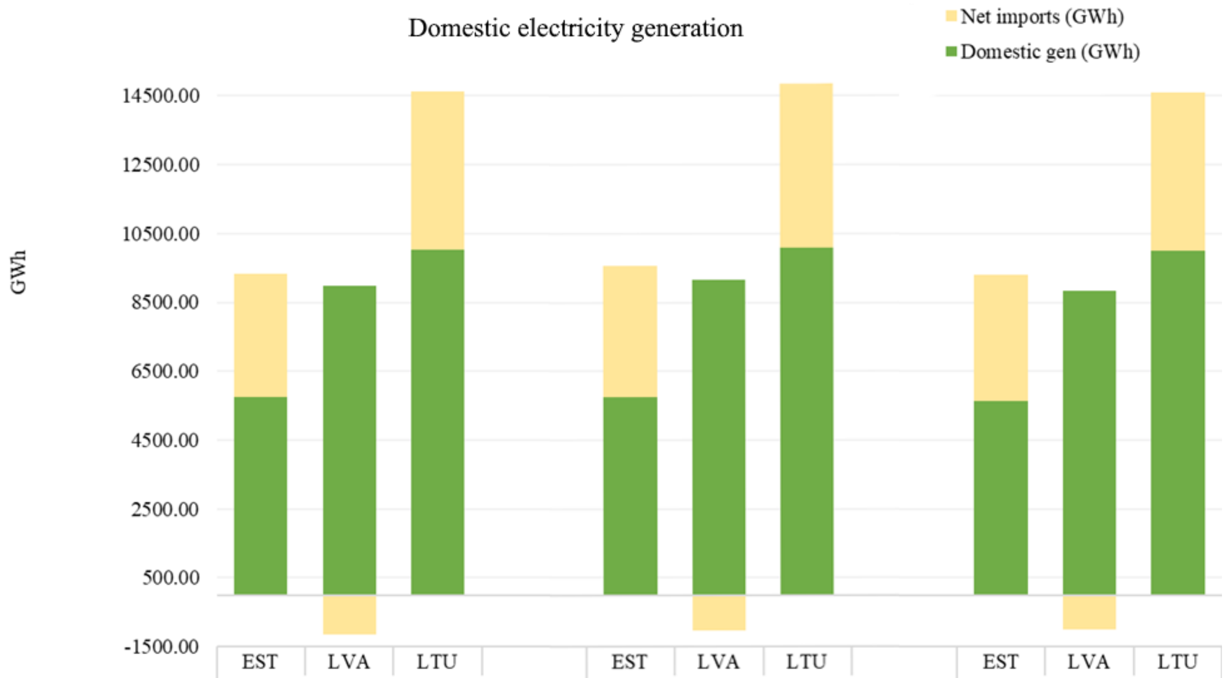
Fig. 5.12. Electricity and heat generation costs for Latvia.

The introduction of local HPs 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.

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

Domestic generation

Latvia, Lithuania and Estonia are in different positions regarding the production of local electricity (see Fig. 5.13). 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.



	EST	LVA	LTU	EST	LVA	LTU	EST	LVA	LTU
	2030ref			2030ref_locHP2			2030ref_lowDH2		
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. 5.13. Domestic electricity generation share.

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

Fig. 5.14 reflects the level of electricity production from renewable resources, including waste. Here, the situation is more favourable, especially in Lithuania, which closed the old combined heat and power plants and switched to biofuels.

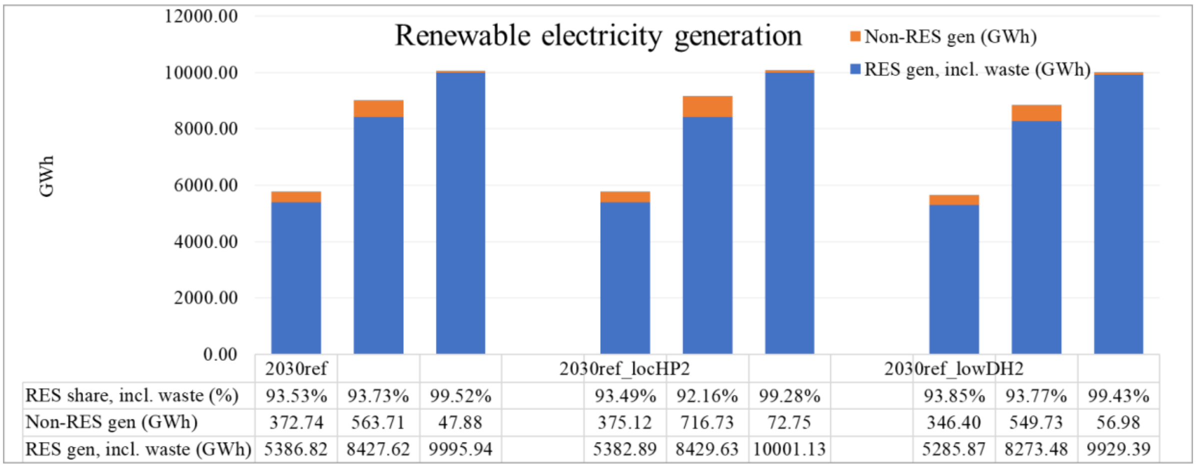


Fig. 5.14. The electricity generation share of renewables.

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. 5.15) is more heterogeneous, differing for the capitals of the Baltic States and their regions.

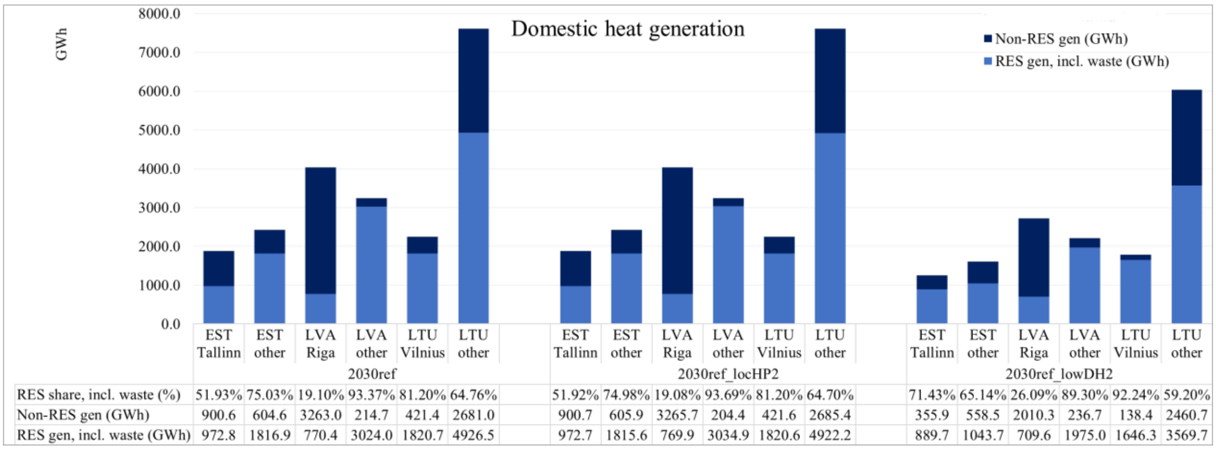


Fig. 5.15. Domestic heat generation share.

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 on 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. Another important metric — the share of renewables in district heat generation — retains low amounts of change in local HP scenarios and are pronounced with low DH scenarios (see Fig. 5.16).

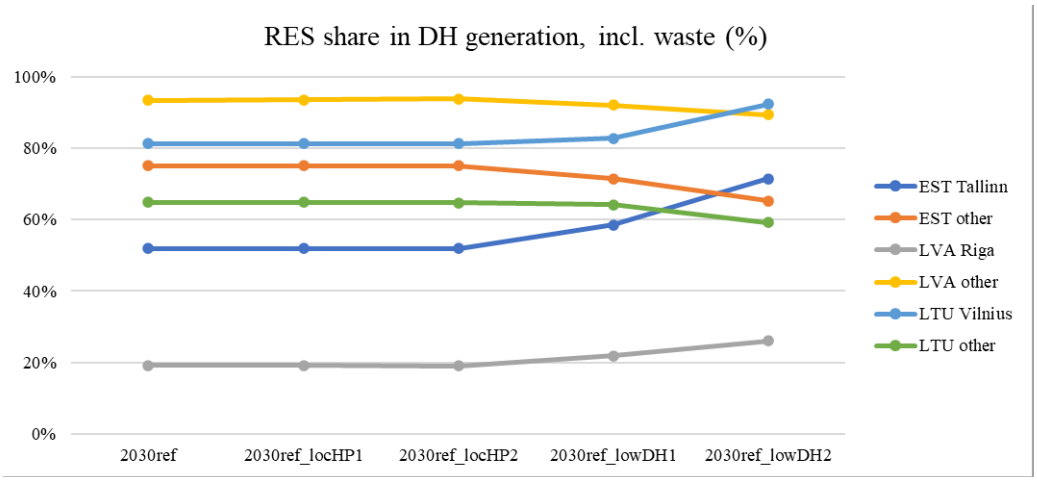


Fig. 5.16. The share of renewables in DH generation.

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.

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 Figures 5.17–5.18.

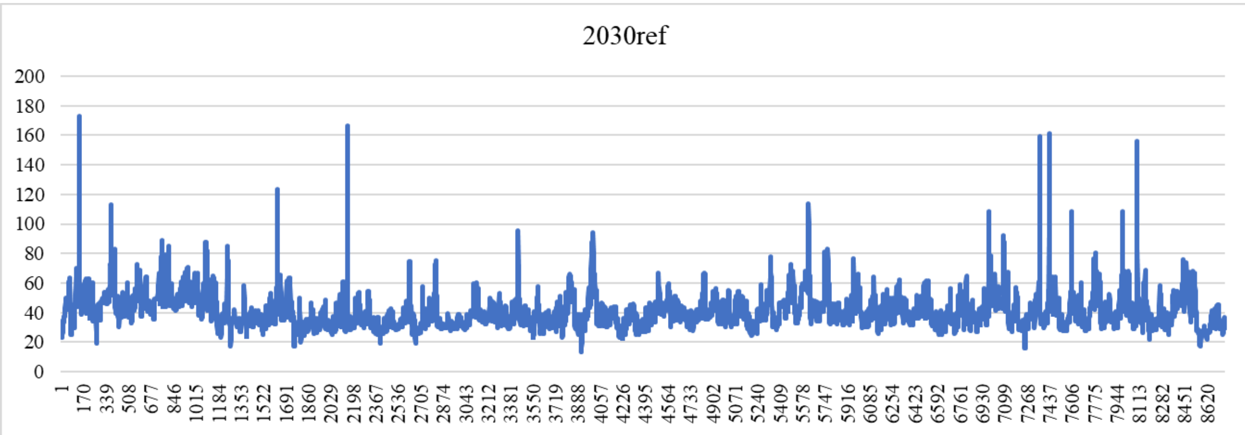


Fig. 5.17. Marginal electricity prices for 2030ref, Eur/MWh.

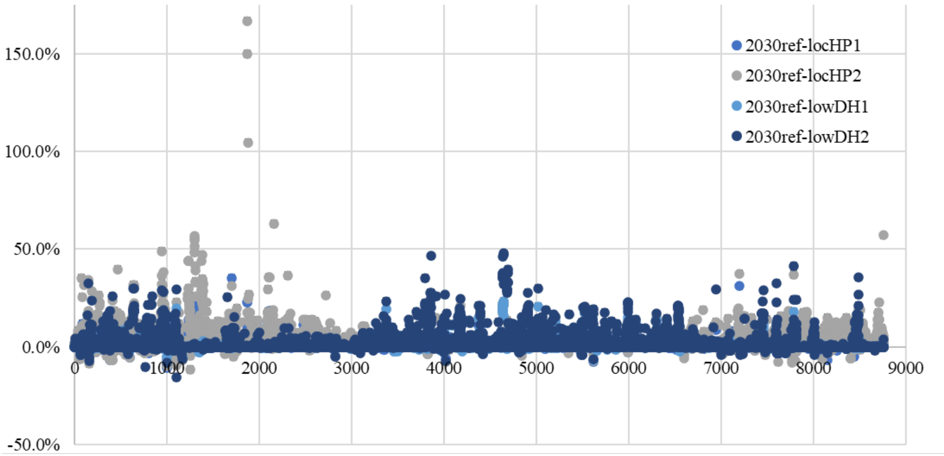


Fig. 5.18. Comparing price differences with base 2030ref scenario.

High prices in several hours indicate a 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.

5.2.3.4. 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 5.11; 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 5.11. 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 quite 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 [160], [161].
- 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 [162]. One of such initiatives could consist in local energy communities which foster both technological and social innovations. As shown in [163], 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 [164], 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 [165].

5.3. Chapter conclusions

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 possible concerns in energy security for each country were raised; 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-bottom solutions, the introduction of local green power generation in the building sector is guided by a bottom-top 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 [166]. 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

6.1.1. Motivation for the research

In order to fulfil the commitments made by the European Commission and approved by Latvia regarding the annual reduction of greenhouse gas emissions into the atmosphere, supported by the National Energy and Climate Plan (NECP) [124] and the Strategy of Latvia for the Achievement of Climate Neutrality by 2050 [167], to increase the use of RES instead of fossil fuels (sections 2.1, 3.1, and 4.2 of the Plan and section 6.3 of the Strategy), the electrification options which have not received enough attention until now, were considered.

One of the areas of decarbonisation and electrification, which has not been studied thoroughly enough, remains the electrification of the kitchen. 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, electric and induction stoves shows that stoves using LPG significantly increase the emissions of CO_2-e (carbon dioxide equivalent) in the atmosphere [168] and have a longer cooking time and a lower efficiency as compared to induction stoves. If we care about indoor air quality during the cooking process, it should be said that induction stoves have the best opportunities to replace the cooking stoves operating on other fuel sources to improve the quality of life and introduce cleaner technologies.

At the same time, the use of various kinds of pots has great additional impact on the effectiveness of cooking on gas, electric and induction stoves. Practical measurements showed that induction heating, in contrast to the heat transfer rate, had a cooking efficiency of 70%, a stove with an electric coil 39% and a stove using natural gas only 28% [169], [170]. Thus, the authors of the above studies made the conclusion that the shape and characteristics of cooktops affect energy consumption more than the cooktop itself. The calculation of the average costs of heating a litre of water daily were calculated for a year in the case of a natural gas, induction, and electric-coil cooktop. Despite the fact that natural gas cooktop had the lowest cooking efficiency, it also has the lowest energy cost for heating water because of the low energy cost per kWh.

Whereas *Eurelectric* in “Decarbonisation pathways, European economy, EU electrification and decarbonisation scenario modelling” [171] claims that the energy intensity for cooking on electrical equipment is 10% lower than that of gas, researchers from Korea explore the possibilities of changing the cooking habits of households to switch from gas stoves to induction ones with calculation of the reduction in GHG emissions for three transition scenarios [172], taking into account the annual population growth in Korea.

Among national studies concerning application of the potential of RES the region, detailed attention is dedicated to the determination of conditions under which it would become possible to provide Latvia with the maximum amount of electricity generated by solar panels [173], evaluation of the integration of renewables to the grid and its potential in Latvia [174], assessment of the impact of promoting efficient energy-saving technologies in the Latvian market, modelling the dynamics of consumption in households [175], assessing the potential of biogas plants to balance power supply from wind power plants [176], as well as assessment of the potential for demand-side management, with the aim to reduce peak load [177], etc. However, 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 liquefied petroleum gas — LPG) with 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 regarding the necessary number of passenger vehicle owners in Latvia that need to transfer from internal combustion engine (ICE) to electrical vehicle (EV), and the resulting reduction in emissions.

6.1.2. Cooking equipment in the households of Latvia: a comparative analysis

Household consumption patterns contribute greatly to the increase in GHG emissions, as people’s demands for comfort increase along with the increase in economic prosperity. The average total energy resource consumption per one person in Latvia is shown in Fig. 6.1.

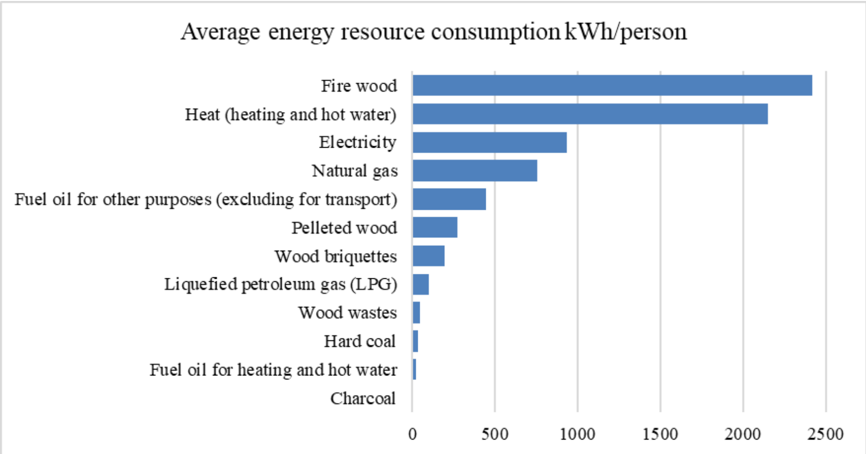


Fig. 6.1. Average energy resource consumption per person in Latvia, 2020. Based on data from the Central Statistical Bureau of Latvia [98].

Firewood and external heat occupy the first positions in average consumption per person, which is explained by the need for heating in the cold winter period, the presence of a large number of private houses in rural areas of Latvia that are heated by wood, and a large percentage of houses connected to central heating in cities. However, the consumption of electricity and natural gas is also significant, approaching 1000 kWh per person.

In turn, from an EU household consumption perspective (see Fig. 6.2), Latvia ranks above the EU average in terms of the proportion of cooking energy consumption to total consumption in households, ranking among countries with a warmer climate, indicating an untapped saving potential in this area.

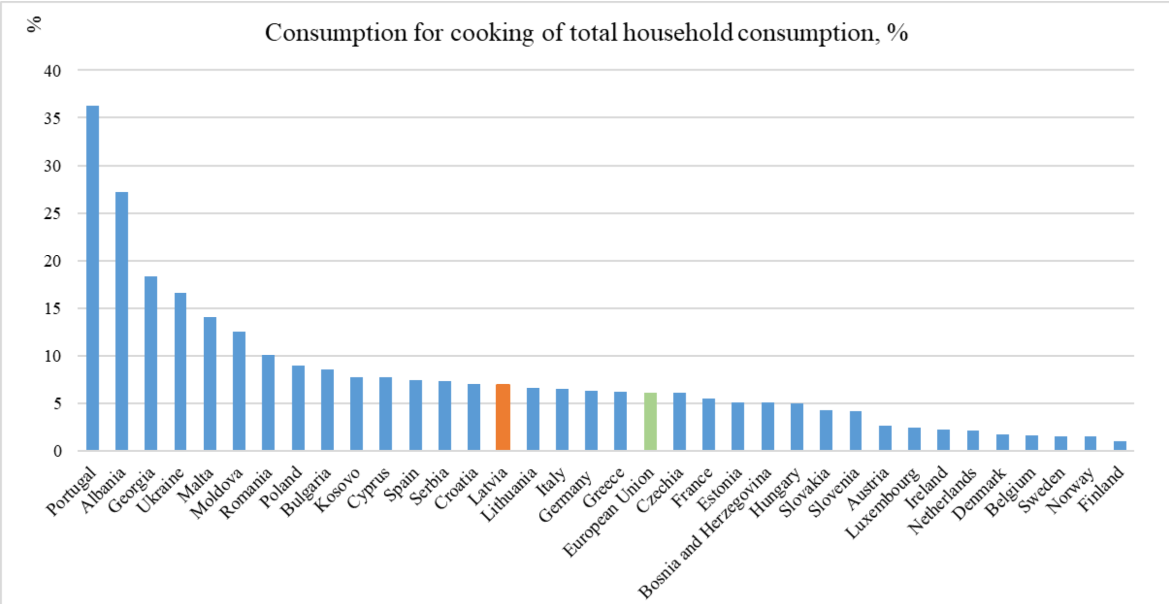


Fig. 6.2. Consumption for cooking out of total household consumption, 2019, %. Based on data from Eurostat [23].

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
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 [99]

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). The last two options can be considered as an undisclosed potential for reducing CO_2 emissions.

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 [99]

Natural gas, which consists of hydrocarbons and is formed in the earth's crust, is usually used for household needs in Latvia. It is a natural resource extracted from the subterranean depths and purified from water, sand and other impurities. However, natural gas infrastructure is relatively expensive and is only available in large cities. Elsewhere, liquefied petroleum gas has historically been used in cylinders and tanks.

The main component of natural gas is methane (70–90 %), and there are also slight amounts of other hydrocarbons, such as propane, butane, and ethane. For household use, the gas is purified and virtually only methane is left. As it is odourless, odorants with a strong smell are added to natural gas to detect gas leaks.

In its turn, liquefied petroleum gas (LPG) is produced in a refining process, where the by-products of the hydrocarbon group are propane and butane. LPG is not extracted out of the depths of the earth, therefore, it is not as pure as natural gas when burned, and emits much more CO_2 and other harmful compounds into the atmosphere. Liquefied petroleum gas consists of propane (90%), methane and butane.

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 connected to the fact that most of them are located in small towns and 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.

6.1.3. The modelling approach

6.1.3.1. Modelling of cooking

For the purpose of comparing indicators from cooking on stoves with different kinds of fuel used, the household consumption of natural gas for cooking was calculated. As the survey held by the author shows, an average household (a family of three people) in Latvia, by cooking on a gas stove, spends an average of 8 m^3 of natural gas monthly, or 8*12=96 m^3 of natural gas per year (which correlates with [178], [179] and the practical measurements made in [171]), and is equivalent to 96*9.7= 931 kWh of energy. The net calorific values provided by "A/S Latvijas Gāze" [180] were used to recalculate the fuel consumption into kWh.

In the next step, the energy consumption of the same average family was calculated when using an electric stove for cooking. Suppose that a family cooks an hour every day during the working week (with 20 minutes for breakfast, 40 minutes for dinner and preparing dinner for the next day). At the weekend, the author suppose that the stove works 2 hours per day, cooking a full breakfast, lunch and, possibly, dinner for the whole family. It was taken into account that usually not all four burners are used at the same time and do not heat up constantly on maximum, but when the desired temperature has been reached, the burners are turned down to a minimum, so it was assumed that only 2 burners work at 2/3 of the power at a time.

The power rating of electric stoves usually ranges from 4 to 8 kW. For calculations, the average indicator was taken — 6 kW. With the constraints assumed, the stove will consume about 0.9 kWh. It will work 9 hours per week and spend 8 kWh, which corresponds to about 33 kWh per month. It should be borne in mind that electric stoves are very different. Depending on the model, the energy consumption can vary greatly.

Thus, the average amount that a household spends on cooking with an electric stove is 33*12=396 kWh per year. The consumption of an electric stove with a glass ceramic plate is by 20% smaller [170], [181], [182], therefore it consumes an average of 317 kWh annually. Induction cookers, however, cannot fall under these averaged calculations, since at a much greater power, they consume less electricity due to the cooking time. Therefore, the annual average consumption for a three-person household was taken from [172], where experimental measurements have been made. The above calculations are depicted in Table 6.3.

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, tCO_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 in 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 [172], where it is based on practical experience. The efficiency of cooking has been taken from different sources such as [169], [170], [183], 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 were calculated by [184] and are presented in Table 6.4.

Calculation of CO2-eq

Volume of burned dry gas	V (Total)	MMsm3/year	96

	COMPOSITION (Mole %)	
GAS PROPERTIES	CO_2	0,35
	H_2S	0,00
	H_2O	0,00
	N_2	5,51
	CH_4	88,27
	C_2H_6	3,48
	C_3H_8	1,31
	iC_4H_{10}	0,29
	nC_4H_{10}	0,40
	iC_5H_{12}	0,14
	nC_5H_{12}	0,10
	C_6+	0,16
		100,00
	MW	18,19
	SG	0,6282

Standard Condition		
P	bar	1
T	°C	15

Density	kg/sm3	0,7601
V (Standard)	sm3/mol	0,0239
W (Carbon)	gr C/mol gas	**12,53**
	kg C/sm3	**0,5235**
GHGs Emission	t CO2-e	**18 42 55**

Table 6.4. CO_2 calculations of the energy consumption by a Latvian household using natural gas for cooking, tCO_2-e/year*

*For getting a visible result from the rather small amount of natural gas, 96 m^3 was assumed as 96 million m^3, and then the result was divided by 1 million.

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, it 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 was mentioned above, this kind of stoves are old equipment, historically their use started in Soviet times, and appropriate documents contain data on LPG consumption rates for cooking, which correlate with the data of the survey — 8.36 litres per person per month [188].

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 6.5 reflects the statistical data concerning Latvian households using gas stoves (operating on both natural gas and LPG) for cooking. The number of natural gas stoves in Latvia was calculated by multiplying the number of households in Latvia with the percentage of households using gas for cooking, the same for the number of LPG stoves. The author did the calculation on the basis of data from the Central Statistical Bureau of Latvia, the "Energy consumption in households" survey [98].

Table 6.5. 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 the significant untapped potential of Latvia 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.

6.1.3.2. Identifying the better potential for decarbonisation by comparing the electrification of stoves to the electrification of passenger cars

In 2019, renewables made up less than 3% of the passenger transport fuel consumption in Latvia, which is far from the EU 2020 target of 10% [185]. Latvia's strategy for achieving climate neutrality by 2050 [167] assumes that the energy transition will be based on a sharp decline in renewable energy prices, with prices for solar panels and wind energy continuing to fall, which is already being observed. Also for the transport sector, it is assumed that in the future, transport energy will be dominated by renewable electricity, advanced biofuels and various electrification technologies, including electric cars. There is an economic rationale for energy transformation (switching from fossil to renewable energy sources), as the additional costs will be covered by savings from reduced air pollution, improved health, lower damage compared to a situation where nothing would be done to mitigate climate change.

Most of the GHG emissions of the transport sector in 2017 were generated from road transport (93.88%), while in the road transport sub-sector the largest emitter by vehicle group is the group of passenger cars. Although the number of motor vehicles in Latvia is lower than the average in the OECD countries and the population is likely to decrease in the future, the number of motor vehicles is expected to increase with the living standards and suburbanisation. According to forecasts, emissions in the transport sector are expected to diminish in 2050 compared to 2017 and 1990 by 53% and 47%, respectively. In order to implement these forecasts and the requirements assumed, Latvia needs to increase significantly the number of electric vehicles in the coming years. Let us perform the calculations required to achieve this goal. Table 6.6. contains characteristics for 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 6.6. 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 (tCO_2-e/year)	2 284 499
CO_2 emissions average per 1 car (tCO_2-e/year)	3.091

Based on data from the Road Traffic Safety Directorate of Latvia [186] and the Central Statistical Bureau of Latvia [98].

To implement the requirements regarding the reduction of emissions, it is possible to apply various plans for the decarbonisation of existing industries and technologies. In the previous chapter, we examined in detail the decarbonisation of Latvian households by electrifying the kitchen. Here, the energy savings and emission reduction from substituting ICE cars to EVs are examined. According to the information of the World Economic Forum [187], the volume of methane produced from household cooking in the United States has the same environmental impact as 50,000 ICE cars. For calculating the energy savings for an ICE car in Latvia, the average fuel consumption was multiplied by average annual mileage per car and converted to kWh: 8 l *13737 km*0.09 kWh = 9 891 kWh. For calculating the EV energy consumption, the assumed average consumption per 100 km was multiplied by the average annual mileage per car: 15 kWh/100 km*13737 km = 2060 kWh. The results of the calculations are described in the next chapter.

6.1.4. Results and discussion

The calculation results shown in Table 6.7 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).

Table 6.7. Calculation of energy savings when switching from gas stoves (natural gas and LPG) to induction stoves

	Energy savings, thsd. kWh	**CO_2 savings, tCO_2-e/year**
The consumption difference (energy savings) between a natural gas stove and an induction stove per year	0.698	0.18

	Energy savings, thsd. kWh	CO_2 savings, tCO_2-e/year
The consumption difference (energy savings) between a liquefied petroleum gas stove and an induction stove per year	2.115	0.5

Table 6.8 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 to induction ones in the case of Latvia; different scenarios of substitution in Latvian kitchens were studied.

Table 6.8. The scenarios of substitution of gas stoves to induction stoves

Scenario No.	Percentage of gas stoves substituted by induction stoves	Energy savings, million kWh/year	CO_2 savings, thsd. tCO_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
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 tCO_2-e 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 6.9 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 6.9. Calculation of energy savings switching from ICE cars to EVs

	ICE car consumption*	EV consumption**	Energy savings, (kWh/year)	CO_2 savings, tCO_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**

	ICE car consumption*	EV consumption**	Energy savings, (kWh/year)	CO_2 savings, tCO_2-e/year
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 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 6.10 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. tCO_2-e/year by switching to EVs or to electric cooking surfaces was made.

Table 6.10. The average cost of EVs and electric stoves in Latvia

	Average cost (EUR)	Number of positions switching	Cost if saving 20 thsd. tCO_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

Thereby, for achieving savings of 20 thsd. tCO_2-e/year, Latvian households need to substitute 6.7 thsd. passenger ICE cars to EVs, or to substitute 62 thsd. gas stoves (both natural gas and LPG) to electric/induction surfaces.

Other results are shown in Table 6.11, which reflects a comparison of CO_2 savings, when subsidising one million EUR to decarbonisation purposes in Latvia.

Table 6.11. 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

To achieve savings of 20 thousand tonnes CO_2-e per year, Latvian households will need to substitute 6.7 thousand passenger ICE cars to EVs, or to substitute 62 thousand gas stoves (both natural gas and LPG), which is 12% of the total number of gas stoves, to 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 Fig. 6.3.

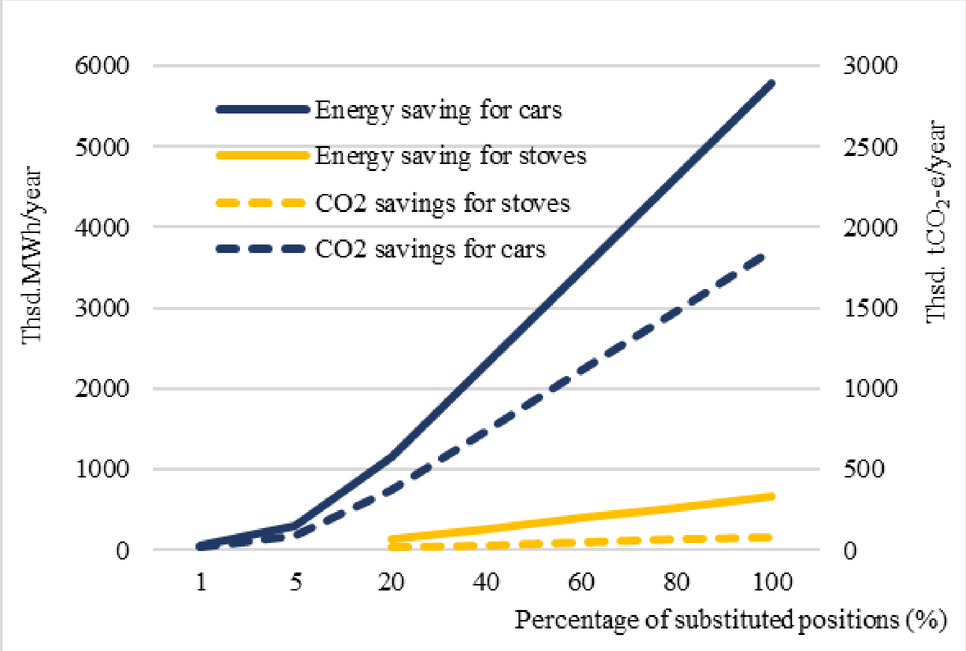


Fig. 6.3. Energy and CO_2 savings.

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.

6.1.5. Chapter conclusions

Cities and towns can be called “super-consumers” of energy. Taking into account the fact that households represent one of the largest group of energy end users in Latvia, it is possible to achieve the most significant energy savings in this sector by improving the energy efficiency of existing buildings by means of introducing new, energy-efficient equipment. 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. No doubt, this does not eliminate the need for decarbonisation in the transport sector either; however, it is necessary to choose an optimal and efficient way to be aware of and use the required resources.

Natural gas is a fossil fuel that is widely used in Latvia — for cooking, heating and energy production. It is considered more environmentally friendly, as its burning leads to significantly lower CO_2 emissions compared to coal or oil. However, the main component of natural gas — methane — is a powerful greenhouse gas, and to achieve the goal of Strategy 2050, its use must be reduced, switching to more environmentally friendly, green types of energy sources. Liquefied petroleum gas is even more a source of harmful emissions and must be replaced in parallel with natural gas or at first.

This part of the Thesis proved 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 behavior changes modelling in dormitories

6.2.1. Motivation for the research

Despite the significance of the set climate and energy goals, to date there is a lack of models to calculate the real small or large contribution of the daily habits of energy consumers being changed, an increase in the awareness of energy consumption in various consumer groups, e.g. dormitories, social homes, offices, etc. A number of topics for research remain undiscovered. The habits of different groups of urban end users are formed over years or even decades. There are many studies that research the saving of energy and the application of new technologies to use energy more efficiently [39], [166], [188]–[196]. However, the habits of the residents themselves, as well as the possibility of their change and the quantitative modelling of these changes in terms of energy consumption are critically little studied. It needs to be explored if there is room for correcting or changing energy habits that will increase efficiency, reduce energy consumption while maintaining the desired level of comfort. It is necessary to measure the contribution that can be made by changing energy consumption habits in different population groups and to find out whether different social groups of residents should be encouraged to change their energy consumption habits and where the gaps are in the energy behaviour of the residents.

To identify the degree of influence of the energy consumption habits of residents on the indicators of the energy system in practice, in 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.

6.2.2. Methodology

Data aggregation

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 6.12. This information includes the following: the number of floors, the approximate number of inhabitants, the living space size and the yearly energy consumption. The yearly energy consumption information is taken from the archived smart meter measurements. The sum of each dormitory reflects the total consumption of the approx. 1500 dormitory inhabitants.

Table 6.12. General overview of dormitories

	Number of floors	**Users**		**Living space**		**Yearly energy consumption, kWh**
		on the floor, number	***in the room, number***	***floor, m^2***	***room, m^2***	
Dormitory 1	5	60	5	360	30	109440
Dormitory 2	5	80	2	480	12	253635
Dormitory 3	5	80	2	480	12	246097
Dormitory 4	5	80	2	480	12	321194

The models developed use information from multiple sources; this was done to tackle the issue of privacy and data availability. The model must be capable of creating a consumption pattern without a continuous consumption sample to address the issue of data availability; in addition, by creating a modelled consumption, the actual user consumption habits are hidden, keeping the privacy priority high on the agenda. Additionally, an overarching limitation is set to the examination of topics related to the energy use matter.

The yearly energy consumption provides guidelines and a boundary but does not provide information on the daily consumption changes. The following aggregated data attempt to provide the daily change information from multiple sources — surveys, smart meter measurements and additional information. These information sources are used due to their availability and functionality.

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. In Figure 6.4, a sample of the conducted survey table is shown, as in the image there are two main axes, the horizontal axis representing the passage of time with 15-minute increments and the vertical axis representing the list of appliances as well as their assumed average nominal power.

The person filling in the consumption survey uses numbers from 1 to N, representing the number of certain appliances used in an exact time period, where every period is 15 minutes. By using a number larger than 1, the user can show the use of multiple appliances of a similar type or greater appliance nominal power than the average specification.

This conducted survey provides the information of the user's consumption through his/her assumptions, meaning the real consumption could be similar or greatly different. This information also lacks the information of day-to-day changes in individual consumption, but this survey was made for the goal of assessing the appliances used and the overall user habits, 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	7:3
01	Stereo	60																															
02	Air conditioning up to 7,500 B	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	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			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. 6.4. Consumption survey snapshot.

In total, slightly under 100 surveys have been collected, and each survey is individually analysed, determining user-indicated consumption habits to create potential day-to-day changes in the individual situation. Due to the lack of alternative consumption pattern depiction, the resulting habits are assumed to be marginally accurate, with some days more accurate than others and used as appliance pattern guidelines.

Smart meters have been deployed in the UPB student dormitories. The deployment contains 39 Smart Low-Cost Advance Meters (SLAM), single-phase meters. In every dormitory, there are three SLAMs deployed per floor. The informational data of the SLAM meter are given in Table 6.13.

Table 6.13. SLAM meter data

Technical data	
Parameter monitoring	*U, I, P, Q*
Nominal reference current	*5:00 AM*
Maximum current	*60 A*
Frequency	*50 Hz*
Reference voltage	*230 V*
Sampling rate	- *Load profiling*
	- *1 min (20 days)*
	- *15 min (24 months)*
	- *Hourly (3 years)*

Metrological data	
Active energy	*Class B*
Reactive energy	*Class 2*

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. The dormitory’s annual energy consumption is given in Table 6.12.

The additional information provides data from the local situation, which is needed to optimally depict the local situation in Bucharest, where the dormitories are located. In order to simulate a natural lighting situation, information of the natural lighting in Bucharest was taken from an online source [197]. The information on this weather website divides the intensity of natural lighting into five parts — night, astronomical twilight, nautical twilight, civil twilight and daylight. For the purposes of sufficient natural lighting, the daylight data were taken as the sufficient natural lighting moment. This provides the information of the natural lighting potential for a whole year.

Model development

This section contains a description of the developed models and their operation logic. A model is a simplified object that retains the most important properties of a real existing object or system and is intended for their study; it is a simplified representation of a real object and / or the processes occurring in it.

Two categories of models were considered — auxiliary (time series analysis) and conclusive ones. Auxiliary models simulate a 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 [198]. One of the 48 collected student schedules is used for each user, providing study occupiedness for every working day of the academic year. This activity is mandatory, with an assumed attendance of 100%. Additionally, up to one hour outside the study schedule start and its end, an additional time interval is added, simulating travel time, longer classes or early arrivals.

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.

The last piece of data to be added is the sleep schedule. No survey has been conducted to assess the actual length of the sleep period of dormitory students. 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. For users who would actually sleep for a consistently short time period, the assumed additional "sleep" period can be addressed as unaccounted-for outside activity period, because of these activities not providing contribution to the overall dormitory consumption. Additionally, it is assumed that users have at least one hour before going to sleep and before they leave for their outside activities. In Figure 6.5, 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 6.14, an hourly example of user behaviour is shown. In the actual model, user behaviour is divided by 15-minute increments but to show a greater range, the sample table is converted to hours. In the first row of this table, specific hours of the day are registered and in the second row, previously examined activities — outside and home activities and sleep — are depicted with a certain colour and number. If we consider a view of 24 hours, in the table below from 00:00 to 9:00, coloured in light blue, the "sleep" period is represented; then in the 10th hour, coloured in red, "home" activity is labelled with 1 and from 11:00 to 17:00, coloured in grey, is "outside" activity depicted with the value of 2. Similarly, the interval from 18:00 to

21:00 is labelled as "home" activity and 22:00 to 24:00 is the "sleep" period. This generated information array is used by the actual model with 15-minute increments to check the user behaviour for every day of the year; additionally, it can be noted that time itself of the first row is also used in the model but converted to minutes.

Table 6.14. 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, using only the daylight portion of the information. 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. This period is assumed as the limit for natural lighting sufficiency and is generated based on information of daily sunrise/sunset time changes every day.

In Table 6.15, an example of a daylight period is shown. The table is divided into three rows showing the day, the start of daylight and the end of daylight. The starting times of daylight are collected in the second row and coloured in orange, while daylight-ending times are in the third row and are coloured in blue. These times are shown in hours and minutes for the example only; in the actual daylight model, these times are converted to minutes. Additionally, due to the model operating on 15-minute periods, the actual used time values are rounded up or down by 15-minute increments.

Table 6.15. Daylight period sample

Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
08:15	08:14	08:13	08:12	08:11	08:10	08:09
16:30	16:32	16:34	16:36	16:38	16:40	16:42

C. Appliance model

The individual user consumption is based on all the appliances used by the user. 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 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 Figure 6.5 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.

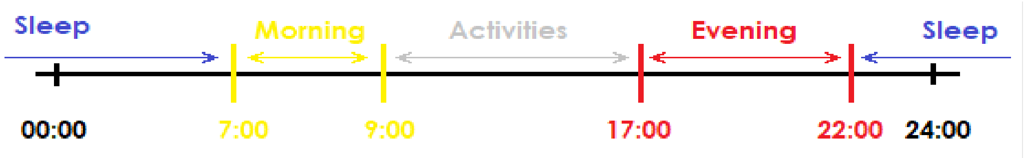


Fig. 6.5. The division of the day into periods.

The control setting of each individual appliance is made unique based on 11 parameters. The following settings are available for all appliances except appliances that operate 24/7:

1. Appliance consumption — a separated setting for the morning/evening period. The setting is used to set the rated power of appliance operation, if more appliances that are similar are used simultaneously or more/less-powerful appliances are used in other periods.
2. Minimum operation time — a separated setting for the morning/evening period with a 15-minute step. The setting is used to set the minimal length of time for which the appliance is used.
3. Maximum operation time — a separated setting for the morning/evening period with a 15-minute step. The setting is used to set the maximum length of time for which the appliance is used.
4. Appliance use chance — a separated setting for the morning/evening period. This setting modifies the frequency of appliance use, giving a chance for an appliance to be used in each operation area with an individual use chance.
5. Window of operation — separated settings for the morning/evening period. These settings limit the use of appliance, if in the operation area the available time is less than needed for using the appliance. Example: if a user has one hour before sleep, he will not use a food cooker for 30–60 minutes.
6. Use period preference — this setting is combined for the morning and evening periods; it sets user preferences of the time period when the appliance would be used. The setting can be set for operation in the morning, evening, morning/evening or both time periods.

Conclusive models

A conclusive model uses the outcome of auxiliary models to simulate the individual consumption pattern, implement changes and test solution feasibility. Regarding conclusive models, there are two positions — user consumption and reduction of appliance consumption. A user awareness model is used to generate the total consumption of an individual user for every day of the year, based on the user behaviour and appliance use preferences. The appliance consumption reduction model uses the ordinary user appliance consumption produced under the user consumption model and simulates for a specific appliance the reduction of appliance use based on user awareness impact.

A. User consumption model

The user consumption model designs the individual user consumption behaviour by generating the user consumption pattern. The user consumption pattern generation takes in mind 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. The modularity of the model is achieved through appliance settings, providing the opportunity to modify the accessibility and operation of each appliance by adjusting the 11 available appliance sets to satisfy the individual use case.

This model operates by, firstly, selecting an individual user from the users' activity schedule, simulated by the user behaviour model, meaning the user has a specific daily occupation schedule which serves as the action basis. Secondly, a list of appliances used and user appliance use preferences are required to be set in appliance model settings, which are based on a single consumption survey. This summarises the model's general operation and the need for individual user data analysis beforehand.

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. In general, the difference between modelled user consumptions is simulated through different appliances and user preferences for using different appliances, but in this case, when the same survey information is used, margins in operation windows, operation start moments, use chance and availability play a large role in individuality creation. The creation of unique outcomes from a single data source is done with randomised values. In the appliance settings, firstly, each appliance has a chance of being used; this chance affects each user individually, producing different outcomes. Secondly, each appliance has a minimum and maximum operation time, which is selected randomly each time the appliance is used; this is unique for every single time the appliance is used unless the maximum and minimum values are the same. Lastly, each appliance has a randomly selected moment when the user starts to use it. This moment is made unique by two things: user availability, which is unique for each individual schedule and the random selected time, making the appliance operation times diverse even between the same settings.

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 between the user patterns with smallest total consumption contributing to a six times smaller consumption than the largest total consumption contributor does. 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.

B. Appliance consumption reduction model

The appliance consumption reduction model addresses the task of exploring user awareness changes through simulation of energy use awareness increase in the form of consumption reduction for selected appliances. The consumption reduction algorithm can be divided into three distinct operation models that can address many appliances.

The first algorithm operation model for consumption reduction is for appliances that are used 24/7, but should not be used in such an extended period of time. This means using sleep mode or shutting down appliances when they are not in use. An appliance is considered in use when the user is at the student dormitory and is not sleeping, this means that periods of sleep and outside activity are the moments when the sleep mode or appliance shutdown is simulated.

The second algorithm operation model assumes that as a result of increased user awareness, the user will try to use certain appliances less, but this does not mean reduction of comfort but rather using sleep modes or shut down for an appliance when, for instance, two entertainment appliances are active, or choosing not to use the appliance for large extended periods by taking breaks from time to time.

The last algorithm is only used for lighting solutions, but is not limited to them. This algorithm combines daylight model and artificial lighting use with a goal to simulate a change in user awareness, moving users to use natural lighting over artificial lighting solutions when possible.

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.

6.2.3. Results and discussion

The simulated results of the models achieve a certain accuracy in comparison to the measurements of real smart meters. This accuracy is determined by result validation. The result validation is covered under the following subsections: Data Analysis and Accuracy of Results, examining the approach used and the achieved results.

Data analysis

Data analysis covers the approaches used in the developed algorithms to test the achieved model result accuracy in comparison to real measurement sample values. Algorithms use two approaches — peak comparison and direct value comparison; each approach examines data differently, but both use data sectoring (see Fig. 6.6), addressing sector similarities. This data sectoring examines each of the divided sectors individually, finding the partial similarities without the overview mismatch. In this way, sectors with a high accuracy can be highlighted, despite the poor accuracy in other sectors.

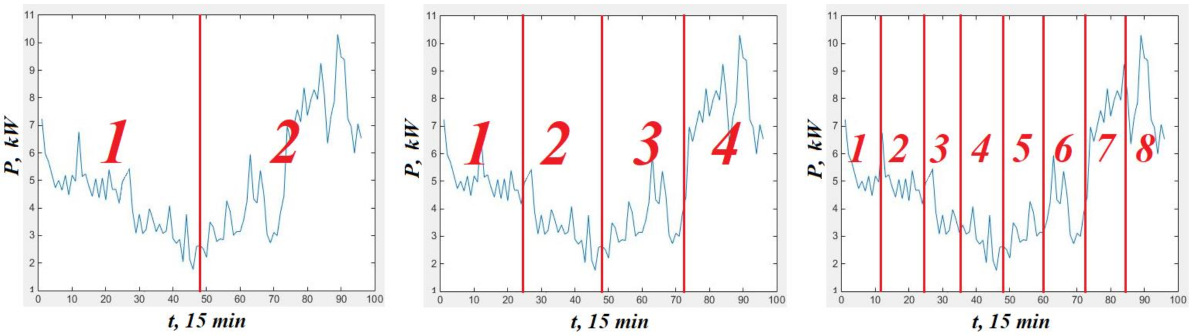


Fig. 6.6. Sector division.

The sector division uses a single day period of 24 hours, which in the model is equal to 96 periods of 15 minutes each. In Figure 48, three stages of sector division are presented, which are used to gradually isolate the compared sectors, thereby increasing the level of detail and reducing the data fluctuation margin. Sector division stages are achieved by repeated sector division in two, resulting in sectors 1 to 2 with a 48 period range, further sectors 1 to 4 with a 24 period range and, lastly, 1 to 8 periods with a 12 period range each. The division into a higher number of sectors is performed if the prior division comparison does not provide high accuracy results, thereby dividing sectors into smaller samples and testing the accuracy once more until the last stage is achieved and data correlation is deemed absent.

Peak comparison

Peak comparison is the first approach used to determine data correlation through periodic peak value selection to generate the consumption silhouette. The silhouette is found for real measurement data and modelled data, and is compared by generalising the change in sector values — rising, declining or without change. This comparison provides a view on generalised value changes and similarities between the data changes.

The peak values are selected based on Equation 6.1; this calculation uses an eight-period step to generalise the peak value and this step is reduced as the size of the individual sectors diminishes.

$$\int \ (j = 1)^{(8^*)}(M_j) \to max, \qquad (6.1.)$$

where: j — Moment in time, refers to 15 minutes *maximum value is dictated by sector size.

M — Measurement reference, kW.

In Figure 6.7, an example of peak comparison is visualised, depicting how the algorithm generates the sector silhouette. The top figures represent the real smart meter measurements and the bottom figures represent the model-simulated consumption result. Additionally, the real and model values are divided in sectors in three stages; here the generalisation of sectors provides the desired result of highlighting similarities. When Stage 3 sector division is achieved, it can be seen that six sectors are similar when comparing the real and model data.

This results in 75% of data similarity based on the approach used, deeming the model situation a close similar depiction.

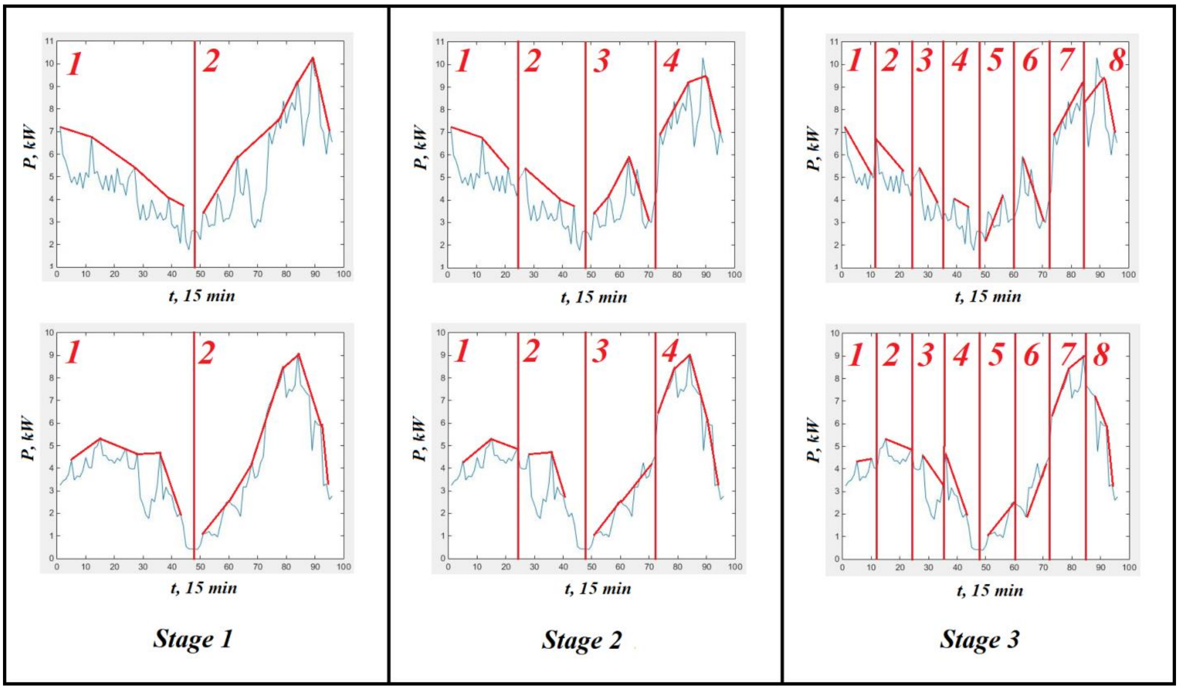


Fig. 6.7. Visualisation of peak consumption approach.

Through this operation, a single real-measurement sample day is compared with every day simulated by the model, finding the most optimal matches.

Direct value comparison

Direct value comparison is the second approach used, which simply examines the fluctuation of the results between real and modelled data. This is done by calculating the value fluctuation of each 15-minute period of the compared data. The fluctuation is determined by using Equation 6.2. The example shows an equation used on the 96-period range, which depicts a whole day, but like the first approach, this approach also uses sector division, and the range is adapted based on the size of the sector tested.

$$\sum_{i=1}^{96^*} |RM_i - MM_i| \rightarrow min, \qquad (6.2.)$$

where: i — Moment in time, refers to 15 minutes;
*Maximum value is based on the sector size.

RM — Real measurement reference, kW;

MM — Modelled measurement reference, kW.

Equation 6.2 is used for every modelled day and the day with the smallest summarised value difference between the real measurements is deemed to be the best model depiction of the real situation.

Accuracy of results

The accuracy of the results is derived based on the analysis provided by the two used approaches — peak comparison and direct value comparison. The use of the approaches can produce one or multiple similar matches for the compared real situation. To conclude the overall similar situation, the approach results must eventually match. The eventual match is found by repeated use of each approach to find additional results and ranking the results from the most matching to the least matching ones. This list is produced by both approaches and is then scanned through to find the same model situation from each approach with the highest similarity value, based on the individual approach. This ultimate result is deemed as the best representation of the real measurements.

The similar situation found proves that the model can provide a close depiction of the real potential consumption because the tested consumption uses preselected consumers which most optimally depict each of the dormitories, thereby no new consumption generations are made meaning that data accuracy is commonly expected. In other words, the model is able to produce almost 1:1 pattern match to real measurements if the model is launched continuously until such a situation is achieved; however, this does not provide the commonly expected accuracy.

One similar situation considered by both approaches was found as shown in Fig. 6.8. In this figure, 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. Additionally, in Figure 6.9, the general change in value is depicted by using simplified vectors; here similarities are also present, with a fairly similar general value change. This further shows that there are many similarities between these situations, but it must be noted that the modelled consumption does have a slightly lower overall consumption. If the overall consumption value were to be generalised, the graphical depiction would pose an even closer resemblance.

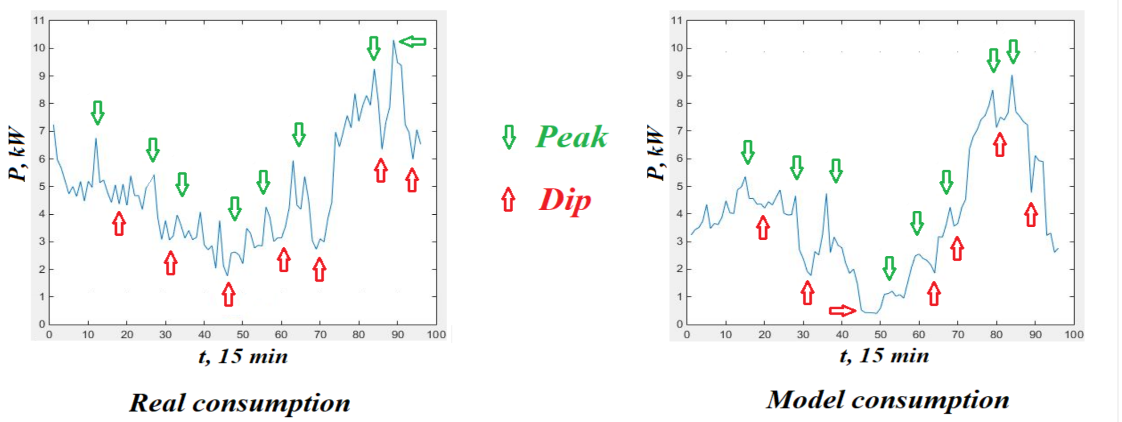


Fig. 6.8. Dip and peak comparison.

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. Nevertheless, the depicted model consumption in Figures 6.8. and 6.9. is deemed as the most accurate representation of the real consumption, based on the accumulated approach results.

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 Figure 6.9, a single day in autumn has been used to show an example of the match found.

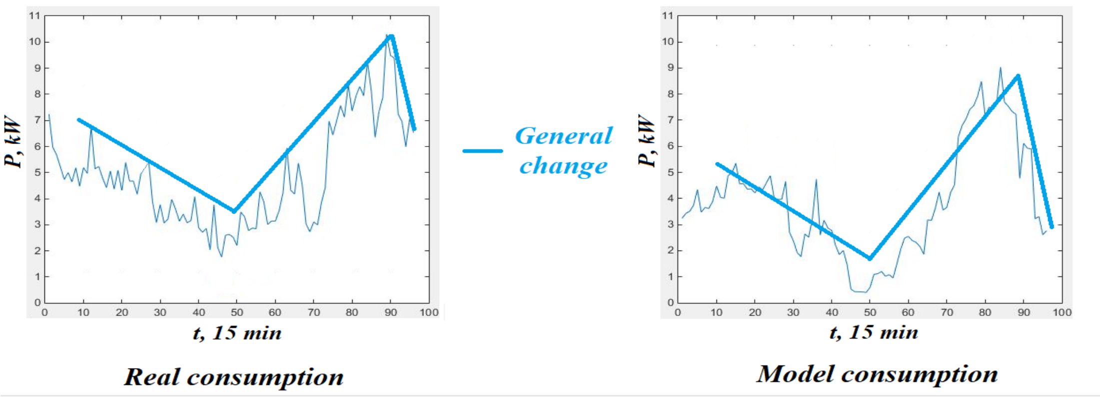


Fig. 6.9. General change in consumption.

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 6.16, 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 6.16. Assessment of measures influenced by user awareness

Parameter	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.

Parameter	Definition
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, we address each pre-selected appliance that was determined to have the potential to be impacted by changes in user awareness. In Table 6.17, the results of 3rd dormitory user awareness increase are assessed and represented for each appliance individually. The test result values for each appliance are shown in percentage of the total annual energy consumption.

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 three 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. In a real situation, it has been assumed that the 50% is achievable, because each user will be impacted by the awareness increase differently, where some with the same knowledge increase will pass the 50% user awareness mark but others will be under this mark and thus the average value could be around 50%.

Table 6.17. 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%

Examining Table 6.17 with a 5% user awareness increase, the results show non-linear changes in the values. This has been expected, because each user has a unique appliance consumption, meaning the user awareness increase for one user is able to provide a larger consumption reduction than that of the other.

One of the interchangeable results are "Natural lighting over Fluorescent" and "Fluorescent to LED conversion"; these are the results of the table in the 1st and 3rd columns. An interesting result that can be highlighted is that the conversion to LED lighting provides a slightly larger consumption reduction than users' more efficient use of natural lighting. This provides valuable information that a user can ensure sufficient savings by merely using more efficient lighting without thinking of behaviour changes themselves. Furthermore, achieving a plausible 50% user awareness provides a theoretical 100% achievement, which can be made by the reduction created by some users converting to a LED solution and other user behaviour changes to use natural lighting more efficiently. The end result of the combined different efforts provides around the same as 100% of the users switching to natural lighting or 100% of the users converting to a LED solution. Another major assessment is the inefficiency of optimised kettle use, although the appliance has a large consumption while operating the total consumption over time is quite small and across all the dormitories the total consumption reduction due to optimised use provides only half a percentage. This result indicates that in the tested cases the optimised kettle use does not provide large consumption savings and the solution will not be included in the final assessment. Column 2 “Natural lighting over LED” will not be addressed in the final assessment either, because these results serve as a means of comparing the efficiency of lighting solutions and highlight the best practice outcome.

6.2.4. Chapter conclusions

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. Sleep mode in Dormitory 3 provided a 2.1% change, while in Dormitory 1 it was 0% due to the lack of excessive unattended PC usage by the model users.
- 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 a 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 adopted 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 to 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. 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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ANNEXES

Annex I

Smart City Questionnaire

The survey is anonymous. The information received from the survey will only be used as aggregate data.

Please do not use any other sources of information than your knowledge! Thank you!

How old are you?

- Below 18
- 19-30
- 31-49
- Over 50

Which country do you live in?

- Latvia
- Romania
- Brazil
- Chile
- other

Do you know what a smart city is? Have you heard of initiatives aimed at helping a city become smart?

- Yes
- Not
- Very little

Do you know about projects in your city aimed at “smart” energy consumption?

- Yes
- Not
- Very little

Are you interested in saving energy?

- Yes
- No

What is your attitude to energy saving technologies?

- I do not know and do not want to know
- I do not know but want to know
- I know but do not use it
- I know and use a little bit
- I know and actively use

What would you like to do to save energy?

- to introduce a new energy saving device that automatically adjusts your resource consumption
- I prefer manual everyday correction of equipment that consumes energy resources

What would encourage you to make more use of energy saving technologies?

- the example of neighbours / friends / acquaintances
- public campaigns explaining the benefits of this kind of technologies
- vividly presented savings of energy and money
- public people showing the use of energy saving technologies
- understanding that I will save the nature and earth resources for my children
- other

Is it important for you to use new modern technologies in your home?

- Yes
- No

How much money would you agree to pay monthly for new technologies in your home, knowing that they will help to save energy and improve the environment?

- 1-2 euros
- 3-4
- 5-10
- 10 euros or more
- 0

I am ready to use the new technology if it pays off:

- after 1-2 years
- 3-4 years
- 5-10 years
- I am not ready

What do you think about choosing another electricity consumption mode for saving resources and money?

- it causes me confusion
- I tried and it did not produce tangible results
- I do not know anything about it
- I heard (from friends / acquaintances / media / ...) that it does not produce significant results
- Stability and predictability are the most important things to me, and I do not want to change anything
- I'm ready to try if I'm convinced of the benefits that I get
- I use it and am satisfied with the result
- I am ready to switch to another mode of consumption
- I'm ready to play the game by managing my resources in the mobile phone application

Annex II

Model Validation for base year

The model is validated by running it for the historical year of 2017 and comparing the results with statistical data for this year. The model performs well, and the differences are relatively small, as shown in Figures A.1–A.2.

In Fig. A.1., statistical and modelled electricity supply in 2017 by source is given for Estonia, Latvia and Lithuania. The modelling results for all the Baltic countries match statistical data quite nicely, as the differences are minimal. Statistically, in Estonia in 2017, 9.2 TWh of electricity was produced from oil shale and oil shale gas, while the model results show 8.9 TWh. Furthermore, electricity net exports statistically were somewhat higher than those modelled, 2.7 TWh vs 2.0 TWh. Other differences are negligible. In Latvia, in 2017, more than 85% of the electricity was produced either in hydropower plants (4.4 TWh) or natural gas power plants (1.7 TWh). The model gives very similar results — 4.4 TWh and 2.0 TWh. Electricity from biomass accounted for 0.4 TWh vs 0.6 TWh, from biogas —0.3 TWh vs 0.3 TWh. In Lithuania, the vast majority of electricity is imported. In 2017, net imports were 8.7 TWh. The model produced a slightly higher value — 8.8 TWh. In the modelling results, electricity production is also marginally higher in biomass, biogas and waste power plants by 0.03 TWh, 0.07 TWh and 0.01 TWh respectively. However, it is lower in oil power plants by 0.1 TWh. Electricity production in wind, hydropower and solar power plants does not differ between historical data and modelling results.

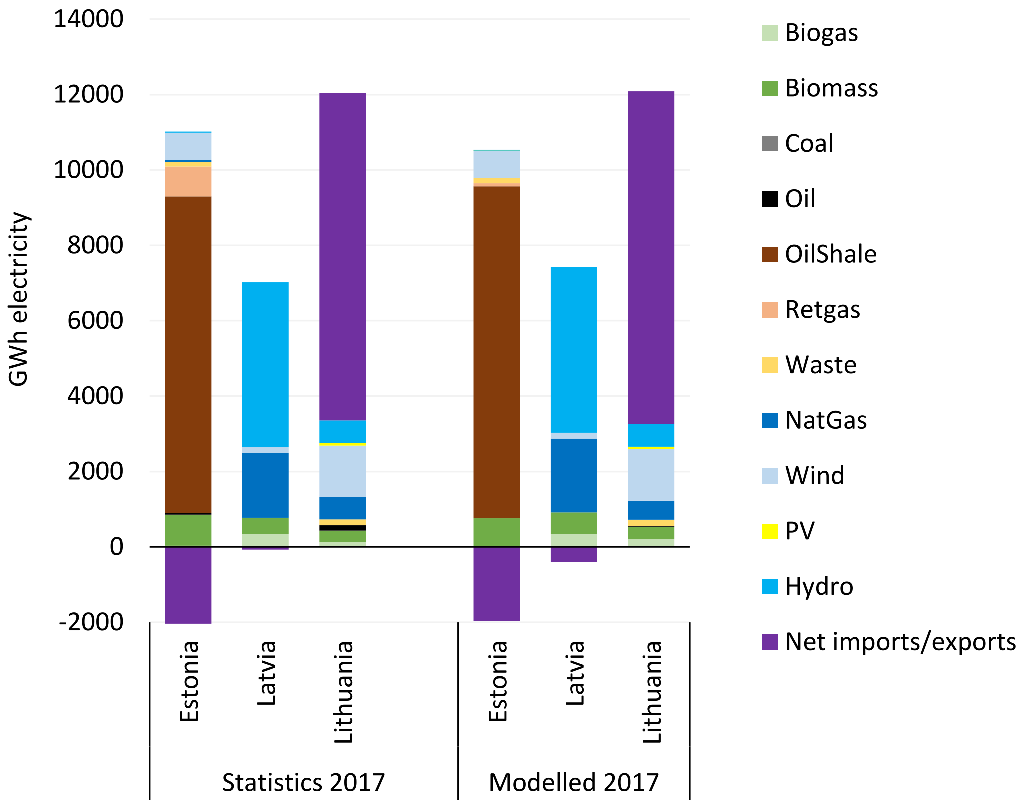
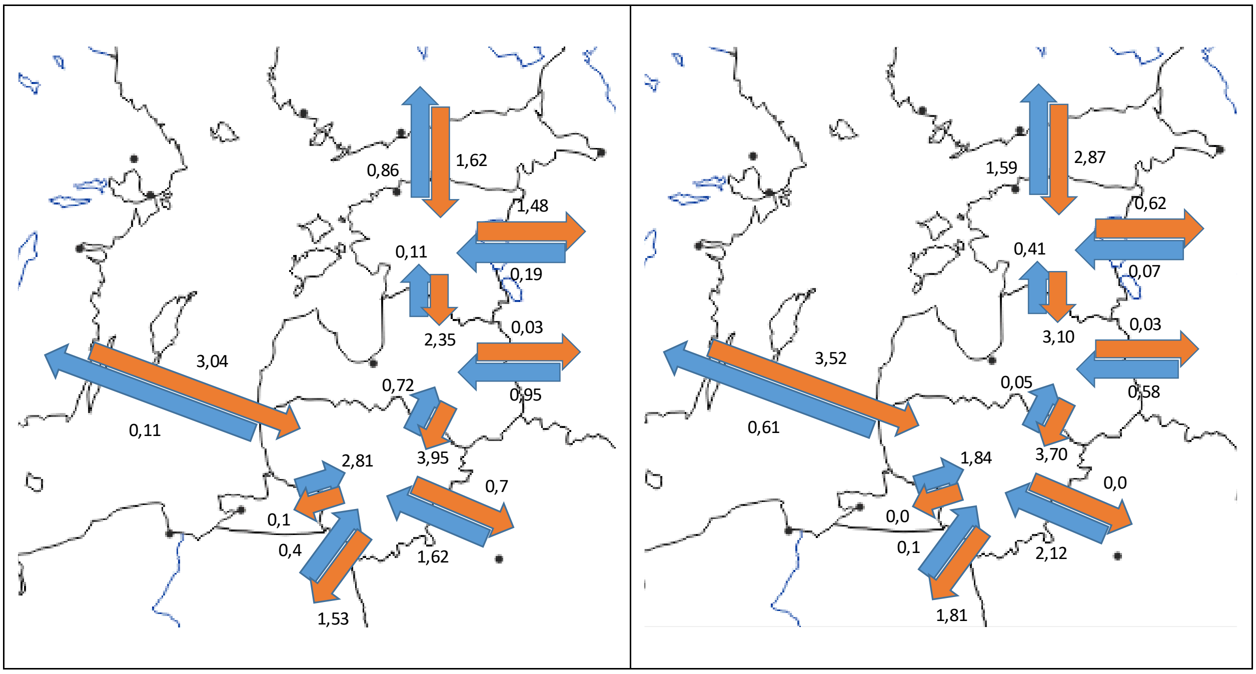


Fig. A.1. Statistical and modelled electricity supply by source and by country in 2017.

Total net imports/exports yielded by the model are close to the historical data. However, there are some differences in import and export flows by country (see Fig. A.2). It is because the Baltic countries have interconnections with Sweden, Finland, Russia, Belarus, and Poland, whose power systems are not modelled. Thus, imports from and exports to these countries are only limited by the capacity of interconnectors and hourly electricity prices. Nevertheless, the overall output of the model is reasonable when assuming calibrated interconnector capacities. The actual modelling of the power flows would be complicated due to transit flows from the Moscow region to the St. Petersburg region through the Belarusia and Baltic electricity networks.



(a) Statistics 2017 (b) Modelled 2017

Fig. A.2. Statistical and modelled electricity imports and exports in 2017 (TWh).

The results for district heating supply by source are very similar to the statistical data, especially for Lithuania (see Fig. A.3.). For Latvia, the model utilises biomass heating and CHP plants a little too much (4.2 TWh vs. historical 3.3 TWh). The most considerable discrepancies are observed in the case of Estonia. Modelling results show 1.1 TWh of district heat generation from natural gas, 0.4 TWh from waste, 1.5 TWh from oil shale and shale gas, 1.8 TWh from biomass, while historically it was 0.7 TWh from natural gas, 0.3 TWh from waste, 1.1 TWh from oil shale and shale gas, 2.5 TWh from biomass and 0.1 TWh from other sources.

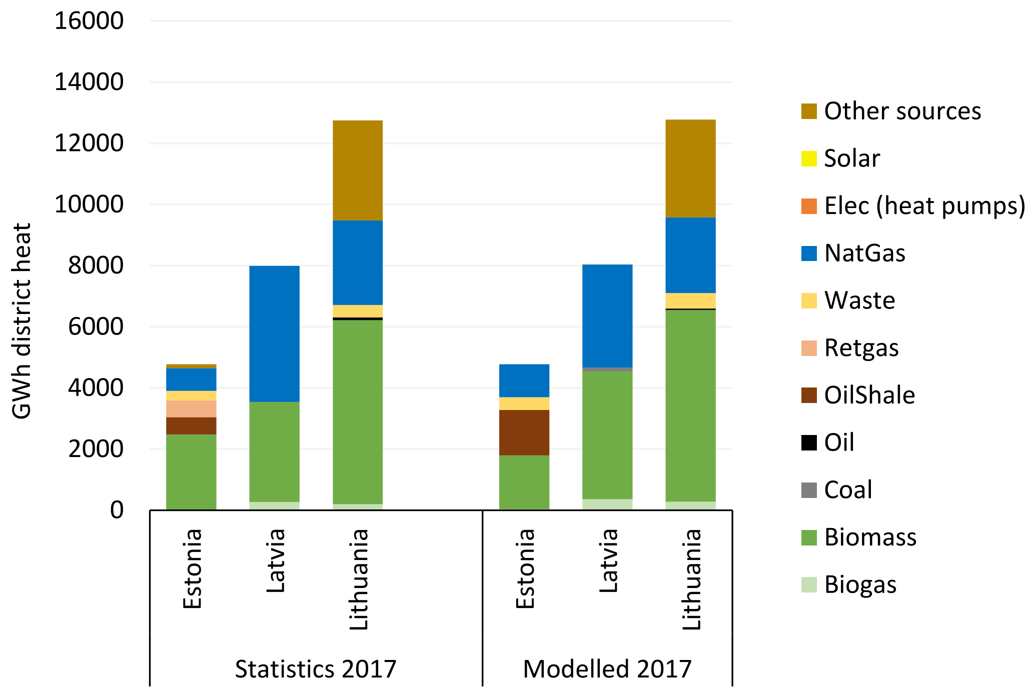


Fig. A.3. Statistical and modelled district heat supply by source and by country in 2017.

We can conclude that the model yields reasonably accurate results for power and heat sectors as the differences between modelling results for 2017 and historical data are insignificant. The outputs of buildings and transport modules are well calibrated to statistics without giving any room for the model to decide what energy carriers to use. Thus, it was considered that the model is sufficiently calibrated and suitable to analysing scenarios for the future years.

Annex III

2030: validation results

Results show a fast transition in power and heat generation towards renewable sources in all three Baltic countries. However, electrification of transport and heating seems to have only a limited role within the next ten years. Overall, the modelling results support the feasibility of national plans in fast transition, but raise energy security considerations for all three Baltic countries. Modelled development would lead to a significant reduction in EU ETS emissions but a slight increase in transport emissions between 2017 and 2030, risking national 2030 non-ETS targets.

Fast transition of power and heat generation from fossil to renewable

According to modelling based on national plans, the Baltic power system will shift from 53% fossil-based electricity generation in 2017 to only 4% in 2030 (see Fig. A.4). Simultaneously, the annual share of electricity produced by wind and PV technologies would increase from 11% to 63%. The fast transition is a result of large investments in wind power and PV technologies, decommissioning of Estonian oil shale-based generation and an increase in emission trade prices.

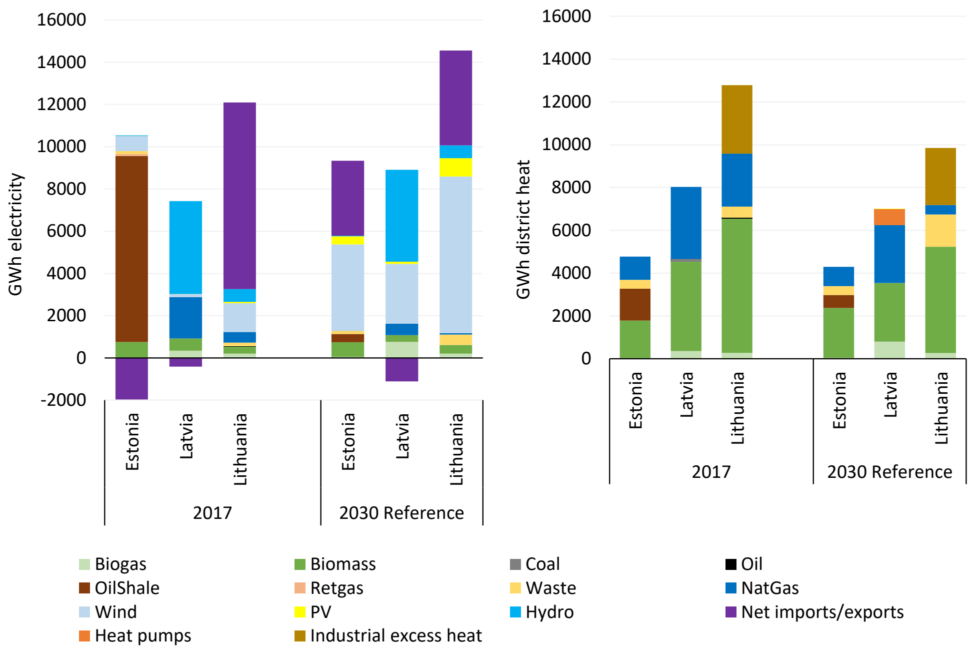


Fig. A.4. Annual electricity and district heat generation by source and by country in 2017 and 2030 reference scenario.

The change is more pronounced in Estonia and Lithuania, while Latvia is expecting more subtle changes. In district heating generation, fossil fuel phase-out is balanced with decreasing demand and existing biomass capacity, leading to a less dramatic transition.

Potential challenges in energy security

The results indicate that the energy security situation will develop differently in each of the three modelled countries (see Table A.1). While the total Baltic domestic electricity generation would slightly increase (by 2.3 TWh) and both the electricity and natural gas import dependency would decrease (by 1.4 and 5.5 TWh correspondingly), the phase-out of dispatchable thermal capacity, the increase in variable renewable energy (VRE) and the desyncronisation from BRELL may impact operational security. Individual challenges for each Baltic country are identified.

In Estonia, modelling the 2030 reference scenario without added domestic capacity to replace phased-out oil shale units leads to volatility and frequent price peaks in the Estonian marginal electricity prices. This points to challenges in operational balancing. To correct the model stability and provide reserves, new capacity needs to be introduced. A comparison between gas turbines, biomass CHPs, batteries, new interconnectors, leaving oil shale units as backup capacity, results in grid-level battery storages being the most cost-efficient option. A 200 MW battery unit is introduced and the two most recent Narva oil shale units (270 MW) are left as backup for the Estonian 2030 reference scenario.

In Latvia, planned wind power investment levels in the 2030 reference reduce the operational hours of CHP units, namely Riga's large natural gas CHPs, to less than 1000 h/a. The model substitutes CHP generation with wind power and heat boilers. This may suggest challenges in unsubsidised commercial feasibility of CHP units, especially during warm-weather years. Notably, sensitivity scenarios indicate that electrification measures could be able to support the operation of CHP units by increasing the value of electricity.

In the Lithuanian 2030 reference scenario, up to 82% of domestic electricity and 57% of the electricity demand would be generated by VRE. The transition to a highly variable system coincides with planned changes in the interconnectors. While the model is able to support high variability by active use of pumped-hydro storage and interconnectors, the resulting high ramp rates in the interconnectors may be an indication of issues.

Table A.1. Summary of energy security indicators by country including annual domestic generation, imports and exports, and domestic share in 2017 and 2030 reference scenario

	Estonia		**Latvia**		**Lithuania**	
	2017	**2030 reference**	**2017**	**2030 reference**	**2017**	**2030 reference**
Domestic generation (TWh)	10.54	5.47	7.43	8.88	3.19	9.20
Total imports (TWh)	3.35	5.65	3.74	2.33	11.37	7.60
Total exports (TWh)	5.31	2.10	4.14	3.44	2.54	3.11
Domestic share (%)	123 %	60 %	106 %	114 %	25 %	63 %
Indicated security concern	Balancing capacity		Commercial operation of natural gas CHPPs		High ramp rates in interconnectors	

Slow changes in transport

In the transport sector, transport volumes increase faster than alternative fuel sources. As a result, fossil fuel demand increases even though the share of electricity and bioliquids increases (see Fig. A.5.). The share of battery electric and hybrid electric vehicles is expected to reach 3% of passenger km's by 2030, and the share of biofuels is expected to increase from 3.4% in 2017 to 6.5% in 2030. The Baltic countries have different target levels for bioliquids ranging from 2% in Latvia to 10% in diesel in Lithuania by 2030. The modelled results include only passenger vehicles.

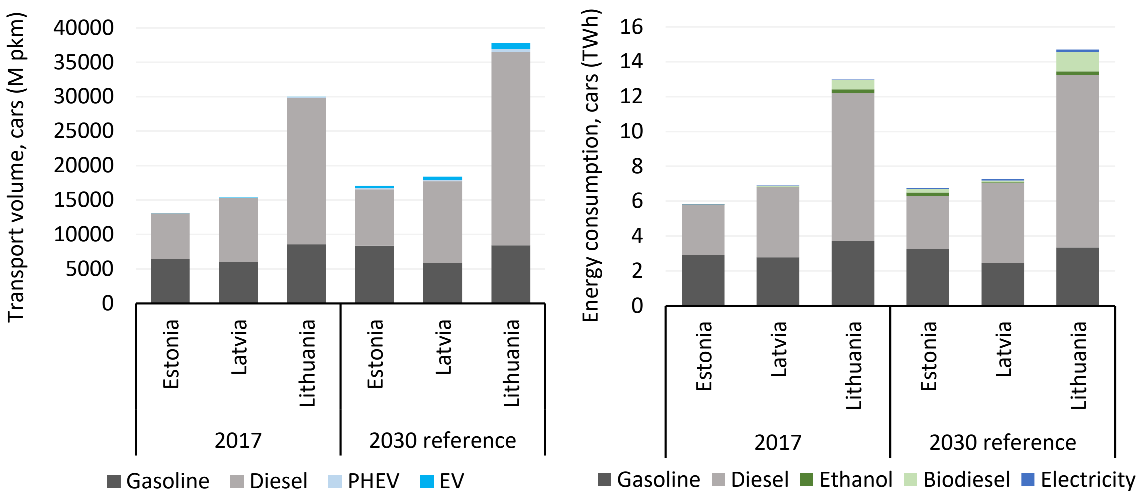


Fig. A.5. Annual transport volume and energy consumption of cars by country in 2017 and 2030 reference scenario.

Reaching climate goals in the power and heat sector

As shown in Table A.2, the share of power production by renewables and waste would exceed 90% in all three countries by 2030. The renewable shares in district heat generation remain lower but vary significantly by area.

Table A.2. Annual share of renewable electricity and district heat generation by country in 2017 and the 2030 reference scenario

	Estonia		**Latvia**		**Lithuania**	
	2017	**2030 reference**	**2017**	**2030 reference**	**2017**	**2030 reference**
ELECTRICITY						
Renewable share (incl. waste) of domestic generation (%)	16%	92%	74%	94%	69%	91%
DISTRICT HEAT						
Renewable share (incl. heat pumps and waste), capital regions (%)	48%	52%	25%	32%	18%	82%
Renewable share (incl. heat pumps and waste), non-capital regions (%)	44%	75%	96%	99%	66%	65%

Emission reductions are substantial in power and heat generation but significantly smaller in the transport and buildings sectors (Figure A.6). The total modelled Baltic CO_2 emissions halve from 21.0 $MtCO_2$ in 2017 to 10.1 $MtCO_2$ in 2030. The majority of the remaining emissions is due to oil use in the transport sector, and the increase in transport emissions (from 6.5 to 6.9 $MtCO_2$) indicates problems in reaching national targets in the EU Effort Sharing Sector.

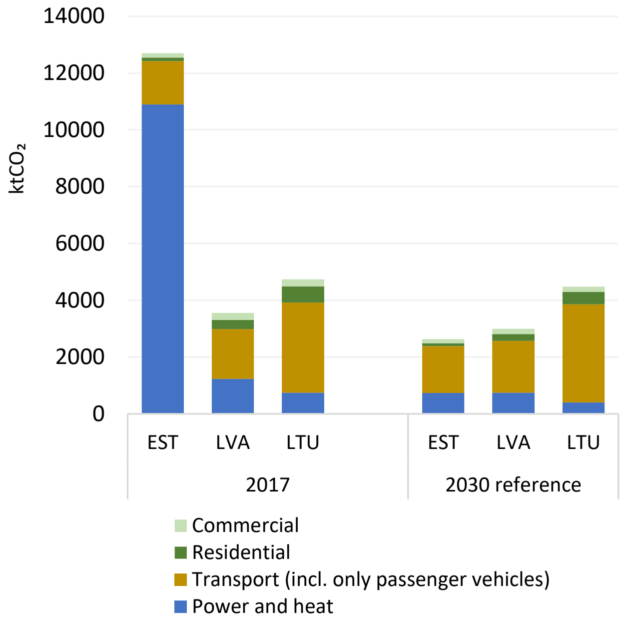


Fig. A.6. Modelled annual CO_2 emissions by sector and by country in 2017 and 2030 reference scenario. Non-CO_2 emissions are not included in the modelling.

Economic indicators

The total modelled annual cost in the power and heat sector increases between 2017 and the 2030 reference in all three countries (from 501 to 602 MEUR/year in Estonia, from 275 to 407 MEUR/year in Latvia, and from 529 to 814 MEUR/year in Lithuania) as shown in Figure A.7. This is mainly due to investment costs in new generation capacity, and changes in import costs and export profits. In Estonia, power generation operational costs diminish due to the change in source, and in Lithuania, operational costs increase due to increased domestic generation. Between 2017 and the 2030 reference, the average marginal price of electricity increases from 35 to 41 €/MWh, and the marginal price of district heat from 18 to 26 €/MWh. Although the overall cost increases, sensitivity scenarios show that lesser investments in wind power would lead to even higher total annual Baltic power and heat sector costs.

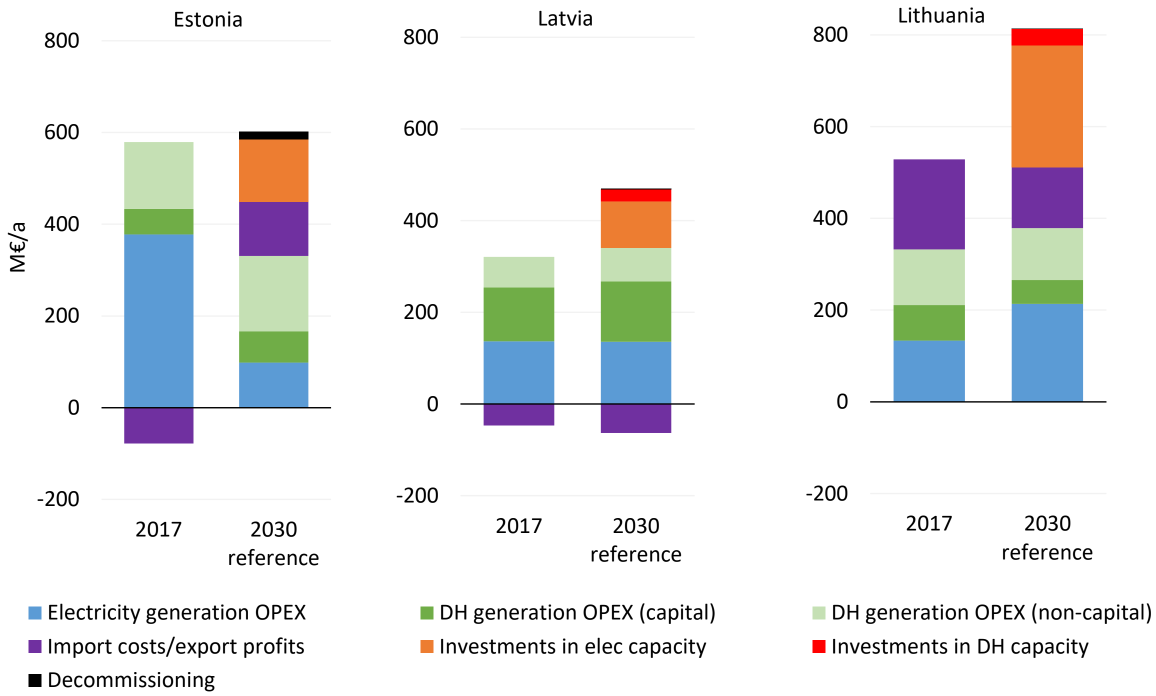


Fig. A.7. Annual system costs for electricity generation by country in 2017 and 2030 reference scenario.

For the transport sector, the model predicts an operational cost rise of roughly 10% mainly due to an increase in the fuel prices. For buildings sector, an operational cost decline of roughly 10% is estimated due to energy efficiency measures and electrification. The investment costs in transport and buildings are not accounted for.

Wind power sensitivity analysis

To improve the reliability of the model results from 2030 reference scenario and compare the impacts of individual measures, a range of sensitivity scenarios were performed. The measures included were wind power, photovoltaics, solar district heating, heat pumps for district heating, building-level heat pumps, building energy renovations, transport biofuels, transport electrification, and lower passenger volumes. Results from the most important one, wind power, are presented here.

Figure A.8. displays the annual power generation mix with different wind power capacities in 2030, ranging from only the existing capacity to nearly double the capacity in the reference. In Estonia and Lithuania, additional wind capacity decreases annual electricity imports nearly linearly in the modelled scenarios, while in Latvia, additional wind power capacity replaces natural gas generation from current capacity to the reference scenario and increases electricity exports beyond the reference scenario.

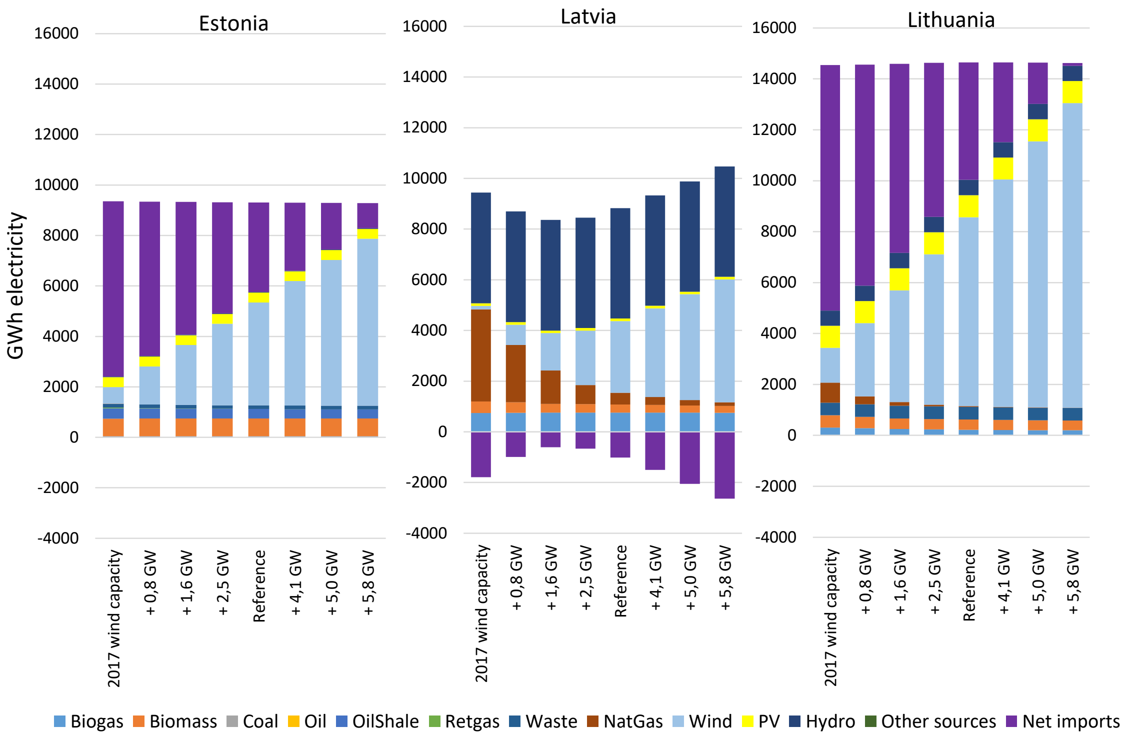


Fig. A.8. Annual electricity generation in 2030 with different wind power capacities by country. Reference assumes +3.3 GW compared to current capacity.

With the given price assumptions, the Baltic cost minimum is found at the level of the reference scenario (−75 M€/a from current capacity to reference). The division of the cost impact between the countries indicates that Lithuania benefits most from added wind (−64 M€/a), Latvia benefits slightly (−21 M€/a), and Estonia suffers slightly (+9 M€/a). However, the country-specific cost analysis holds some uncertainty since international import prices and reserve capacities are modelled with simplifications.

Addition of wind power increases the Baltic renewable generation share from 66% to 92% and the domestic generation share from 50% to 74%, and reduces emissions (−1.2 $MtCO_2$) effectively between the lowest wind sensitivity and the reference. However, wind deployment beyond the reference primarily benefits domestic generation.

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