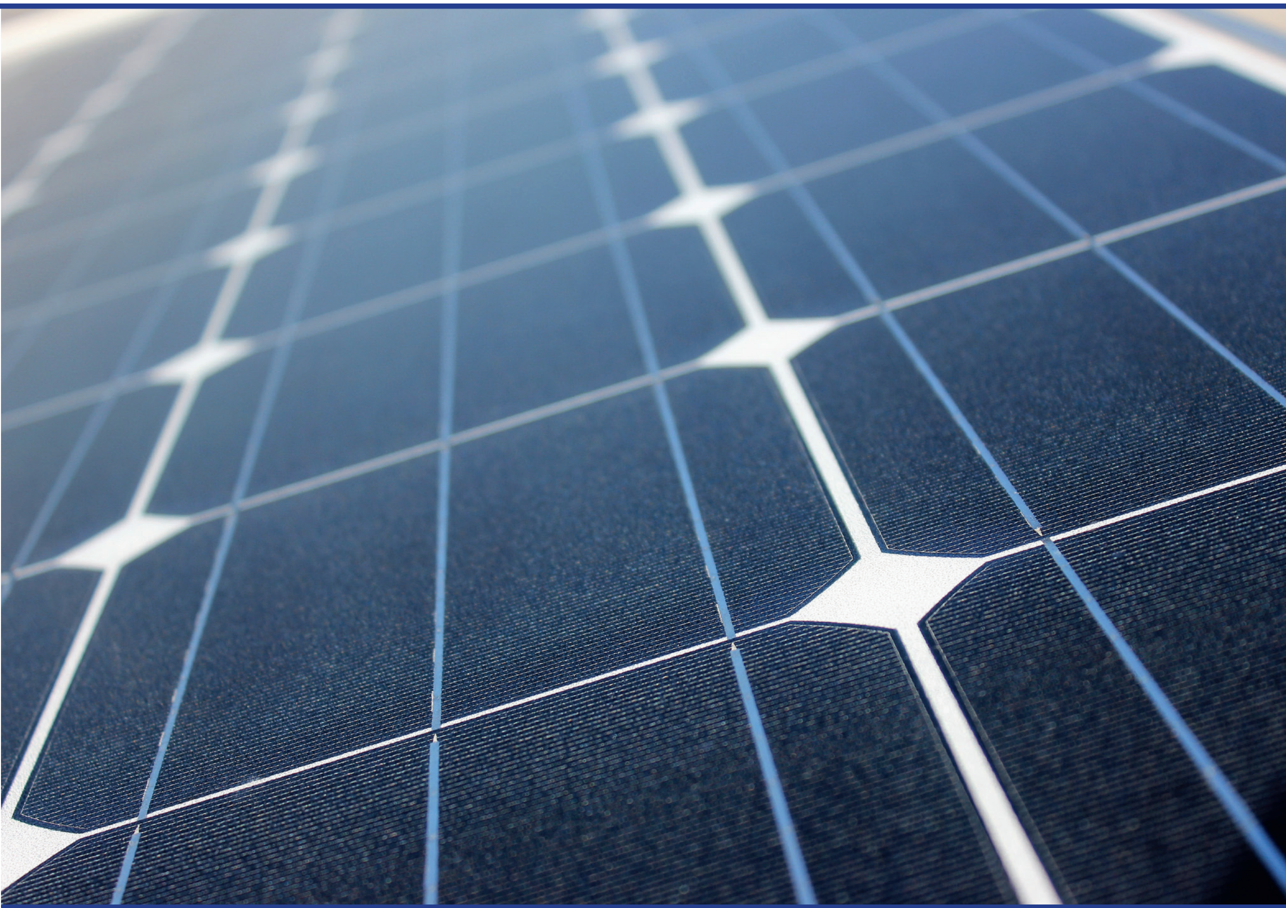
RIGA TECHNICAL UNIVERSITY

Dace Lauka

SUSTAINABILITY ANALYSIS OF RENEWABLE ENERGY SOURCES

Summary of the Doctoral Thesis



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RIGA TECHNICAL UNIVERSITY
Faculty of Power and Electrical Engineering
Institute of Energy Systems and Environment

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Summary of the Doctoral Thesis

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DOCTORAL THESIS PROPOSED TO RIGA TECHNICAL UNIVERISTY FOR THE PROMOTION TO THE SCIENTIFIC DEGREE OF DOCTOR OF ENVIRONMENTAL ENGINEERING

To be granted the scientific degree of Doctor of Environmental Engineering, the present Doctoral Thesis will be publicly defended on 28 August 2018 at 2pm at the Faculty of Power and Electrical Engineering of Riga Technical University, Āzenes iela 12/1, Room 115.

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DECLARATION OF ACADEMIC INTEGRITY

I hereby declare that the Doctoral Thesis submitted for the review to Riga Technical University for the promotion to the scientific degree of Doctor of Environmental Engineering is my own and does not contain any unacknowledged material from any source. I confirm that this Thesis has not been submitted to any other university for the promotion to other scientific degree.

Dace Lauka ……………………………….. (signature)

Date ………………………..

The Doctoral Thesis has been written in English. It consists of an introduction; three chapters; Conclusion; 30 figures; 9 tables; the total number of pages is 146. The bibliography contains 60 titles.

TABLE OF CONTENT

INTRODUCTION

Climate change is one of the most controversial issues. There is a part of society that believes that climate change is happening due to the change in people's economic activity, while the other part believes that over the course of millions of years the temperature in the Earth's atmosphere changes cyclically. Whichever the truth, action towards climate change and possibilities to reduce the environmental impact are becoming more proactive in the last decades. One of the ways to mitigate environmental impacts is the shift from using fossil fuels towards using renewable energy, which would directly reduce the amount of greenhouse gas emissions in the atmosphere. The promotion of the use of renewable energy is also in line with the targets set by the European Union (EU) for the next decades.

One of the top targets for European Union (EU) is to reduce greenhouse gas (GHG) emissions. Each Member state has undertaken to reduce the greenhouse gas (GHG) emissions and to achieve targets set for 2020 and 2030. Energy strategy 2020 sets forth that the primary energy consumption should be reduced by 20 % (compared to the forecasted development tendency), portion of the renewable energy sources (RES) into the total energy consumption should be increased by 20 %, and greenhouse gas emissions should be reduced by 20 % compared to 1990 level.

The EU has set numeric targets for increasing the share of renewable energy in final energy consumption. The author believes that in order to ensure that the introduction of renewable energy resources are in line with the objectives set by the directive, it has to be sustainable. Sustainability refers to factors linked to the economy, innovation, climate and environmental adequacy and climate change mitigation. Based on sustainability factors, the author puts forward four aspects in this thesis, which shows that the choice of renewable energy resources is not one-sided, but linked and evaluated from various aspects.

Aim and objectives

The aim of the Thesis is to analyse the possibilities of using renewable energy sources from the perspective of sustainability analysis.

The following tasks have been set to achieve the goal:

- to study renewable energy sources (RES) usage potential from the point of view of environmental and climate aspect in the next 10, 20 and 30-year period using system dynamic modelling;
- to study how economical aspects − demand response analysis and investment analysis, allow analysing and predicting RES potential in sectors;
- to study RES perspective from the side of engineering aspect using TOPSIS and scenario analysis;
- to study and evaluate renewable energy sources potential thought regression analysis, time series analysis and scenario analysis.

Research topicality and hypothesis

The hypothesis of the Doctoral Thesis is that sustainable development and the long term performance of renewable energy is characterized by aspects that are related to climate and environment, engineering, economic aspects and aspect of renewable energy source assessment.

The society is becoming increasingly interested in environment related issues, renewable energy, both the direct and indirect environmental pollution, as well as in other environmental issues. These are the various drivers that determine on what the attention should be focused. The main drivers of sustainable resources management and energy production and use are the directives and planning documents that are drafted at the state and the European Union level.

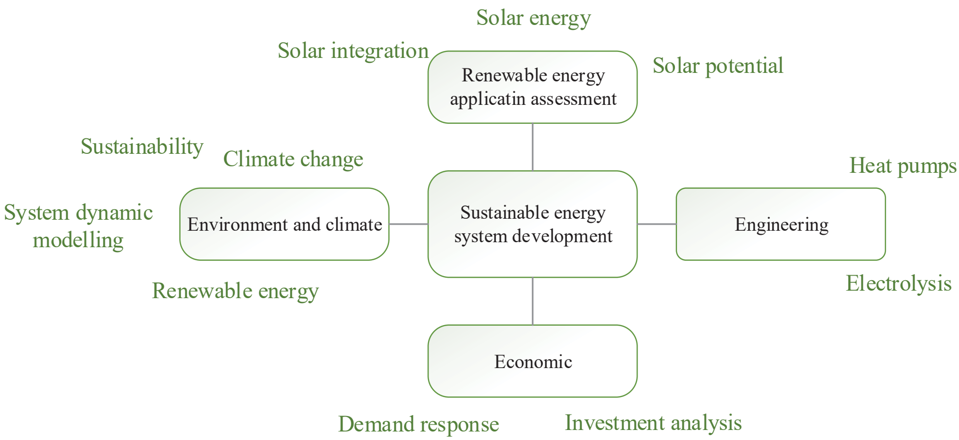

Fig. 1.1. Hierarchy of sustainability analysis of renewable energy sources.

Most of the targets included in directives and planning documents refer to the share of renewable resources in final energy consumption. In order to transition towards sustainable use of renewable energy resources, it is not enough to meet the targets set by the European Union, but it is necessary to analyse all the affecting factors. The hierarchy of sustainability analysis for the use of renewable energy is presented in Fig. 1.1. In order to find out what is the basis for the sustainability analysis of the use of renewable energy resources, it is necessary to consider the factors that influence the possibilities of their use. Within the Thesis, the issue of the sustainability analysis of renewable energy production and use is studied and analysed from the environmental and climate, technological and economic aspects. Initially, the attention is drawn to an aspect that is directly related to the use of renewable energy resources – environmental and climate aspect. The environmental and climate aspect is the one that has been focused on during the last decades. From the scientific point of view, more and more studies are being carried out regarding the reduction of environmental impacts and the introduction of renewable energy sources in various sectors of economy. The research problems are generally related to the possibilities of reducing greenhouse gas emissions; they can be reduced by switching to renewable energy resources (see Table 1.1, *1*). The reduction of the environmental impact both at the European Union and Latvian levels occurs through transitioning to RES (see Table 1.1, *2 and 3*), and the share of RES in final energy consumption is determined by the EU directives and local planning documents.

The transition to renewable energy is closely linked to the adaptation of existing technologies or the introduction of new technologies into the energy production system (see Table 1.1, *4 and 5*). Technology exchange or its adaptation to the use of RES is associated both with the environmental and climate aspects, as well as economic aspects.

The introduction of "greener" technologies is connected with issues that are related to the economic side of technology introduction and the possibility of cost-saving. Through the economic techniques and analysis (see Table 1.1, *6, 7 and 8*), the economic aspects are very closely related to engineering aspects, as well as environmental and climate aspects.

The final and, in author's opinion, the most important factor influencing the transition towards opportunity of sustainable use of renewable energy resource is in-depth study of the application of a particular resource (see Table 1.1, *9 and 10*). The results of the study regarding the issue of which of the renewable energy sources should replace fossil resources for energy production differ. The author's publications regarding environmental and climate aspects point out that there is a high potential for energy production from biomass and by solar energy. The author's recent studies show that solar energy has a great potential in the climatic conditions in Latvia.

In the Doctoral Thesis, the author elaborates on four aspects − (1) environmental and climate; (2) engineering; (3) economic; and (4) renewable energy source − and analyses the interconnections between these aspects. Further in the Thesis, the author refers to the 10 major publications, which correspond to the articles given in Table 1.1.

Table 1.1

Scientific publications used in the Doctoral Thesis to study sustainability analysis of renewable energy sources

Studied aspect	No.	Title of publication
Environment and climate	1	Analysis of GHG reduction in non-ETS Energy Sector
	2	Modelling the Baltic power system till 2050
	3	Modelling the Latvian power market to evaluate its environmental long-term performance
Engineering	4	Analysis of use of bioenergy production by-products to enhance electrolysis process
	5	Heat Pumps Integration Trends in District Heating Networks of the Baltic States
Economic	6	Demand response analysis methodology in DH system
	7	Analysis of Industrial Electricity Consumption Flexibility. Assessment of Saving Potentials in Latvia and Kazakhstan
	8	Results of Investment Analysis in Power Transmission in Latvia and Lithuania
Renewable energy application assessment	9	Solar power and heat production via photovoltaic thermal panels for district heating and industrial plant
	10	First solar power plant in Latvia. Analysis of operational data

Scientific novelty

In order to test the hypothesis, various types or research methodologies were used. The distribution of applied methodologies within sustainability analysis of RES is given in Fig. 1.2.

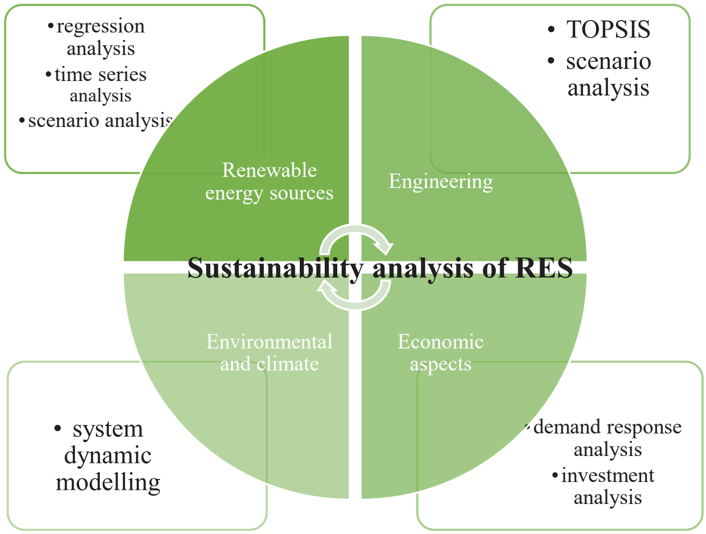

Fig. 1.2. Methodologies applied for the sustainability analysis of RES use.

The Doctoral Thesis includes the analysis of the sustainability of RES, accordingly to four significant aspects that characterize the possibilities to use these resources in a sustainable way. The selection of renewable energy resources and their relation to the chosen factors are characterized by the applied research methods, which are both qualitative and quantitative scientific research methods − literature analysis, data collection and analysis, experimental design and execution, data statistical analysis and mathematical modelling.

System dynamics (SD) modelling was used to provide understanding of the amounts of GHG and to predict their development trends. SD modeling uses and simulates different scenarios to predict the potential increase in the share of renewable energy in final energy consumption. The analysis of demand response and investment analysis were used to assess the economic aspects of resource use potential. The engineering aspects of the use of renewable energy resources are evaluated using multi criteria analysis TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) technique and scenario analysis. The correlation and regression analysis, time series method and scenario analysis have been used to determine the potential of renewable energy resources.

Scientific Significance

The Doctoral Thesis has high scientific significance both in Latvian and international contexts, as it includes the development and approbation of the following methodologies that demonstrate multi-tiered sustainability aspect analysis of the use of renewable energy sources:

- the development of a system dynamics model, incorporating different development scenarios, predicting GHG reductions and the increase in the share of renewable energies;
- assessment of the potential for renewable energy resources in a sector through economic analysis – demand-response analysis and investment analysis;
- assessment of engineering and technical factors of renewable energy resource use through scenario analysis and multi-criteria analysis;
- analysis of the potential and prospects of solar energy as one of the renewable energy sources using scenario analysis, time series analysis method and regression analysis.

Practical Significance

The use of RES is essential for reducing GHG emissions. The transition from fossil resources to renewable energy contributes to the independence of the energy sector at national level.

The European Union has set ambitious targets for the use of renewable energy sources in final energy consumption; therefore, the performed assessment of the sustainability of renewable energy resource use ensures a more substantial approach to the integration of renewable energy resources into energy production.

The assessment of use of renewable energy resources including the environmental and climate, economic, and engineering aspects, and in-depth research on renewable energy application allows to account for the potential of resource use from a sustainability perspective. There is no coherent approach to the introduction of RES, their implementation is related to different transitional methodologies.

The results of the Doctoral Thesis provide both scientific and practical reasoning for the use of renewable energy resources. The results of the Doctoral Thesis can be used to improve national and international policies. The results of the Doctoral Thesis are relevant not only to scientists and industry professionals, but also to those involved in the development of the national economy.

Approbation of the research results

Scientific publications about the research topic

1. Lauka, D., Haine, K., Gusca, J., Blumberga, D. Solar energy integration in future urban plans of the South and Nordic cities. Energy Procedia, 2018 (*will be indexed in Scopus*).
2. Lauka, D., Barisa, A., Blumberga, D. Assessment of the availability and utilization potential of low-quality biomass in Latvia// Energy Procedia, 2018, (*will be indexed in Scopus*)

3. Rozentale L., Lauka D., Blumberga D. Accelerating power generation with solar panels. Case in Latvia// Energy Procedia, 2018, (*will be indexed in Scopus*)
4. Lauka, D., Blumberga, D. First solar power plant in Latvia. Analysis of operational data. Energy Procedia, 2018 (*will be indexed in Scopus*).
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15. Lauka, D., Blumberga, D. Electrolysis Process Analysis by Using Low Carbon Content Additives: a Batch Test Study. Energy Procedia, Volume 72, June 2015, 196−201, Scopus, times cited – 1.

Other scientific publications

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2. Pastare, L., Aleksandrovs, I., Lauka, D., Romagnoli, F. Mechanical pre-treatment effect on biological methane potential from marine macro algae: results from batch tests of Fucus vesiculosus. Energy Procedia 95 (2016) 351−357.

3. Bazbauers, G., Bariss, U., Timma, L., Lauka, D., Blumberga, A., Blumberga. D. Electricity saving in households due to the market liberalization and change in the consumer behaviour. Energetika 2015, 61(3−4), 108−118.
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2. Lauka, D., Barisa, A., Blumberga, D. Assessment of the availability and utilization potential of low-quality biomass in Latvia// International Scientific Conference “Environmental and Climate Technologies”, CONECT 2018, 16–18 May 2018, Riga, Latvia
3. Rozentale, L., Lauka, D., Blumberga, D. Accelerating power generation with solar panels. Case in Latvia// International Scientific Conference “Environmental and Climate Technologies”, CONECT 2018, 16–18 May 2018, Riga, Latvia
4. Lauka, D., Blumberga, D. First solar power plant in Latvia. Analysis of operational data// International Scientific Conference “Environmental and Climate Technologies”, CONECT 2018, 16–18 May 2018, Riga, Latvia.
5. Pakere, I., Lauka, D., Blumberga, D. Solar power and heat production via photovoltaic thermal panels for district heating and industrial plant. 3nd International Conference on Smart Energy Systems and 4th Generation District Heating, The National Museum of Denmark – Copenhagen, 12.09.2017 − 13.09.2017.
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Thesis Outline

The Doctoral Thesis is based on ten thematically unified scientific publications. Those publications are presented and results have been approbated in various scientific conferences. Publications are accessible in cited international databases. The aim of these publications is to describe the connection between various aspects of the development of sustainable analysis of renewable energy sources.

This Thesis consists of introduction and three chapters:

- literature review,
- research methodologies,
- results and discussion.

In the introduction, the aim of the Doctoral Thesis, the scientific and practical importance of the work, as well as a brief outline of the approbation of published research results at various scientific conferences are presented. The introductory part of the work also includes publications, monographs and patents that relate to other areas of research of the author.

The first chapter of the work includes a literature review of the topic under study. The second chapter of the work describes research methods that are related to the research of sustainable use of renewable energy resources. The Doctoral Thesis concludes with results and discussions regarding the work that has been done, and answers the question of sustainable use of renewable resources. The Bibliography contains 60 titles, but as the Doctoral Thesis is based on the thematically unified ten scientific publications, bibliography contains 209 titles.

1. LITERATURE REVIEW

1.1. Environment and climate

The evaluation of the implementation of renewable energy resources in the author's work is carried out from four selected aspects. The first aspect of sustainability analysis of renewable energy sources usage is connected to environment and climate aspect. Environmental and climate analysis and connection to renewable energy sources are presented in *Papers No. 1, 2* and *3*. (see Table 1.1).

Each Member state has undertaken to reduce the greenhouse gas (GHG) emissions and to achieve targets set for 2020 and 2030. Energy strategy 2020 sets forth that the primary energy consumption should be reduced by 20 % (compared to the forecasted development tendency), portion of the renewable energy sources (RES) into the total energy consumption should be increased by 20 %, and greenhouse gas emissions should be reduced by 20 % compared to the level in 1990. Energy sector (the largest carbon dioxide emission contributor in the EU) is a key player in climate change mitigation. According to the Statistical Office of the European Union (Eurostat Energy statistics, 2015) electricity generation from renewable energy sources in the EU-28 has increased from 14.8 % in 2005 to 25.4 % in 2013. The increase of the renewable energy share in the EU can be explained by the combination of higher consumption of final energy from renewable energy sources and of a decrease of the total gross final energy consumption compared to 2010. In the research the author addresses two major questions topical not only for Latvia but also for other EU countries: (1) To what extent the power sector can achieve ambitious long-term goals set by the European Commission? (2) What are the major preconditions leading to achievement of the EU climate and energy goals in the power sector?

1.2. Engineering

The second aspect relates to engineering solutions regarding renewable energy sources. The author has carried out studies related to the use of such RES as heat pumps and from biomass waste made additive to enhance hydrogen production in electrolysis process. Research on technological solutions for RES is discussed in *Papers No. 4 and 5* (see Table 1.1).

The role of renewable energy technologies is increasing due to the climate change and in some cases due to the security issues of national energy. Besides positive environmental aspects of renewable energy technologies, the issues of non-regularity of the renewable energy (specifically PVs and wind energy) production and its correspondence to energy demand stimulate development of new energy accumulation approaches. In addition to grid balancing activities, use of compressed air energy storage, combined hydrogen storage technologies are often analysed to ensure effective solutions for wind and solar generated electricity (Zoss, et al., 2014) (Hedegaard & Meibom, 2012). Integration of heat pumps into district heating (DH) systems is also considered as one of the methods to increase consumption of renewables based electricity.

Hydrogen is considered as a clean energy carrier for the future energy demands. Despite the fact, that the electrolysis is considered as a clean energy production process, efficient use of electrolytes and water plays an important role for the environmental performance of the system. By now, the major part of water electrolysers are based on alkaline electrolytes or proton exchange membrane units, which are primary produced for the needs of electrolytic processes (Barbir, 2005) (Carmo & Fritz, 2013). Use of noble metals and different alloys, as electrocatalysts generates environmental pressures in resource consumption category and due to its limited geographical availability – in transportation category. Use of energy production by-products as electrolytes can improve the overall environmental and also economic performance of the integrated system. In research, a green, locally available and sustainable alternative for utilising biomass ash as electrocatalyst for H_2 generation is proposed.

1.3. Economic

There are several methods of achieving long-term goals and results in renewable energy source integration in industry and other sectors. Demand response and investment analysis allows analysing and predicting RES potential in sectors. The research regarding demand response analysis and investment analysis is presented in *Papers No. 6 and 7* (see Table 1.1).

1.3.1. Demand response analysis

Low carbon society needs technological and management changes in the energy sector. One of possibilities is connected with demand response (DR) actions. (Gils, 2014) (Khabdullin, et al., 2017). The issue of demand management was known until the 1980s and it included such activities as energy saving and efficiency, load management, etc. (Balijepalli, et al., 2011) (Shoreh, et al., 2016) In electricity and district heating (DH) systems interventions in energy end user load can improve the economic feasibility of cogeneration plants and help to avoid investments in additional generation as well as network capacities (Bradley, et al., 2013). By adjusting the demand to the present availability of fluctuating resources, curtailments can be reduced and the overall RE (renewable energy) share can be increased (Miezis, et al., 2016) (Schuchardt, 2017) (Albatayneh, et al., 2017) (Latosov, et al., 2017) (Alam, et al., 2016).

The industrial potential of demand response is not completely comprehended, especially with regard to emerging modern technologies in smart grid. In Latvia and Kazakhstan consumer side flexibility already has not been widely researched. There are factors that lead to a potential increase of industrial demand response (Shoreh, et al., 2016) (Söder, et al., 2017). All factors are necessary for the industrial sector and also related to and affect one another: advancement in smart meter technology that allows controlling and monitoring responsive loads in near real-time scales, advent of aggregators that can manage smaller loads participating in power markets, environmental concerns related to the increase of fuel consumption, reliability concerns to prevent blackouts, and the Auto-DR promising technology (Shoreh, et al., 2016).

Another energy intensive sector is energy producers − district heating companies. Step by step industrial sector by using innovative technologies and governmental regulation, e.g. taxes, subsidies and changes in energy price helps to transit from existing DH system to 4th generation DH system. GHG can be reduced in every heat supply system element using different methods.

(Ziemele, et al., 2014). Reduction can be done at one or at all DH system elements: heat sources, heat transportation system, and heat consumers. Demand response is one of the methods that can be used to reduce CO_2 emissions at all system stages, where energy consumer, society and state are the winners.

1.3.2. Investment analysis

Another way of promoting sustainable renewable energy source integration in system is connected to investment analysis. Author's research (Table 1.1, *Paper No. 8*) shows the results of a scenario methodology where each scenario consists of a possible future and shows how to react in the future. Four main scenarios were used in investment algorithm in the EMPS model.

Application of this methodology for the study of a GHG emission free power system in two Baltic states is described. The input data are mainly based on statistical data from Latvia and Lithuania and information about the established and planned projects for new renewable power production in the Baltic region. Model and algorithm was applied to analyse the power system by 2050.

1.4. Renewable energy source assessment

In the first paragraph it is mentioned that one of the important sustainability factor is renewable energy sources. The author would like to focus on solar energy as sustainable renewable energy source in next 10, 20 and 30 years. Studies relating to solar energy potential and solar energy as sustainable resource are analysed in *Papers No. 9 and 10* (see Table 1.1).

Energy is a prerequisite for every activity – it is needed to ensure different processes and systems on a daily basis. The implementation of solar energy technologies would significantly mitigate and alleviate issues associated with climate change, energy security, unemployment, etc. Therefore, more and more technologies are being used to produce electricity from solar energy. (Seshie, et al., 2018) (Kabira, et al., 2018) (Sampaio & Gonzalez, 2017) (Peng, et al., 2013) (Tyagi, et al., 2013).

Comparing renewable energy source technologies, the solar energy technologies – photovoltaic, solar collector, and solar hybrid systems – is a relatively new industry (Shahnazari & Lari, 2017). Solar energy can be used for both space heating and hot water production. In research of Soloha et al. show, that such countries as Denmark and Germany, with similar climatic conditions as Latvia, are the leading countries of solar energy integration of different systems. Possibilities for the use of solar energy are promoted not only from political aspect – the goals set by the EU – but also from the technological one. The integration of solar energy in existing DH systems is a development opportunity (Pakere, et al., 2017) (Lund, et al., 2010) (Truong & Gustavsson, 2014). It is expected that solar energy, especially solar energy based on photovoltaic (PV) technology, will make up a share of about 20 % of total RES heat contribution by 2030 (Zervos, et al., 2010) (Pakere, et al., 2018) (Soloha, et al., 2017).

2. RESEARCH METHODOLOGY

In order to test hypothesis, various types of research methodologies were used – system dynamics (SD) modelling, demand response and investment analysis, MCA TOPSIS, scenario analysis, the correlation and regression analysis, and time series method.

2.1. Environmental and climate aspects through system dynamics modelling

In this section, through the system dynamics methodology the use of renewable energy sources is predicted in 10, 20 and 30 years perspective. This section provides an overview of methodologies used for analysis of greenhouse gas emissions and renewable energy source opportunities in the next decade, and corresponds to methodology part in Papers No. 1, 2 and No. 3.

System dynamics is a computer-aided modelling approach to understanding the behaviour of complex systems over time. The 'open' structure and ability of SD models to examine the behaviour of key variables over time and to highlight the leading driving forces that have effect on system's performance was considered the major reason why particular approach was chosen.

A system dynamics model was developed for greenhouse gas emission prediction. There are five main steps in creating a system dynamics model: problem formulation, creating a dynamic hypothesis, model formulation and simulation, model testing and policy design and testing. The time interval for modelling is one year and the modelling period is from year 2005 until 2030. Historic data were used to validate the model for the period from 2005 until 2012.

The underlying structure of the system dynamics model for non-ETS energy sector is explained by the causal loop diagram demonstrated in Fig. 2.1.

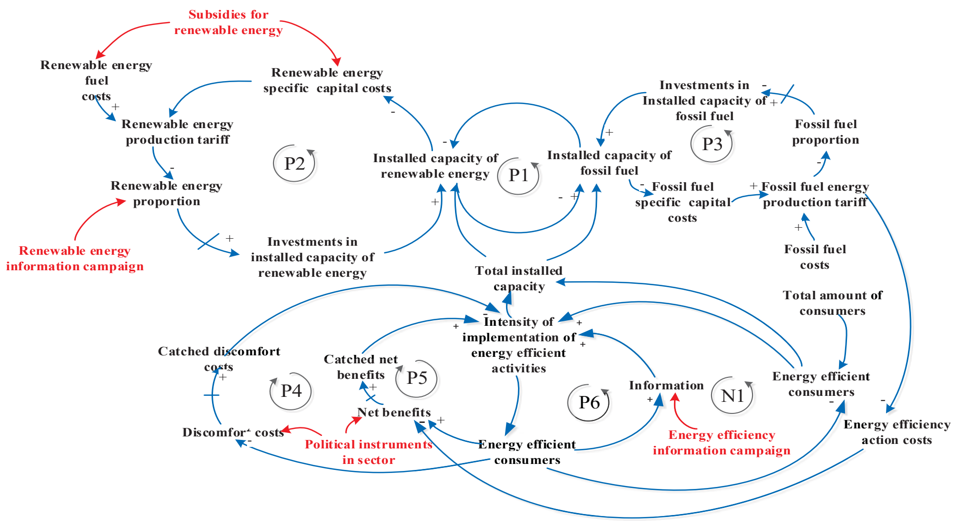

Fig. 2.1. Diagram of the main causal loops for the energy sector.

In the model, there are six main positive or intensifying loops, and one negative or balancing loop. The loop P1 shows how the installed capacity of RES and the installed capacity of fossil fuel mutually interact – the higher the RES capacity, the lower the capacity of fossil fuel, and vice versa. Loops P2 and P3 explain internal dynamics of each energy resource group. All three positive loops P4, P5 and P6 with a delay are hindered by the negative loop N1.

In the diagram, red colour is used to depict the system's pressure points or policy instruments, which are required to reduce the impact of energy sector on the environment and GHG emissions.

Availability and quality of data always constitute an important issue in all modelling studies. There is no model that describes the analysed system perfectly. Simulation data demonstrate only the tendency, not precise figures. Validation of SD model allows understanding whether the particular model is fit for the envisaged use (Forrester & Senge, 1980). This allows forming a model that can be trusted, based on observations and data from a real system (Barlas, 1996) (Sterman, 2000). Barlas (Barlas, 1996) explains why data availability is not significant for creation of a good system dynamics model. Evans (Evans, et al., 2011) states that model calibration and validation can be done either by using historical data or data from literature.

The research on CO_2 emission forecast and electricity production from RES involved the following four steps: (1) selection of technologies; (2) determining technical and economic input data of various types of power plants, including the existing support measures; (3) system dynamics model formulation and simulation; and (4) installed capacity and CO_2 emission forecast according to the forecast period. The developed model contains six generation technologies (Fig. 2.2.) The model was developed and validated based on the Latvian case study.

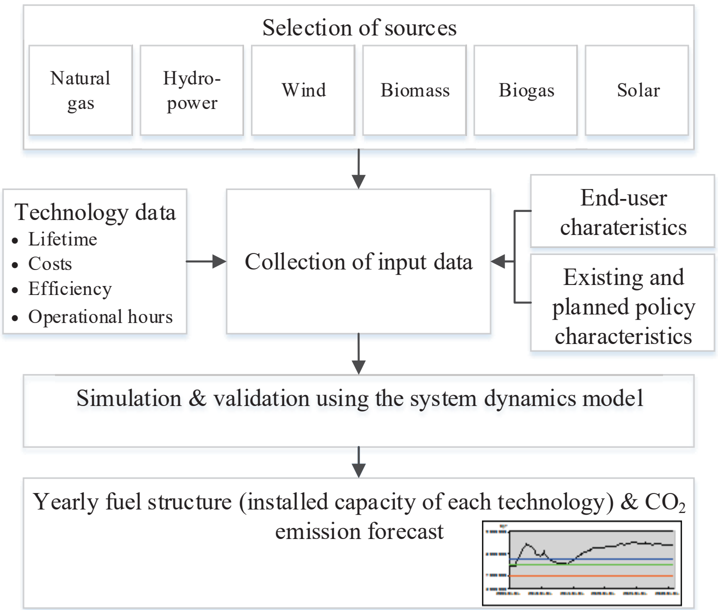

Fig. 2.2. Simplified scheme of research approach.

The dynamics hypothesis assumed that technologies are replaced by each other according to system's state in each modelling step. Thus, if the share of one fuel increases, the share of the other will decrease. In Fig. 2.3., a causal loop diagram showing the nature of the interaction between the installed capacity of renewable energy technologies and fossil energy technologies is given as an illustrative example.

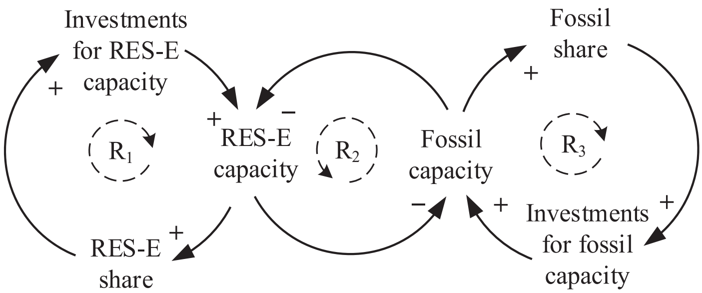

Fig. 2.3. Causal loop diagram representing the dynamics between technology stocks.

The reinforcing loop R1 representing the installed capacity of electricity that has been produced from renewable energy sources (RES-E) shows that the larger the investment aimed to increase the RES-E capacity, the larger the share of renewable energy sources in the fuel mix. Meantime, the greater the share of RES-E, the larger the investment aimed to increase the installed RES-E capacity. The reinforcing loop R2 represents the interaction between the installed capacity of RES-E technologies and fossil fuel installations. R2 shows that the larger the capacity of RES-E facilities, the smaller the installed capacity of fossil fuel installations is and vice versa. The reinforcing loop R3 representing the installed capacity of fossil-based power generation shows that the lower the installed capacity of fossil fuel installations, the lower the proportion of fossil fuels is in the fuel mix. Meantime, the lower the proportion of fossil fuels in the fuel structure, the smaller investment aimed to increase the fossil capacity. The smaller the investment, the smaller the capacity of fossil-based installations is.

Key stocks and flows of the proposed system dynamics model are presented in Fig. 2.4. For the sake of simplicity, only two resource flows, renewable and fossil energy, respectively, are shown. However, the real model consists of several resource flows corresponding to national electricity generation mix in Latvia.

Installed capacity stocks (MW) with corresponding investment in-flows and depreciation out-flows form the basic structure of the model. Further investment decisions regarding all provided technologies are done based on electricity generation costs. This is an equilibrium model, thus the larger the investment share of one technology (e.g. renewable-energy-based), the smaller share of all investments reaches the other technology (e.g. fossil-fuel-based). Total annual investments in terms of megawatts per year are equal to total annual depreciation, which is affected by technology lifetime. Annual electricity generation from each type of resource is determined taking into account the installed capacity and specific full load hours of a technology.

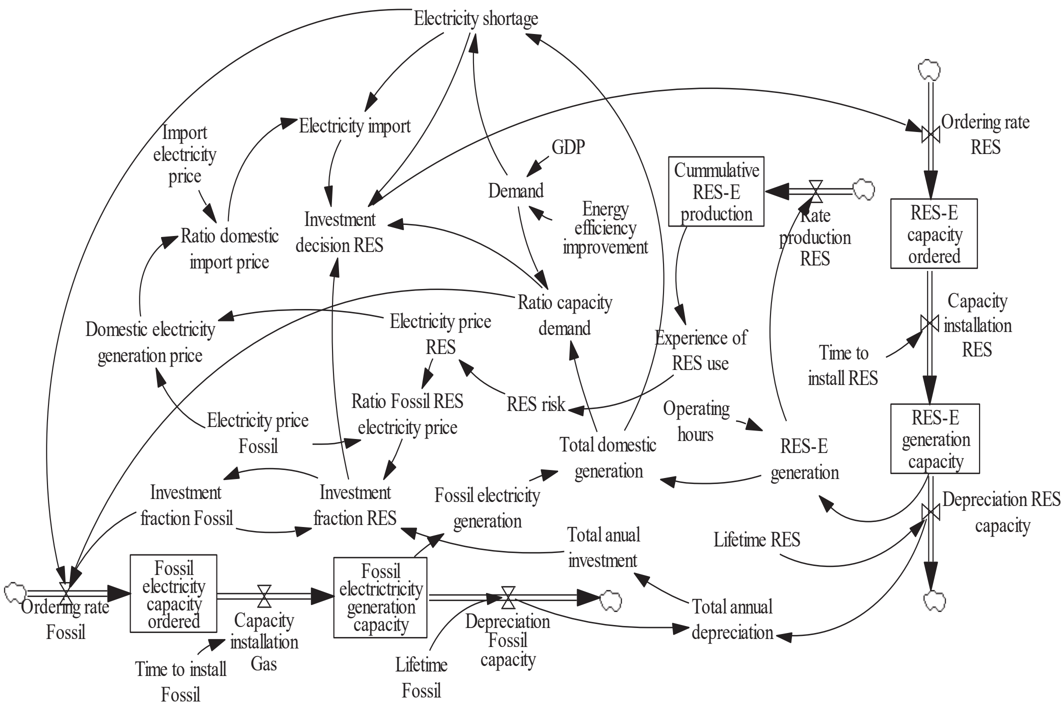

Fig. 2.4. Key stocks and flows of the Latvian electricity sector model.

A perfect competitive electricity market is assumed. All generating units with the same type of technology are accumulated to represent individual generation technology, so that the competition is reflected among primary electricity generators. Which of these fuels the electricity producer will choose, depends on the relative costs of the alternatives. Investment decisions are fundamentally based on total revenues gained by investors (Pereira & Saraiva, 2013) and electricity price is an important factor determining the willingness to invest in new electricity generation capacity (Nielsen, et al., 2011). In the proposed model, electricity generation costs are used as the main indicator based on which investment decision is made. Each market share of alternative technological option is integrated into the system dynamics model using the multi-nominal logit model (Moxnes, 1990):

$$MS_i = \exp^{-\alpha \cdot P_i} / \sum_j \exp^{-\alpha \cdot P_j} \tag{2.1}$$

Total costs, i.e. the average cost of electricity production for each technology alternative were determined considering 4 major components: (1) the cost of fuel; (2) capital costs; (3) operation and maintenance costs; and (4) a relevant premium, e.g. cost of CO_2 emissions (negative effect) or state support incentives (positive effect). In addition to the premium, renewable energy resources consider also a fifth component − risk factor associated with the use of technology. The risk factor represents the negatives associated with the use of renewable energy sources, e.g. a lower automation of solid biomass fuel compared to natural gas. The value of this parameter depends on the amount of accumulated experience with technology use. The average electricity generation cost of a fuel option is determined using (2.2):

$$P = C_{fuel} / \eta + C_{capital} + C_{O\&M} + C_{tax} + R - S \quad . \tag{2.2}$$

It is assumed that if there is under-capacity at a given modelling step, then imports will be increased; otherwise, the decision is based on comparison between the imports price and the inland generation cost similarly as it was done in (Hasani-Marzooni & Hosseini, 2013). Electricity import price is modelled as an exogenous variable based on the average electricity price in Nord Pool Spot (32 EUR/MWh in 2012 (Spot, 2013)). Annual electricity price increase of 3 % is assumed for the coming years. Constraints on transmission capacity among the various regions within the Nord Pool Spot electricity market are not considered in the model.

2.2. Engineering calculations

This section provides an overview of methodologies used for heat pump integration and the additives made from biomass waste to enhance hydrogen production in electrolysis process, and corresponds to methodology part in *Papers No. 4 and 5* (see Table 1.1).

The research hypothesis is that integration of heat pumps into the DH system can cause the increase of demand for the electricity produced from RES. To prove this hypothesis, we need to define the share of renewable energy in DH system; determine the potential for the use of heat pumps in the Baltic States and the influence of the COP of heat pumps to the RES based heat production trends.

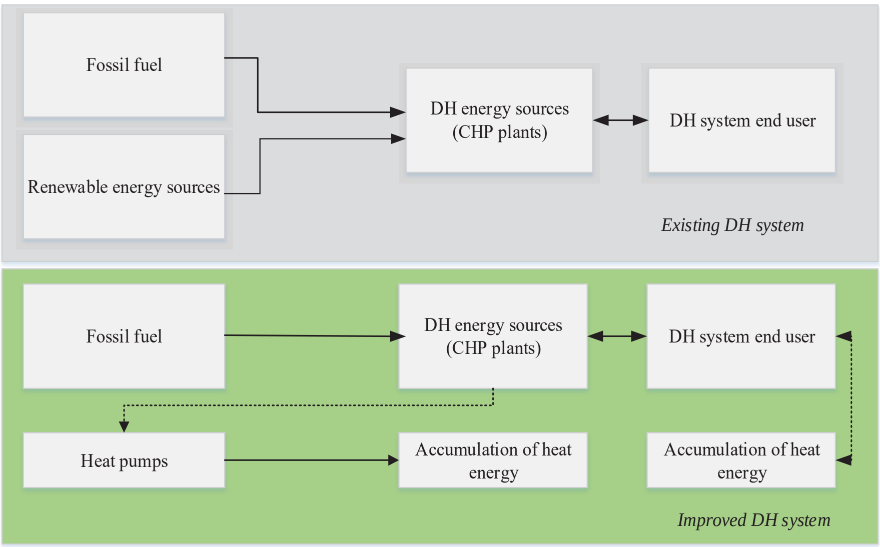

Fig. 2.5. Scheme of integration of heat pumps in DH systems.

Within the framework of the research it was assumed that the heat pumps are integrated into the existing DH systems of Latvia, Estonia and Lithuania, in order to replace some of the fossil fuel used as an energy resource. The proposed methodology is suitable for use in analysis of energy systems of Latvia, Estonia and Lithuania. The DH system model consists of energy source, heat networks and end user. If the energy source of the DH system includes combined heat and energy production, then one of the most important issues of sustainable development is the energy resource that is used in CHP.

One of the technological solutions that would allow eliminating or significantly reducing the effect on climate change is substitution of fossil fuels with renewable electricity generation resources. Figure 2.5. shows a scheme of an existing DH system and proposes an integrated system.

To analyse suitability of the wood ash as catalyst, TOPSIS was applied. Within the study, the samples are evaluated by the following three criteria: pH value, diameter of catalysts, and sample surface characteristics. Criteria weights are determined based on expert assumptions.

The first step of TOPSIS analysis includes normalization of values. The normalisation matrix can be determined with different normalization models: vectorial, linear, non-linear and logarithmic (Zenonas, et al., 2009). Within the current study Witendorf linear normalization model is used (2.3), (2.4).

$$b_{ij} = \frac{\max a_{ij} - a_{ij}}{\max a_{ij} - \min a_{ij}} \text{, if max } a_{ij} \text{ is preferable;} \quad (2.3)$$

$$b_{ij} = \frac{a_{ij} - \min a_{ij}}{\max a_{ij} - \min a_{ij}} \text{, if min } a_{ij} \text{ is preferable.} \quad (2.4)$$

The second step in TOPSIS is the development of normalized and weighted matrix by multiplying criteria weight (w_i) by normalized criterion values (b_{ij}) (2.5).

$$v_{ij} = b_{ij} \cdot w_i \quad (2.5)$$

The third step in MCA is definition of a positive-ideal (2.6) and negative-ideal solution (2.7).

$$A^+ = \mathrm{Max}_i \, v_{ij} \quad (2.6)$$

$$A^- = \min_i v_{ij} \quad (2.7)$$

Then the ideal-positive separation (2.8) and negative-ideal separation (2.9) needs to be calculated.

$$S^+ = \sqrt{\sum_{j=1}^{n} \left(v_{ij} - v_j^+\right)^2}, \; i = 1, 2,.., m \quad (2.8)$$

$$S^- = \sqrt{\sum_{j=1}^{n} \left(v_{ij} - v_j^-\right)^2}, \; i = 1, 2,.., m \quad (2.9)$$

The final step in MCA is calculation of the relative closeness to the ideal solution:

$$C_i^* = \frac{S_i^-}{(S_i^+ + S_i^-)}, \; i = 1, 2,.., m \tag{2.10}$$

If $C_i^* = 1$, the alternative is the ideal solution and if $C_i^* = 0$, the alternative is the negative-ideal solution. The coefficient of closeness is used to rank the alternatives in a preference decreasing order. The alternative with the maximum utility value is the most preferable solution (Dace, et al., 2014) (Xi, et al., 2010).

2.3. Economic calculations for energy savings

This section provides an overview of methodologies used for energy sector analysis through demand response and investment analysis, and corresponds to methodology part in *Papers No. 6, 7 and 8* (see Table 1.1).

2.3.1. Demand response analysis

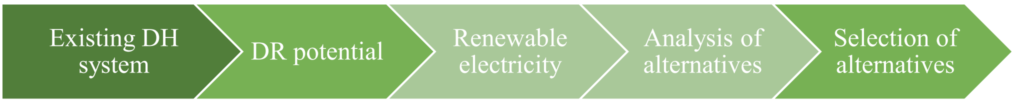

Fig. 2.6. Methodology algorithm for analysis of DR possibilities.

In next years, DH system will change and one of the DH system heat sources can be electricity. There are several limitations and regulations when and why use electricity as source in DH system. At the moment electricity cannot be used for heat generation, because of heat and electricity tariff. Electricity price is higher that heat energy price. Use of electricity as source in DH system requires innovative technology solutions with integration of DR and DSM elements to create the conditions when energy end user gradually starts understanding when to use and how to increase energy efficiency at end-user's side. DH system operation depends on climate conditions – wind, temperature, solar radiation, etc. It is possible to calculate the correction of heat consumption of DH system according to indoor and outdoor temperatures with Equations 2.11 and 2.12.

$$k_t = \frac{t_t - t_{\text{outdoor1}}}{t_t - t_{\text{outdoor2}}} \tag{2.11}$$

$$Q_t = Q_{\text{yearly}} \cdot k_t \tag{2.12}$$

Other flexibility of heat load is connected with a number of heating hours, which mainly depend from outdoor temperature. Number of heating hours is assessed by meteorological data from climate handbooks or statistical data information sources, for example Nomenclature of territorial units for statistics (Nuts-2). Correction of heating hours, which influence demand response, is presented by hourly correction coefficient:

$$k_h = \frac{n_t}{n_{\max}} . \quad (2.13)$$

Both correction coefficients allow defining hourly and daily demand response potential in electricity consumption for DH system pumps, fans and other electrical devices as well as possibilities to integrate renewable electricity in DH system.

In food industry cooling and ventilation are the biggest electricity consumers. Flexible loads in the cross-sectional technologies cooling and ventilation evaluation is based on their annual electricity demand. These demands are estimated by using data and assumptions provided by different experts. By dividing annual electricity demand by the number of full load hours, the installed capacity is obtained 2.14. In contrast to energy intensive processes, no revision outage is considered for calculation of installed electrical capacities.

$$P_{\text{installed};j} = \frac{E_i}{n_{\text{FLH};i}}, \text{MW} \quad (2.14)$$

In the assessment of potential load reduction and increase, fixed shares in current load and unused capacity available for demand response are assumed. Taking into account the load in the current and subsequent hours, they allow for the calculation of suitable loads according to Equations 2.15 and 2.16.

$$P_{\text{reduction};i(\tau,t)} = E_i \cdot r_{\text{load},i(\tau,t)\tau} \cdot r_{\text{reduction},i}, \text{MW} \quad (2.15)$$

In case of a load increase, all demand of the following maximum time (hours) while shifted load has to be balanced can be advanced.

$$P_{\text{increase};i\,(\tau)} = \left[P_{\text{installed};i} \cdot \left(1 - r_{\text{revision},i}\right) - r_{\text{load},i(\tau)} \cdot E_i\right] \cdot r_{\text{increase},i}, \text{MW} \quad (2.16)$$

Its upper limit is set by the installed capacity. Estimated energy demands, utilization levels and demand response shares of the industrial cross sectional technologies are summarised in Table 2.1.

Table 2.1.

Parameters for Calculation of Demand Response Potentials.

Industrial process	n_{FLH}	$r_{reduction}$	$r_{increase}$
	h/a	%	%
Cooling in food industry	6000	50	90
Ventilation in food industry	7000	50	0

Installed electrical capacities are calculated according to Equation 2.17:

$$P_{\text{installed};i} = \frac{E_i}{[N_{hours} \cdot r_{\text{use},i} \cdot (1 - r_{\text{revision},i})]}, \text{MW} \tag{2.17}$$

2.3.2. Investment analysis

A scenario methodology is used to analyse the power system in 2050 by the EMPS model and an investment algorithm for evaluation of profitability of expansion of transmission links (Graabak, et al., 2015). The EMPS model can be combined with an algorithm for analysis of profitable investments in transmission and generation capacities (Wolfgang, 2008). This is a one-stage investment analysis that finds profitable investments from a given start-year where capacities are known, e.g. 2010, to a given future year, e.g. 2050. First, the model is solved for the future year without any new investments, i.e. the capacities used for the future year are the remaining part of the capacities that existed in the start-year. Next, the model checks which investments are profitable at simulated prices. This calculation includes a comparison between average annual operating profits over simulated climate years towards annualized investment costs. For all investments that are profitable at simulated prices, some new capacity is included before the next simulation.

The EMPS model is now solved again using the adjusted capacities for the future year, and profitability for investments is checked again for the new power prices, and capacities are adjusted again. The algorithm converges when: all implemented investments are profitable and no additional investments are profitable.

This approach gives a reasonable suggestion for a balanced development of capacities, and simulated prices for the future year will reflect both operating- and investment costs. There are however no guarantees that the model will find the global optimum for the combination of investments that should be carried out.

The marginal profit for investing in 1 MW extra transmission capacity is calculated by Equation 2.18 (Graabak, et al., 2015):

$$\pi_k = \frac{\sum_{t \in T, i \in I, l \in L} max\{0; [p_{i,t,l,m_k}(1 - t_{m_k n_k}) - p_{i,t,l,m_k}]; [p_{i,t,l,m_k}(1 - t_{m_k n_k}) - p_{i,t,l,m_k}]\} h_l \times 10}{I^{numb}} - c_k^{inv}, \forall k \in K^{Trans} \tag{2.18}$$

The investment alternative k is for transmission between the areas m^k to n^k. If for instance the price in a given week is largest in area m^k and the price difference is large enough to compensate for the losses in transmission, the marginal profit is calculated as

$$p_{i,j,m^k}(1 - t_{m^k m^n}) - p_{i,j,n^k} > 0. \tag{2.19}$$

If the price is largest in area n^k, the opposite difference is utilized, see (2.18).

For each time-step, the gains of having 1 MW extra capacity are checked. In the EMPS model, the full transmission capacity will always be utilized to send energy towards the high-price area if the price-difference is large enough to pay for the losses. Therefore, the average annual operating profits for transmission lines can be calculated by Equation 2.21. When the operating profits for all investment alternatives have been calculated, the benefits of extra capacity are compared with investment costs. We now interpret the simulated average annual operating profits as the expected annual operating profits, accounting for uncertain climate variables. Then the expected annual profit of investing in 1 MW extra capacity for investment k is the following (Graabak, et al., 2015):

$$\pi_k^{tot} = \pi_k^{op} - c_k^{inv}, \quad \forall k \in K \, . \tag{2.20}$$

In every round of the investment algorithm loop, we consider whether the capacity for a specified investment alternative should be increased, decreased or be unchanged. The capacity is increased if the following condition is satisfied (Graabak, et al., 2015):

$$\frac{\pi_k^{tot}}{c_k^{inv}} > z_k \tag{2.21}$$

Four main scenarios of investment algorithm were used in the EMPS model. Two of the scenarios are based on RES in Baltics, there are no further investments in Russia and Belarus allowed, and the difference between these two scenarios is that scenario A1 is based on the existing connection to Russia and Belarus, but in scenario A2 there is no connection to Russia and Belarus. The other two scenarios differ in that there is no RES but there is Susplan scenario.

2.4. Renewable energy source integration calculations

The use of solar energy becomes more and more affordable, which can be justified by the rapid development of technologies and their price levels, as well as the amount of solar energy used over the last few years.

The author carried out a research (see Table 1.1, *Paper No. 10*) about the largest solar energy plant in the Baltics, which allows to comprehend the potential of solar energy. The obtained serial data and measurements are based on solar energy plant in Latvia. In solar park, 216 solar panels with a total area of 850 m^2 (including the area between panels) were installed for electricity generation, with a total installed capacity of 40 kW. Measurements were taken over 24 h period from January till December 2016. Time series data processing and data correlation was performed with MINITAB 18. For regression analysis data of produced electricity and global radiation were analysed.

As it was mentioned in literature review, solar energy more and more is integrated into systems, where one of the possibilities is to integrate it in district heating system (see Table 1.1, *Paper No. 9*).

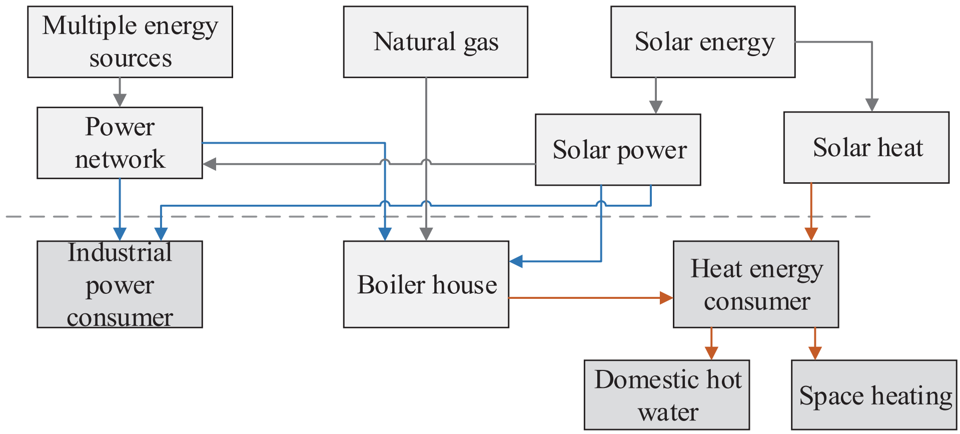

Fig. 2.7. Energy flows of analysed system.

The case study of the research is a boiler house of a DH system, which supplies central heating for and domestic hot water preparation. The boiler house uses natural gas as an energy source for heat production and is directly linked to the industrial consumer with particular heat and electricity consumption. The DH Company considers using solar energy instead of natural gas to reduce energy prices and overall environmental impacts. Research analyses the installation of PVT technology and integration into the existing DH system because there are both heat and power consumers. Figure 2.7 shows the system boundaries and energy flow connections.

In *Paper No. 9* (see Table 1.1) several different scenarios are compared in order to find the optimal design of the solar energy system for the particular case study. The scenarios differ in terms of the size of installed PVT area and an excess power utilization setup.

The main input data for the research are real hourly power and heat consumption. The power consumption is the sum of particular boiler house and industrial plant electricity consumption. The annual power consumption is around 750 MWh, with heat consumption of 20 142 MWh.

Hourly climatic conditions (ambient temperature and global horizontal irradiation) for Riga, Latvia, are used for the solar energy yield calculation. Data are obtained from the State Ltd "Latvian Environment, Geology and Meteorology Centre". The annual average outdoor temperature for the particular area in 2016 was 9 °C, but solar radiation – 991 kWh/m^2. To develop the mathematical model, several technical parameters and assumptions were used. The detailed assumptions used for calculations are presented in *Paper No. 9* (see Table 1.1).

3. RESULTS AND DISCUSSION

This section presents the results of studies conducted for sustainability analysis of renewable energy sources. This section refers to the results of the two previous sections and on *Papers No. 1 – 10* (see Table 1.1).

3.1. Environment and climate

Greenhouse gases and their reduction measures are directly related to the use of resources. On the basis of historical data and the adoption of different development scenarios, forecasts for future development of emissions can be developed. The developed SD model is tested for the non-ETS energy sector of Latvia. Three scenarios for GHG emission target are analysed (see boundary lines in Figs 3.1 and 3.2).

1. In 2020 GHG emissions exceed the 2005 level by 17 %.
2. In 2030 GHG emissions remain at the 2005 level.
3. In 2030 GHG emissions are 10 % below the 2005 level.

The reference or base scenario characterizes the situation, when system develops without implementation of any additional policy measures. In case in the non-ETS sector no policy instruments are used in addition to those, which are already effective or planned, GHG emissions in 2030 are a little above the target "GHG emissions as in 2005", reaching 1.99 million tones CO_2 per year. The GHG emission reduction is present in the production of electric power, the use of oil products and coal at individual heat sources, as well as in the natural gas consumption within the centralized district heating. However, increase in natural gas consumption at individual heat sources rises. By using the modelling, 8 policy scenarios are simulated. Results of the reference scenario are illustrated in Figs 3.1 and 3.2 and compared to the results of the rest two scenarios.

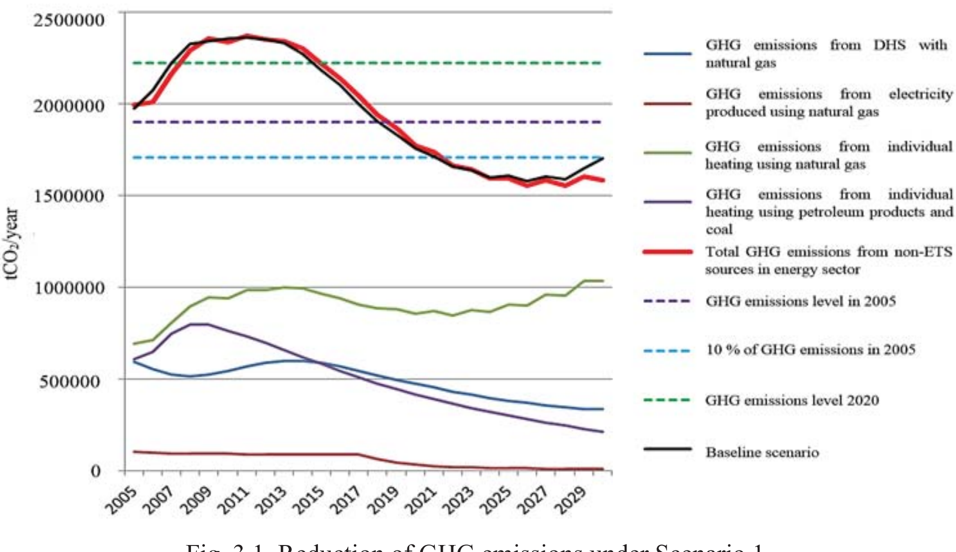

Fig. 3.1. Reduction of GHG emissions under Scenario 1.

Scenario 1. Energy efficiency measures at end consumers in all sectors are subsidized, and information campaign on energy efficiency measures takes place. In Fig 3.1, it can be seen that GHG emissions reduce by 0.1 $GgCO_2$, if compared to the base scenario.

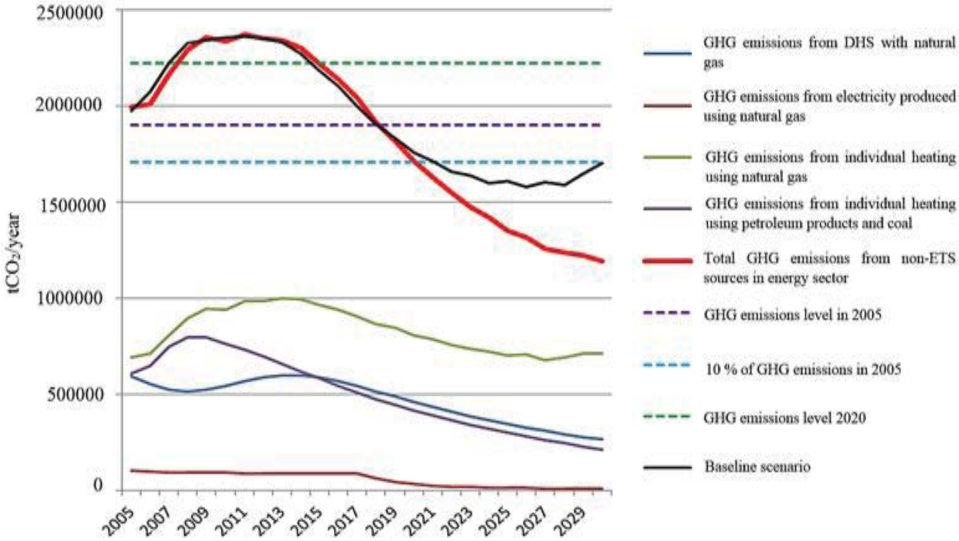

Fig. 3.2. Reduction of GHG emissions under Scenario 2.

Scenario 2. Energy efficiency measures at end consumers in all sectors are subsidized, information campaign on energy efficiency measures takes place, capital costs of renewable energy sources are subsidized, information campaign on the use of renewable energy sources takes place and fuel costs of renewable energy sources are subsidized. Figure 3.2 shows that GHG emissions reduce by 0.51 $GgCO_2$, if compared to the base scenario.

When implementing Scenario 1, the cumulative GHG emission reduction is 0.25 million tons of CO_2, if compared to the base scenario. In order to implement this scenario, in the period of time from 2016 until 2030 state aid in the amount of 500 million EUR would be required. Under Scenario 2 the cumulative GHG emission reduction is 1.2 million tons of CO_2, if compared to the base scenario. In order to implement this scenario in the period of time from 2016 until 2030 state aid in the amount of 930 million EUR will be required. GHG reduction measures can be implemented one by one, without performing other measures.

Figure 3.3 shows modelling results for installed electricity generation capacity in Latvia by 2050. With an increasing natural gas price, the use of other resources will become more attractive. Besides, the already widely used hydropower generation, especially wind and solar energy, is expected to compete with electricity production from natural gas. The proportion of solar and wind power is going to rise from June 2016 forward because of the repeal of current quota cancellation for new installations, i.e. new installations will receive state support in form of a feed-in tariff for the produced electricity again. The second reason for rise in use of RES is the decrease of investment costs, which is forecasted by manufacturers (Criqui, et al., 2015).

This way renewable energy technologies become more competitive in line with increasing price of natural gas.

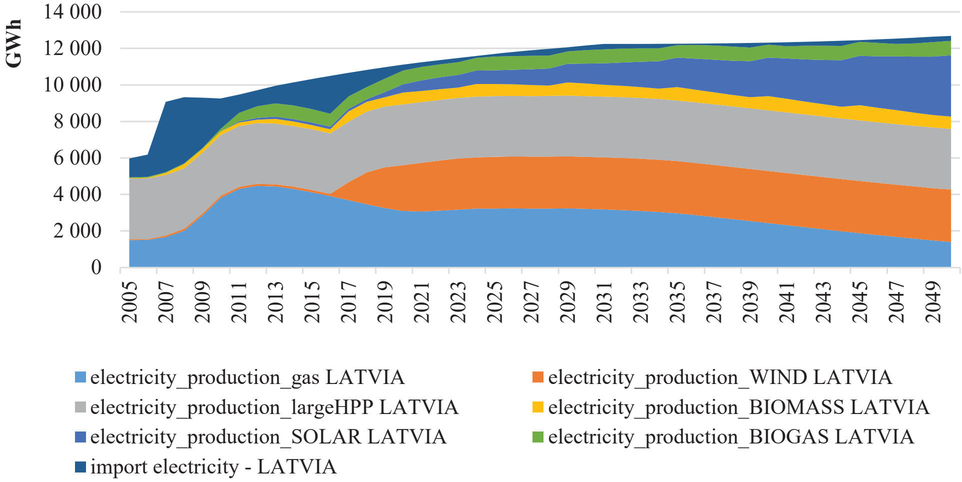

Fig. 3.3. Electricity generation forecast in Latvia by 2050.

The results suggest that the consumption of natural gas for electricity generation in Latvia will decrease in the coming decades. In the mid-term (by 2030), around 64 % of energy consumed could be generated from RES. Meanwhile, by 2050 the share of fossil fuels will not exceed 10 % of the total generation capacity.

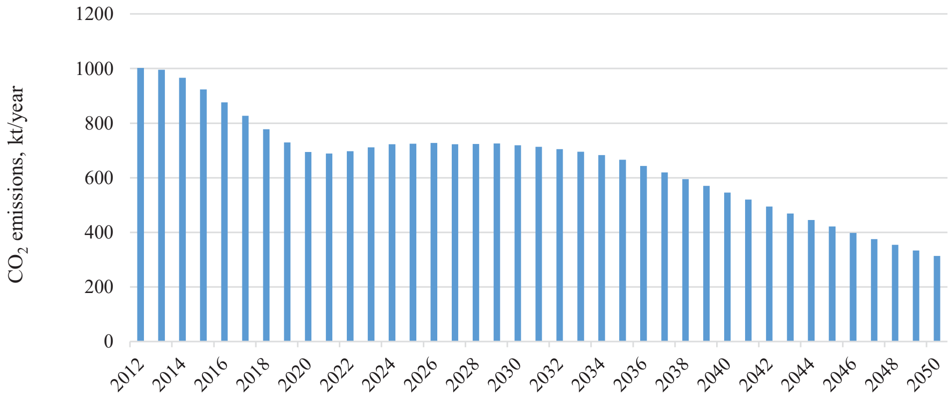

Fig. 3.4. CO_2 emission forecast from electricity generation in Latvia by 2050.

The environmental performance of the electricity sector was evaluated based on carbon intensity. In Fig. 3.4, results of CO_2 emission forecast in Latvia by 2050 are presented. Modelling results demonstrate that decreasing natural gas share in electricity production will allow reducing CO_2 emissions from electricity sector significantly. A decline of almost 70 % in power sector emissions can be achieved by 2050 compared to 2012 level. However, this decrease will not allow reaching zero-emission level as planned by the EC in its Roadmap for low carbon economy in 2050. Therefore, alternative policy strategies should be developed to allow achieving CO_2 emission reductions greater than these. It should be also noted that the forecasted 70 % emission reduction is mainly facilitated by the presence of state support measures and any discontinuation of those can lead to a delay in renewable electricity capacity increase.

3.2. Engineering

Heat pump utilization in order to increase electricity consumption and, subsequently, increase the share of renewable resources in national energy sector, is illustrated by simulation of capacity changes. It is assumed that the maximum possible objective will be achieved by 2030.

Heat pump integration into DH system can be simulated according to three development scenarios – pessimistic scenario, moderate scenario, and optimistic scenario. Analysis of the effects of the heat pump performance is equal for all the scenarios and shows that 5200 MW of thermal energy covered with heat pumps might be reached with 1733 MWe of electrical energy if COP = 3, 1300 MWe if COP = 4 and 1040 MWe if COP = 5. As it was mentioned, COP is usually in a range from 3 to 5 and, as can be seen in all three scenarios, heat pumps with higher COP are more effective, because they consume less electricity.

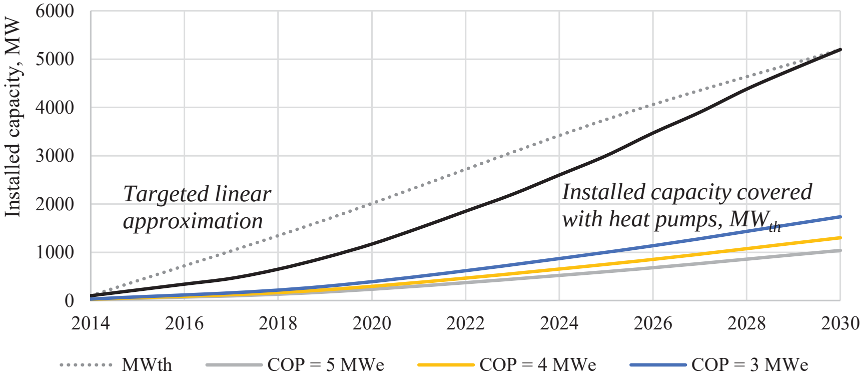

Fig. 3.5. Installed capacity covered with heat pumps in Latvia for pessimistic development scenario.

Scenario A, which is depicted in Fig. 3.5, shows exponential development trend. The pessimistic scenario assumes that the integration of heat pumps into DH system and electricity consumption reduction targets will approach the aim very slowly: the full saturation will be reached only by the end of the modelling period. Scenario B is a moderate scenario performing an S-type development. The moderate scenario assumes initially slow development of heat pump integration in district heating system that will, eventually, accelerate. This scenario occurs when certain policy instruments interfere with the development of heat pump integration process – according to the model results the acceleration starts in 2020 and already by 2023 it will reach the targeted level of the installed thermal capacity covered with heat pumps.

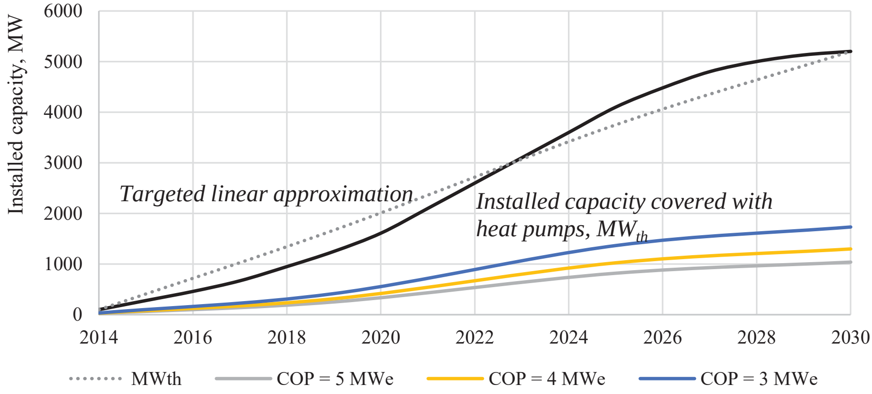

Fig. 3.6. Installed capacity covered with heat pumps in Latvia for moderate development scenario.

Moderate scenario is characterized by the fact that the national policy does not support the development of heat pumps, so it hinders development. However, if the policy is changed towards the reduction of use of fossil resources and transition to renewable resources, we can await faster development. Scenario C is an optimistic scenario and it anticipates relatively fast heat pump development, which takes place due to the implementation of many different policy tools that promote the development of heat pump integration (see Fig. 3.7). Introduction of the goal-seeking growth model is the shortest way to reach the targeted installed capacity of heat pumps in DH systems. But as the behaviour is driven by developed new policy instruments, a specific policy platform in the field of heat pump integration in DH systems needed to be applied already before 2015.

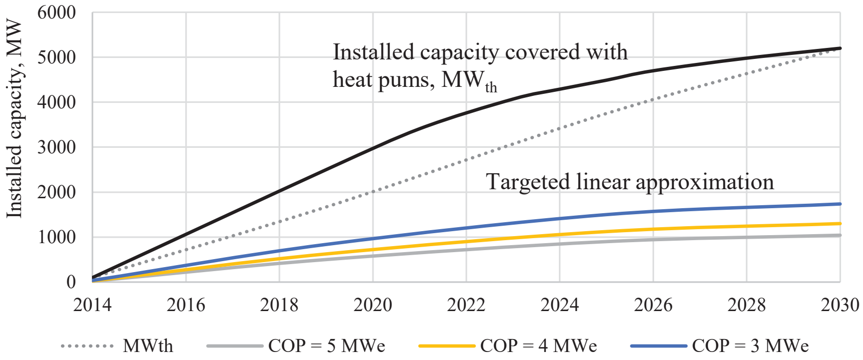

Fig. 3.7. Installed capacity covered with heat pumps in Latvia for optimistic development scenario.

Results of the study show that there is a good technical perspective for introduction of renewable energy generated electricity accumulation through integration of heat pumps into the DH system of Latvia. It may be concluded that hypothesis of the paper is approved: integration of heat pumps into the DH would raise the demand for electricity generated from renewables.

The aim of the research regarding biomass ash use was to define the best alternatives for use of biomass ash as a catalyst for water electrolysis processes for hydrogen production. Multi-criteria analysis TOPSIS method was selected for the assessment of defined alternatives. Using multi-criteria analysis four wood fuel ash catalyst alternatives with different composition were evaluated: S25, S50, S75, and S100. Three criteria with specific weights were defined – pH, diameter of catalytic spheres and surface characteristics of the spheres.

The weighted normalized decision matrixes were used to find the positive-ideal solution and negative-ideal solution with respect to the specific physical parameters of the developed catalysts. Performed MCA analysis showed that S25 can be defined as an appropriate sample for electrolysis process: the coefficient of closeness for this alternative is 0.87 to positive-ideal solution. The negative ideal solution is sample S75 with a value of coefficient of closeness equal to 0.13.

The results of the experiment confirmed that hydrogen production via water electrolysis, if biomass ash catalysts are used, is more effective if the proportion of ash is 25 % straw ash and 75 % wood ash. However, additional hydrogen production monitoring, based on direct continuous measurement method with a gas analyser, might be useful to reduce the uncertainty associated with the use of "bubble method".

3.3. Economic aspect

3.3.1. Demand response

Methodology is approbated by use of certain climate data in one of the regions in Latvia. DH system operation depends on climate conditions – wind, temperatures, solar radiation and other. It is possible to calculate the correction of DH system heat consumption according to indoor and outdoor temperatures by Equations 2.11 2.12 (see sub-chapter 2.3) and the results of calculation of correction coefficients are presented in Fig. 3.8.

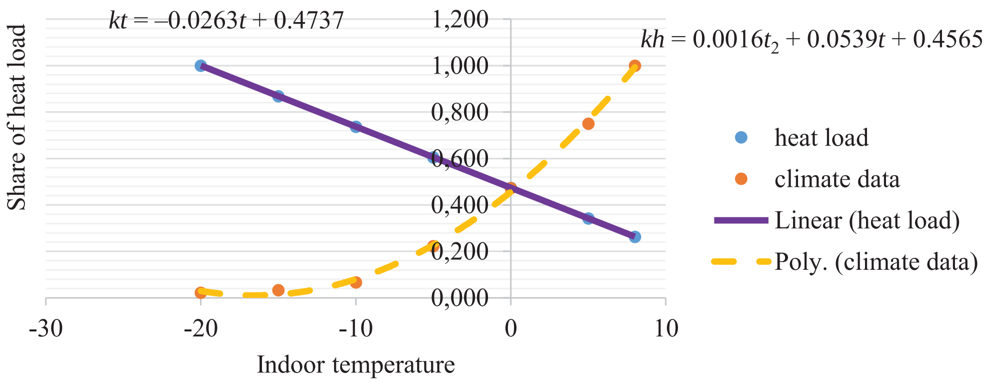

Fig. 3.8. Potential diagram of demand response.

In the diagram correlation between two factors k_t and k_h can be seen. Diagram shows that the most important flexibility of DR potential is available by reducing the angle of slope of correction coefficient changes versus indoor temperature. DR in electricity use is an approach with high level of novelty and has a wide potential in future. Demand response in DH systems depends on electricity price in comparison with heat energy price and increase of renewable electricity share.

After using equations and parameters for calculations, the first results of calculation are presented in Fig. 3.9. Figure 3.9 shows average potentials for load reduction by shifting to a later point in time, subdivided by consumer. As cooling and ventilation are the main electricity consumers in food industry, the results show difference between average potential of Latvia and Kazakhstan for load reduction. The difference between Latvia and Kazakhstan is 52 and 82 MW, respectively. For industrial cooling average potential for load reduction is 5 MW in Latvia and 57MW in Kazakhstan.

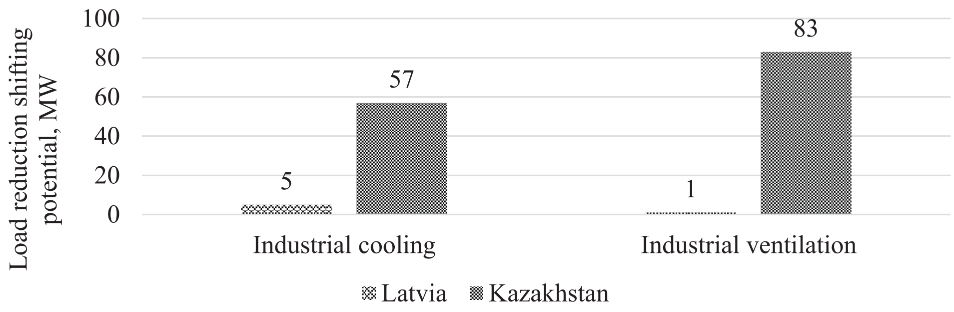

Fig. 3.9. Average potential for load reduction by shifting to a later point in time, subdivided by consumer.

The results are similar for industrial ventilation and its average potential for load reduction – in Latvia 1 MW, but in Kazakhstan 83 MW. The quantification of flexible loads in industry comprises two countries. Special attention is paid to the evaluation of temporal availability and geographic allocation of qualified consumers. Load profiles of the corresponding processes and appliances are considered in order to analyse the temporal variability of the overall demand response potential.

3.3.2. Investment analysis

The results from EMPS model and an investment algorithm for Latvia and Lithuania are shown in Fig. 3.10. The starting capacity for all four scenarios is 1600 MW. After investments the highest capacity is for scenario A2, more than 1900 MW.

The total energy production by four scenarios in Latvia and Lithuania is shown, and all scenarios include production from renewable resources.

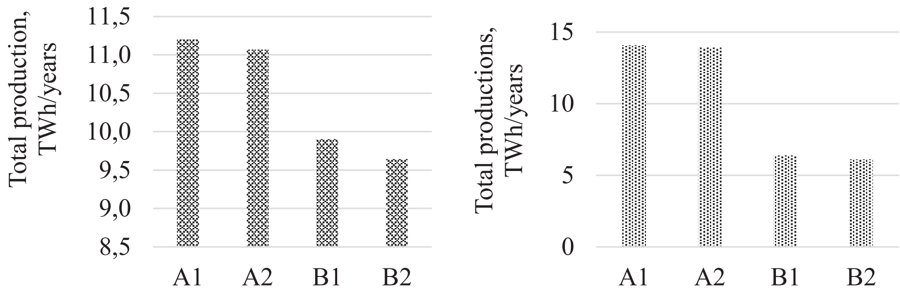

Fig. 3.10. (a) Total production in Latvia by scenarios; (b) Total production in Lithuania by scenarios.

The scenarios A1 and A2 by total production are quite similar. Also, there are no large differences between Latvia and Lithuania. Both scenarios (A1 and A2) are based on RES use and no further investments in Russia and Belarus are allowed. The main difference in these two scenarios is that scenario A1 includes the connection to Russia and Belarus, but scenario A2 has no further connections to Russia and Belarus. The total production in Latvia in scenario A1 is 11.2 TWh/year and in scenario A2 is 11.1 TWh/year, but in Latvia total production in scenario B1 is 9.9 TWh/years and in B2 it is 9.6 TWh/year.

Analysing the four scenarios by the type of resource used, Lithuania has higher potential of RES that could be used for production. In comparison, Lithuania has bigger potential in wind and bio-resources use for production, but Latvia has hydro energy potential. Use of solar energy for production is quite similar for both of Baltic States. The wind potential for Latvia is more than 5 TWh/year. Use of hydro source for production in Latvia is almost 10 times higher than in Lithuania.

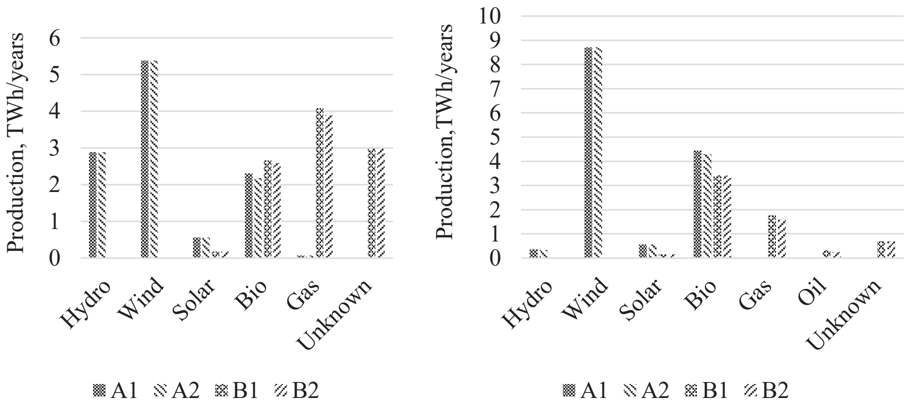

Fig. 3.11. (a) Production in Latvia by sources in different scenarios; (b) Production in Lithuania by sources in different scenarios.

The main difference between Latvia and Lithuania in both scenarios is the use of gas as source. Latvia is more dependent and production from gas is more than 2 times higher than in

Lithuania. Investment algorithm allows predicting the amount of investment and total production. More appropriate scenarios for Latvia and Lithuania are RES scenarios.

3.4. Assessment of renewable energy source

In MINITAB 18 data from four 10kW inventors were analysed. In data processing tool one-year data was operating. The data after processing in the MINITAB 18 program shows very well the seasonality of Latvia and the most intense solar radiation in the summer months from April to August (see Fig. 3.12).

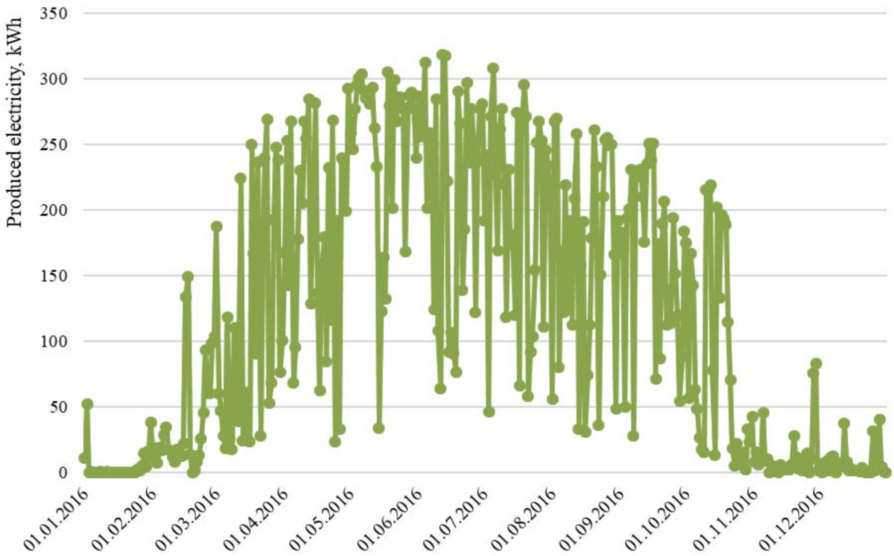

Fig. 3.12. Produced electricity, kWh.

Regression analysis was done by MINITAB 18 software. Solar plant produces on average 45 MWh, and about 6 MWh in summer months. For regression analysis twelve samples were used which was not enough to provide a very precise estimate of the strength of the relationship. Measures of the strength of the relationship, such as R-Squared and R-Squared (adjusted) can vary a great deal because of the size of analysed sample. Regression analysis show that R-sq is 95.65 %, produced electricity can be explained by regression model (2.22):

$$Y = -0.5583 + 0.07581X - 0.000194X^2. \quad (2.22)$$

One data point has a large residual and is not well fit by the equation. This point is marked in red on the plots. As data analysis has less than 15 data points, data cannot be interpreted using the p-value. With small samples, the accuracy of the p-value is sensitive to non-normal residual errors.

The analysis of the regression shows that there is close correlation between electricity generation and solar radiation. Although there is a correlation between these two factors, there are other factors that influence the amount of produced electricity, such as selected technology, technology maintenance, and location of solar panels, panel efficiency and other minor factors. From this research, it can be seen, that electricity produced from solar energy has a strong correlation with global radiation in climate conditions in Latvia. The author concludes that the use of solar energy in Latvia has potential, but the use of solar energy is associated with other factors that need to be taken into account in order to be integrated, for example in the district heating system.

According to the methodology described above, the solar power generation was modelled on an hourly basis and the results obtained were aligned with the power consumption.

When installing 1000 m^2 of PVT (S1), the main part (88 %) of generated solar power directly covers the power consumption. Only a small part needs to be exported to the grid or converted to heat. Therefore, the solar fraction for power consumption coverage reaches only 13 %. In the scenario (S3), the maximal generated power in the summer period is almost the same as total power consumption. There are more hours when excess solar power occurs; therefore 16 % of generated solar power should be converted to heat because in those periods heat tariff is higher than power market price. It would be economically reasonable to export to the grid only 4 % of generated solar power as excess power occurs mainly when the electricity market price is low. In scenario S5 with the largest PVT area installed and without the power accumulation, a large part of the generated solar power exceeds power consumption (see Table 1.1, *Paper No. 9 (Fig. 7)*). The power converted to heat reaches 32 % of generated power; and it is economically reasonable that around 10 % of electricity is sold and exported to the grid.

The largest solar fraction (SF) for power generation is set in scenario S8A with Li-ion batteries for power accumulation. The other part is exported to the grid and sold at a daily market price. The solar heat generated by PVT technology directly covers the heat demand. In the particular case heat demand is relatively high. Therefore, almost all solar heat even in 3000 m^2 PVT scenario can be used either for space heating in cold season, or for domestic hot water preparation during the summer (see Table 1.1, *Paper No. 9 (Fig. 9)*). Additional heat is produced from solar power, but only in cases when heat demand is high enough. The maximal SF for heat demand coverage reaches 7 % in scenarios S5 and S8A. Heat demand rapidly increases in the winter period due to space heating in buildings and it cannot be totally covered by solar energy without additional accumulation technologies.

Calculated economic indicators show that scenario S5 has the highest NPV value and lowest LCOE − 34.10 EUR/MWh. The system payback time is 12 to 13 years and it is similar for all scenarios. The environmental impact of all scenarios was compared by using GHG analyses. The emission factor is much higher for DH heat; therefore, avoided emissions from PVT heat generation mainly determine the results of the environmental analyses. The highest score for total avoided CO_2 emissions is in Scenario S5. In order to obtain more precise environmental analyses results, a detailed life cycle analyses should be done for particular scenarios.

CONCLUSIONS

1. Sustainability analysis of renewable energy sources allows viewing the resources from four aspects. In the Thesis, analysis of renewable energy sources nexus with environmental and climate, engineering, economic and renewable energy source aspects is given and analysed in three sections. Each section used a variety of methodologies that describe the relationship between renewable energy and selected aspects. Various types or research methodologies were used − system dynamics modelling, demand response analysis, investment analysis, scenario analysis, multi-criteria analysis - TOPSIS, and time series and regression analysis.
2. The developed system dynamics model allows analysing the possible GHG emission reduction and impact on this reduction caused by the suggested policy instruments. The model allows for evaluation of economic and financial factors. Testing of the system dynamics model in the conditions of Latvia demonstrates that the highest effect in GHG emission reduction can be achieved by substituting the fossil fuel with the renewable energy sources. According to scenarios 1 and 2, when implementing scenario 1, the cumulative GHG emission reduction is 0.25 million tons of CO_2, if compared to the base scenario. In order to implement this scenario, in the period of time from 2016 until 2030, state aid in the amount of 500 million EUR would be required. Under scenario 2 the cumulative GHG emission reduction is 1.2 million tons of CO_2, if compared to the base scenario. In order to implement this scenario in the period of time from 2016 until 2030, state aid in the amount of 930 million EUR will be required. GHG emission reduction measures can be implemented one by one, without performing other measures.
3. As the largest contributor of the European Union's total carbon dioxide emissions, energy sector plays an important role in mitigating climate change. A system dynamics approach was applied to simulate development of electricity sector in the region under the existing policy design by 2050. Results show that renewable resources have the potential to integrate in the electricity generation balance significantly in the long-term. The most promising sources will be solar, wind, biomass and biogas. There is, however, a major precondition for this to happen. The cost of electricity produced from renewable energy sources must be competitive with the cost of electricity produced from the natural gas. Based on results, it will be possible due to already historically observed market trends – increasing price of natural gas and decreasing investment costs of alternative energy technologies. Nevertheless, presence of additional support measures (such as a feed-in tariff for electricity from renewable energy sources or taxes) is vital to ensure the desired transition. In case these preconditions are in place, there is a potential to reduce carbon dioxide emissions from Latvian power sector by around 70 % by 2050, compared to 2012. These findings demonstrate the significant potential of the power sector to contribute to low-carbon economy. Results show that the proposed simulation model can be adapted for use in other countries with similar power market structure as in Latvia.
4. Heat pump utilization is needed in order to increase electricity consumption and, consequently, increase the share of renewable resources in the national energy sector. Heat pump integration into district heating system was simulated according to three development scenarios – pessimistic scenario, moderate scenario and optimistic scenario. Results of the

study show that there is a good technical perspective for introduction of renewable energy generated electricity accumulation through integration of heat pumps into the DH system of Latvia.

5. Another engineering aspect shows that renewable energy source wastes have potential as amendment in electrolysis process. Suitability analysis of biomass combustion ash use as catalyst in water electrolysis process was researched in the Doctoral Thesis. MCA TOPSIS method was used to compare various parameters of the catalysts in terms of getting higher H_2 production rate. Four wood fuel ash catalyst alternatives with different composition were evaluated: S25, S50, S75, and S100. Three criteria that are necessary for performance ranking were selected within the study: pH, diameter of catalytic spheres, and surface characteristics of the spheres. Weights of the criteria were based on literature analysis and also the opinion of the field experts was taken into account. It was proved that there is a perspective to use the biomass ash as a catalyst in water electrolysis processes. Environmental performance of such substitution might be significant – reduction of use of chemical catalysts is ensured. However, detailed calculation of technical, environmental and economic effectiveness (for example rate of hydrogen production per material economy and resource effectiveness) is required. The study proved that TOPSIS method is an appropriate method for analysis of bio-based water electrolysis catalysts. Also at wider scale, the use of the method might be included in an experiment planning phase to choose better alternative for further experiments.
6. There are several methods to reduce non-renewable resources use and increase share of renewable energy sources. Demand response and investment analysis allows increasing of RES share. Demand response in electricity use is an approach with high level of novelty and has wide potential in future. Demand response in DH systems depends on electricity price in comparison with heat energy price and increase of renewable electricity share. Investment algorithm allows predicting the amount of investment and total production. After research, investment analysis shows that the more appropriate scenario for Latvia is RES scenario. Investment algorithm can be used in other countries provided that all the necessary input data is available.
7. Currently, the transition from fossil to renewable sources is a topical issue, and solar energy is one of the promising resources. The results show that, from April till September, more than 6000 kWh of electricity is produced monthly; solar energy plant produces ~45 MWh/year. Regression analysis was carried out for produced electricity versus global irradiation. Regression analysis shows that $R\text{-}sq$ is 95.65 %, produced electricity can be explained by regression model $Y = -0.5583 + 0.07581X - 0{,}000194X^2$. The relationship between produced electricity (MWh) and global radiation (kWh/m^2) is statistically significant ($p < 0.05$). It is necessary to obtain additional data in order to conduct in-depth research on factor correlation.
8. Continuing exploration of solar energy determine that solar energy can be integrated in one of the systems to produce electricity or heat. Solar energy is widely discussed as a solution for sustainable development of the DH and energy sector. Therefore, the research analyses installation of photovoltaic thermal hybrid (PVT) for heat and power production. The generated solar power ranges from 109 MWh to 307 MWh per year, but the generated heat

is from 444 to 1330 MWh per year. The highest solar fraction can be obtained in scenario with maximal PVT installation with accumulation added (S8A). Solar fraction (SF) reaches 38 % of total heat and power consumption in scenario S8A. However, this scenario has also the highest costs. Results show that in case of 3000 m^2 PVT installation without accumulation, a lot of excess power is generated. When analysing hourly power market prices, it is economically beneficial to convert most of the excess power to heat because the electricity market price is lower than the DH heat tariff. The economic analysis shows that the highest NPV value and lowest LCOE has the scenario with maximal installed PVT area and without the accumulation (S5). The calculated value of LCOE for all scenarios is lower than when using reference costs of energy. The total avoided emissions are higher for the scenarios without power accumulation. The specific avoided CO_2 emission costs show that the optimal scenario is the one which has the 2000 m^2 PVT area installed. The obtained results show that PVT technology can be an optimal solution for integration in DH system. This is due to high DH base load of heat demand and additional power consumption. A relatively high solar fraction for large scale PVT systems can be reached in colder climate zone of northern Europe. The methodology can be used to analyse the possibility to determine the optimal PVT capacity and economic parameters. The hourly solar power analyses show that it is reasonable to convert excess power to heat and cover the heat load when the power market price is low.

9. In summary, it can be concluded that sustainable development and the long term performance of renewable energy can be characterized by aspects that are related to climate and environment, engineering aspects and economic aspects.

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Dace Lauka is researcher and lecturer at the Institute of Energy Systems and Environment of the Faculty of Power and Electrical engineering, Riga Technical University. Throughout her 6 years at RTU, she published more than 20 scientific publications. Dace is co-author of 4 monographs and 3 patents. Dace is able to substantiate her scientific work by participating in various scientific conferences and through the implementation of scientific projects. Research area include sustainable use of resources, renewable energy sources and environmental technologies.