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

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MULTI-PERSPECTIVE ANALYSIS FOR THE TRANSITION TOWARDS 4TH GENERATION DISTRICT HEATING

Summary of the Doctoral Thesis

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DOCTORAL THESIS
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To be granted the scientific degree of Doctor of Environmental Engineering (Dr. sc. ing.), the defence of the present Doctoral Thesis will take place on 3 August at 2:00 p.m., at the Faculty of Power and Electrical Engineering of Riga Technical University, Azenes 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 the present Doctoral Thesis has not been submitted to any other university for the promotion to other scientific degree.

Jelena Ziemele ………………………….(signature)

Date ………………………

The present Doctoral Thesis is written in English and consists of an introduction, 3 chapters, conclusions, and a bibliography with 62 reference sources. It is illustrated by 34 figures and 6 tables. The total volume of the Thesis is 202 pages including 14 appendices.

TABLE OF CONTENTS

LATENERGI

The work has been supported by National Research Program “Energy efficient and low-carbon solutions for a secure, sustainable and climate variability reducing energy supply (LATENERGI)”.

Topicality of the Doctoral Thesis

Sustainable development of district heating (DH) is one of the main challenges in the European Union. Tackling this challenge would have a positive impact on the security of energy supply, climate change mitigation, and the country's economic competitiveness. The DH system in Latvia supplies 67 % of the population. Therefore, the development of this sector is important from the technical, economic, socioeconomic, environmental and institutional aspects.

Currently, there are active debates about the introduction of the 4th generation district heating (4GDH) system. These 4GDH systems are based on renewable energy sources. Heat energy is transmitted through the smart network, which is integrated in smart energy systems and operates at low-temperature regime. Supplied heat energy is used in low-energy space heating, cooling, and hot water systems, thus reducing the environmental impact of these systems.

The Doctoral Thesis provides a multi-perspective methodology for the assessment of the transition towards 4GDH systems.

The Aim and Tasks of the Doctoral Thesis

The aim of the Thesis is to provide a structured, multi-perspective methodology based on parsimony principle that can be used to assess the transition from the existing DH system to the 4GDH system. The developed methodology can be used to elaborate and compare several potential DH development scenarios.

The following objectives are set to be accomplished within this research:

1) to analyse the existing DH system, and to evaluate the technical, economic, socioeconomic, environmental and institutional indicators;
2) to create the holistic methodology in order to evaluate the most suitable solution for the transition of DH systems towards 4GDH that aids decision makers, heat consumers and other interested parties to rank all development scenarios and to rank DH producers' performance;
3) to develop a system dynamics (SD) model for the DH system and to study multi-perspective scenarios that show how 4GDH can be reached in near or distant future, depending on used policy instruments.

Hypothesis of the Doctoral Thesis

The improvement of technical, economic, socioeconomic, environmental and institutional efficiency in DH allows moving towards the 4GDH system. These efficiency improvements are required at all DH stages – at the heat source, in distribution grids, and at the end consumer –, and they incorporate the utilization of renewable low-temperature heat sources, heat supply through low-loss grids to low-energy buildings, and smart management of the energy systems. Depending on the used policy instruments, the 4GDH conditions in Latvia could be reached in near or more distant future. The hypothesis is that in the optimistic scenario 4GDH conditions could be reached in Latvia by 2020, but in the pessimistic scenario – by 2030.

Research Methodology

The developed methodology consists of four main, interlinked parts – empirical study, system dynamics modelling, multi-criteria decision making section, and decision makers section –, which all together provide a multi-perspective analysis for the conversion from a conventional DH system to the 4GDH system.

The complexity of the applied methodology was developed over the time to match the growing complicatedness of studied research questions regarding the analysis of technological, economic and environmental improvements by using statistical analysis in the first study's step (see Fig. 1.1.). The second step involved socioeconomic and institutional improvements and a more advanced methodology (decomposition analysis, benchmarking, and multi-criteria analysis).

The third step applies the system dynamic modelling approach with the implementation of policy instruments for energy system planning. The developed multi-perspective analysis gives an insight that allows moving from the existing DH system towards 4GDH.

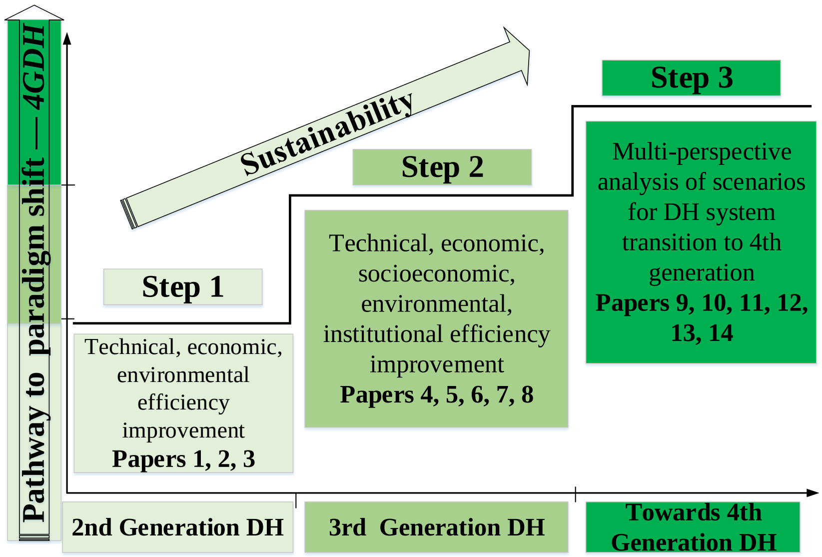

Fig. 1.1. The publications used to study multi-perspective analysis for the assessment of DH systems' development toward 4GDH (the enumeration of the publications corresponds to the full titles given below).

Scientific significance of the Doctoral Thesis

This Thesis provides a multi-perspective analysis methodology for the assessment of the transition towards 4GDH systems. The novelty of this Thesis lays in the application of the methodology which consists of four main, interlinked parts: empirical study, system dynamics modelling, multi-criteria decision making section, and decision makers section. The developed methods are linked together to better describe the complex relations within DH systems.

The developed system dynamics model describes the interrelated behaviour in all three stages of the DH system (at the heat source, in distribution networks, and at the consumer) and allows analysing the feedback loops in the system. Each of these stages is characterized by a number of indicators (technological, economic, socioeconomic, environmental, institutional) and equations that describe the changes and interactions within the DH system. Based on the applied policy instruments and the combinations of renewable energy technologies, the model allows analysing numerous potential development scenarios.

Moreover, there are substantial differences between the behaviour of the participants of the DH system in the terms of financial models and involved parties. By using multi-criteria analysis, the DH system's efficiency can be evaluated from the point of view of system's operators and developers. Depending on the used policy instruments, the system dynamics model indicates that the 4GDH system can be reached in near or distant future, thus this model is able to show the influence of the several hundred combinations of various policy tools and allows integrating the additional policy tools as well.

Practical significance of the Doctoral Thesis

The studies on the implementation of 4GDH in the existing DH system foster the transition to low carbon society. The developed SD model allows identifying the dynamics of CO_2 emissions' reduction. There is a practical significance for various interested parties – DH system's operators and developers, final consumers, policymakers, and scientific community. The presented framework allows evaluating various DH development scenarios from the point of view of DH system's operators and developers. The DH system operators can determine their efficiency level and compare this level with other industry's participants. The multi-criteria analysis results allow choosing investment policy for the developers and DH operators. The developed system dynamic model for non– Emission Trading Scheme (non– ETS) DH sector could be used for the municipal level as well as at the local level.

The developed model allows forecasting the dynamics of the change in heat energy tariff and identifying the mechanisms that influence tariffs. The heat energy forecasting tools are important for all society. The developed methodology can be used to elaborate and compare several potential DH development scenarios towards the 4GDH systems. The implementation of 4GDH system occurs slowly, and its acceleration requires politically farsighted decisions at all levels of DH system's decision making. Therefore, the results of this Thesis can be used as a starting point for the planning of an institutional and organisational framework at the national, municipal, and local level as well as for planning the DH system stages (heat source, distribution heat network, heat consumers). Practical applicability of this methodology can be found in scientific community for the investigation of the DH system's pathway towards 4GDH. This presented framework can be directly applied to other heating systems by adjusting the input data and other relevant mechanisms.

Approbation of the Study

The research results have been approbated in 12 international scientific conferences and published in 16 scientific articles (12 in SCOPUS database and 7 in ISI Web of Science database).

Reports at International Scientific Conferences

1. Ziemele J., Blumberga D., Talcis N., Laicane I. Industrial Research of Condensing Unit for Natural Gas Boiler House // RTU 53rd International Scientific Conference, Conference Proceedings, 11–12 October 2012, Riga, Latvia.

2. Ziemele J., Blumberga D. Inovatīvu degšanas tehnoloģiju ietekmes uz klimatu samazinājuma vērtējums // Latvijas Universitātes 71. zinātniskā konference „Ģeogrāfija. Ģeoloģija. Vides zinātne", 1. februāris, 2013, Rīga, Latvija.

3. Ziemele J., Pakere I., Blumberga D. Development of District Heating System in Case of Decreased Heating Loads // ECOS 2014, 15–19 June 2014, Turku, Finland.

4. Ziemele J., Pakere I., Blumberga D., Žogla G. Economy of heat cost allocation in apartment buildings // International Scientific Conference "Environmental and Climate technologies – CONECT 2014", October 2014, Riga, Latvia.

5. Ziemele J., Pakere I., Talcis N., Blumberga D. Multi-criteria analysis of district heating systems in Baltic States // 6th International Conference on Applied Energy, ICAE 2014, 30 May – 2 June 2014, Taipei, Taiwan.

6. Ziemele J., Gravelsins A., Blumberga D. Decomposition analysis of district heating system based on complemented Kaya identity // 7th International Conference on Applied Energy, ICAE 2015, 28–31 March 2015, Abu Dhabi, United Arab Emirates.

7. Ziemele J., Gravelsins A., Blumberga A., Vigants G., Blumberga D. System dynamics model analysis of pathway to 4th generation district heating systems in the Baltic States // 1st International Conference on Smart Energy Systems and 4th Generation District Heating, 25–26 August 2015, Copenhagen, Denmark.

8. Ziemele J., Gravelsins A., Blumberga A., Blumberga D. The effect of energy efficiency improvements on the development of 4th generation district heating // International Scientific Conference "Environmental and Climate technologies – CONECT 2015", October, 2015, Riga, Latvia.

9. Ziemele J., Gravelsins A., Blumberga A., Blumberga D. Sensitivity analysis of district heating system model for transition from fossil fuel to renewable energy sources // 29th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems, ECOS 2016, 19–23 June 2016, Portorož, Slovenia.

10. Ziemele J., Pakere I., Chernovska L., Blumberga D. Lowering temperature regime in district heating network for existing building stock // 19th Conference on Process Integration, Modelling and Optimisation for Energy Saving and Pollution Reduction, PRES 2016, 27–31 August 2016, Prague, Czech Republic.

11. Ziemele J., Gravelsins A., Blumberga A., Blumberga D. Development of heat saving platform in the system dynamics model for transition to 4th generation district heating // 2nd International Conference on Smart Energy Systems and 4th Generation District Heating, 27–28 September 2016, Aalborg, Denmark.

12. Ziemele J., Timma L., Kubule A., Blumberga D. A holistic methodology to assess the transition to 4th generation district heating systems // International Scientific Conference of Environmental and Climate Technologies CONECT 2016, October 2016, Riga, Latvia.

Publications on the topic of the Thesis

1. Ziemele J., Blumberga D., Talcis N., Laicane I. Industrial research of condensing unit for natural gas boiler house // Environmental and Climate Technologies (ISSN: 1691-5208) – 2012, 10, 34–38, doi:10.2478/v10145-012-0023-9 (in Scopus).

2. Ziemele I., Pakere I., Blumberga D., Zogla G. Economy of Heat Cost Allocation in Apartment Buildings // Energy Procedia on International Scientific Conference "Environmental and Climate Technologies, CONECT 2014" (ISSN: 18766102) – 2015, 72, 87–94, doi: 10.1016/j.egypro.2015.06.013 (in Scopus and ISI Web of Science).

3. Ziemele J., Pakere I., Talcis N., Cimdina G., Vigants G., Veidenbergs I., Blumberga A., Blumberga D. Analysis of wood fuel use development in Riga // Agronomy Research (ISSN: 1406-894X) – 2014, 12(2), 645–654 (in Scopus).

4. Ziemele J., Pakere I., Blumberga D. Development of District Heating System in Case of Decreased Heating Load // The 27th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems (ECOS 2014). Conference Proceedings (ISBN: 978-163439134-4) – 2014, 2044–2055 (in Scopus).

5. Ziemele J., Pakere I., Talcis N., Blumberga D. Multi-criteria Analysis of District Heating systems in Baltic States // 6th International Conference on Applied Energy, ICAE 2014. Energy Procedia (ISSN: 18766102) – 2014, 61, 2172–2175, doi:10.1016/j.egypro.2014.12.102 (in Scopus and ISI Web of Science).

6. Ziemele J., Vigants G., Vitolins V., Blumberga D., Veidenbergs I. District heating systems performance analyses. Heat energy tariff // Environmental and Climate Technologies (ISSN: 16915208) – 2014, 13(1), 32–43, doi: 10.2478/rtuect-2014-0005 (in Scopus).

7. Ziemele J., Gravelsins A., Blumberga D. Decomposition Analysis of District Heating System based on Complemented Kaya Identity // 7th International Conference on Applied Energy, ICAE 2015. Energy Procedia (ISSN: 18766102) – 2015, 77, 1229–1234, doi:10.1016/j.egypro.2015.07.164 (in Scopus and ISI Web of Science).

8. Ziemele J., Pakere I., Chernovska L., Blumberga D. Lowering Temperature Regime in District Heating Network for Existing Building Stock // Chemical Engineering Transactions (ISBN 978-88-95608-42-6) – 2016, 52, 709–714, doi:10.3303/CET1652119 (pending in Scopus and ISI Web of Science).

9. Ziemele J., Pakere I., Talcis N., Blumberga D. The Future Competitiveness of the Non-Emissions Trading Scheme District Heating Systems in the Baltic States // Applied Energy (ISSN: 03062619) – 2016, 162, 1579–1585 (in Scopus and ISI Web of Science).

10. Ziemele J., Gravelsins A., Blumberga A., Blumberga D. System Dynamics Model Analysis of Pathway to 4th Generation District Heating in Latvia // Energy (ISSN: 03605442) – 2016, 110, 85–94 (in Scopus and ISI Web of Science).

11. Ziemele J., Gravelsins A., Blumberga A., Blumberga D. The Effect of Energy Efficiency Improvements on the Development of 4th Generation District Heating // International Scientific Conference "Environmental and Climate Technologies, CONECT 2015". Energy Procedia (ISSN: 18766102) – 2016, 95, 522–527 (in Scopus).

12. Ziemele J., Gravelsins A., Blumberga A., Blumberga D. Sensitivity analysis of district heating system model for transition from fossil fuel to renewable energy sources // The 29th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems (ECOS 2016). Conference Proceedings – 2016, XX-XX (pending in Scopus).

13. Ziemele J., Gravelsins A., Blumberga A., Blumberga D. Combining energy efficiency at source and at consumer to reach 4th generation district heating: economic and system dynamics analysis // Energy (ISSN: 03605442) - 2017, in Press,1-12, (In Scopus).

14. Ziemele J., Kubule A., Blumberga D. Multi-perspective methodology to assess the transition to 4th generation district heating systems // International Scientific Conference of Environmental and Climate Technologies CONECT 2016. Energy Procedia (ISSN: 1876-6102) – 2017,113,17-21. (Pending in Scopus).

Methodological material and patents

1. Blumberga D., Gedrovičs M., Kirsanovs V., Timma L., Kļaviņa K., Kubule A., Kļaviņš J., Muižniece I., Kauls O., Barisa A., Bāliņa K., Lauka D., Ziemele J., Kārkliņa I. Laboratory Works for Students of Environmental Engineering, Vol. 3 (original title in Latvian "Laboratorijas darbu krājums vides inženierzinātņu studentiem. 3. daļa") // Riga Technical University Press (ISBN: 978-9934-10-747-4) – 2016 – 92 p.

2. Blumberga D., Ziemele J., Lubiņš A., Vīgants E., Žandeckis A., Vīgants Ģ., Kirsanovs V., Veidenbergs I. Wood pellet burner, "Ludzas Bio-enerģija" Ltd.: LV-14670; 20.06.2013.

Other publications

1. Cimdina G., Veidenbergs I., Kamenders A., Ziemele J., Blumberga A., Blumberga D. Modelling of Biomass Cogeneration Plant Efficiency // Agronomy Research (ISSN: 1406894X) – 2014, 12, 2, 455–468 (in Scopus).

2. Cimdina G., Slisane D., Ziemele J., Vitolins V., Vigants G., Blumberga D. Sustainable Development of Renewable Energy Resources. Biomass Cogeneration Plant (ISBN: 978-609-457-640-9) // The 9th International Conference "Environmental Engineering" – 2014, Vilnius, Lithuania, doi:10.3846/enviro.2014.256 (in ISI Web of Science).

3. Selivanovs J., Blumberga D., Ziemele J., Barisa A. Research of Woody Biomass Drying Process in Pellet Production // Environmental and Climate Technologies (ISSN: 16915208) – 2012, 10(1), 46–50, doi: 10.2478/v10145-012-0017-7 (in Scopus).

Structure and Description of the Doctoral Thesis

The present Doctoral Thesis is based on 14 thematically unified scientific publications. Those publications have been published in various scientific periodicals and are accessible in scientific information repositories and cited international databases. The goal of these publications is to transfer and approbate the framework of multi-perspective methodology to assess the transition of the existing DH system towards 4GDH.

This Thesis consists of an introduction and three chapters:

1) Sustainable future of district heating,
2) Research methodology,
3) Results and discussion.

In the introduction, the goal of the Thesis and underlying tasks are given, followed by the definition of the Thesis's structure and a short description of the approbation of presented Thesis by means of the publications and participation in the international scientific conferences.

Chapter 1 characterizes the main components of 4GDH systems, insights into the up-to date situation in Latvian DH system, and opportunities to integrate 4GDH elements in the existing systems. Moreover, Chapter 1 provides an overview of the literature, with focus on the studies of the technological, economic, environmental, social, etc., efficiency aspects of various DH stages (heat sources, distribution networks, and heat consumers) and their improvement opportunities.

Chapter 2 describes the methodologies used in the research of various efficiency improvements in the DH stages and in the multi-perspective analysis that allows identifying the most suitable scenario to introduce the 4GDH system and the achieved near-zero emissions. The different methodologies that summarize into the multi-perspective analysis include empirical study, system dynamics and multi-criteria decision making analysis, and economic and policy analysis. The results obtained from the application of the proposed methodology are presented in Chapter 3. Finally, the conclusions, a list of references, and the appendices are given at the end of the Thesis.

1. SUSTAINABLE FUTURE OF DISTRICT HEATING

Energy consumption for district heating and cooling purposes constitutes a significant share of the European Union's (EU) total energy demand; in 2014, it was approximately half of EU's energy demand [1]. Therefore, as supported by the EU's Strategy on Heating and Cooling [1] as well as the Energy Efficiency Directive [2], efficiency measures should be introduced into all three parts of district heating (DH) systems, i.e., heat sources, distribution networks, and the final consumers. Also, the increase in energy generation from renewable energy sources is promoted at the EU level [3], and the research on sustainable energy systems is progressing [4]. With the development of technologies, energy efficiency and renewable energy-based solutions are gradually introduced into DH systems, thus moving towards 4th generation district heating (4GDH) systems.

A shift in the existing paradigm is needed to reach a sustainable district heating (DH) system, where transition from existing DH towards the 4GDH system should be made. The concept of 4GDH systems is defined as *systems that provide the heat supply of low-energy buildings with low grid losses in a way in which the use of low-temperature heat sources is integrated with the operation of smart energy systems. This concept involves the development of an institutional and organisational framework to facilitate suitable cost and motivation structures*" [4] (see Fig. 1.2.).

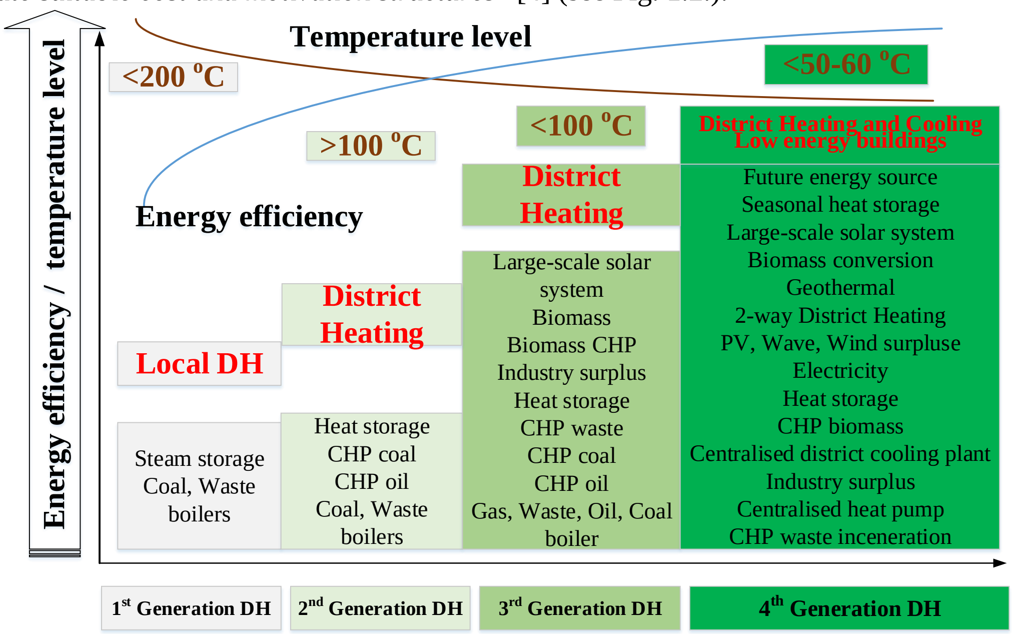

Fig. 1.2. Illustration of the concept of 4GDH in comparison to the previous three generations [4].

A paradigm shift is a fundamental change in the basic concepts and experimental practices of a scientific discipline. Kuhn contrasted these shifts, which characterize a scientific revolution, to the activity of normal science, which he described as scientific work done within a prevailing framework (or paradigm) [5]. Continuous improvements (technical, economic, socioeconomic, environmental, institutional, etc.) in all DH stages over the time will lead to the 4GDH concept (paradigm shift), which is characterized with low-temperature heat sources, low-temperature distribution networks, and low-energy buildings in common smart energy system.

The implementation of the 4GDH system is not straightforward, but it requires various preconditions to be met by the participants of the ETS and the rest of the participants given as non-ETS [6]. There are substantial differences between the participants of the ETS and non-ETS in the terms of financial models and involved parties. As for now, the implementation of 4GDH systems has been studied from various aspects. The research by Sperling and Möller [7] shows the benefits and difficulties for the integration of renewable energy in a DH system and the role of renewable resources within the development strategy of the urban area. Policy-making process was studied by Østergaard and Lund [8]; their research was done on the aspects of combining the EU policy goals with country's strategy and city's development opportunities using innovative solution. Although the implementation of 4GDH systems was examined from the political, economic, technical and environmental aspects, little attention has been paid to studying these given aspects together in one system and studying the system from various perspectives.

Since the DH system is a complex system which has developed over time, the behaviour of this system can be described with dynamic framework. Several researches are devoted to the question – how large could be the share of the renewable energy achieved at DH both in the short term [7] and long term perspective [8]. Different tools are used for the modelling: a tool for modelling of energy systems – EnergyPLAN [7], a model of linear optimization – Balmorel model [9], MARKAL model [10], and others.

The multi-perspective methodology is an important tool to study, develop and apply, since in DH systems, these perspectives can be differing among several interested parties: municipality, the owners of a DH company, the developers of new infrastructure, the owners of residential and business properties, as well as final consumers living in the area, and others [11].

2. RESEARCH METHODOLOGY

The construction of DH systems in various locations differs by technological solutions used in heat sources, distribution networks, and consumers, as well as by the fuel used in heat energy production and the institutional framework in place, etc. In this Thesis, all methods are applied to Latvian DH system. But the developed methodology could be applied to other DH systems if corresponding initial data and the data on other renewable technologies are added.

2.1. Conceptual Scheme for the Multi-perspective Methodology used to Assess the Transition to 4GDH

In this Thesis, a multi-perspective methodology for the assessment of the transition to 4GDH systems is provided. The proposed methodology summarizes system thinking, policy analysis, economics, and decision science and psychology (inconvenience costs) and can be used to assess the conversion from a conventional DH system to the 4GDH system (see Fig. 2.1.).

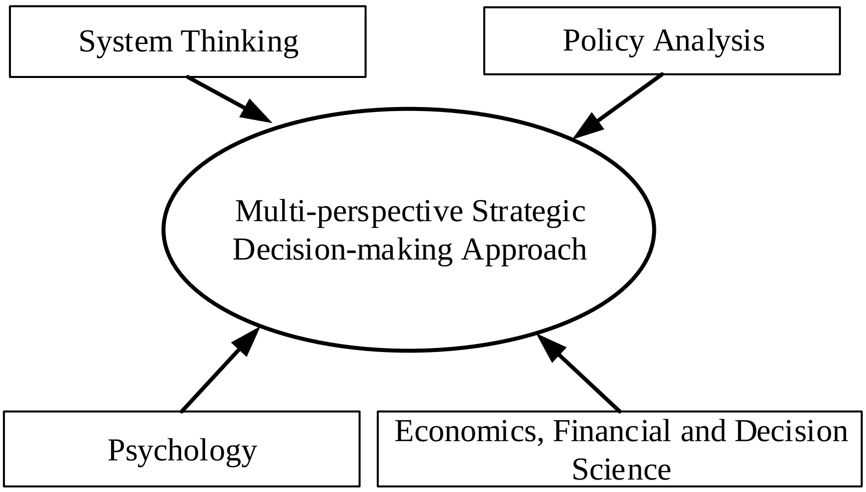

Fig. 2.1. Scheme of a multi-perspective methodology (adopted from [12]).

The developed methodology allows elaborating and comparing several potential DH development scenarios towards 4GDH systems.

The complexity of the applied methodology (see Table 2.1) was developed over the time, to match the growing complicatedness of studied research questions regarding the analysis of technological, economic, socioeconomic, environmental and institutional improvements and the insight into different scenarios, which allows moving the existing DH towards 4GDH.

Table 2.1

Breakdown of the methodologies used in the Thesis*

Methodology used	Papers													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Observation study and analytical analysis	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Statistical data analysis	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Decomposition analysis							X							
Benchmarking						X								
Delphi method				X	X	X		X		X	X		X	X
Multi-criteria analysis				X	X	X			X					X
Sensitivity analysis				X								X		
System dynamics method										X	X	X	X	X
Multi-perspective analysis										X	X	X	X	X
Economic feasibility analysis										X			X	

* The convergence of the methods presented in Table 2.1 to the extended conceptual scheme for the multi-perspective methodology in Fig. 2.4.

Empirical study	Multi-criteria decision-making	System dynamics	Economy evaluation and Decision-making

2.2. Empirical Study

The research in the present Thesis starts with empirical study in order to determine the equations which characterize different DH stages – heat source, distribution networks, and consumers – and to select independent variables for the research.

2.2.1. Regression Analysis

Regression analysis designates the changes in random variables into precise quantitative parameters – expresses the importance of the stochastic links with functional correlation. As a result of the regression analysis, it is possible to obtain quantitative parameters for the closeness of the statistical correlation of the independent and dependent random variables and to determine the regression coefficients. Its aim is to obain the graphical or analytical relationships between the variables.

2.2.2. Forecasting Model Time Series

The regression analysis is widely used for the prediction and forecasting that allows understanding and scheduling the development of DH systems. The improvements of environmental efficiency at municipality level were evaluated by using the STATGRAPHICS Centurion forecasting model (ARIMA (p, d, q) × (P, D, Q)). The developed STATGRAPHICS Centurion forecasting model was compared with the regression model developed from the yearly data.

2.2.3. Index Decomposition Analysis

Index decomposition is the equation based on Kaya identity [13], and it is widely applied for the analysis of the dynamics in CO_2 emissions [14]. DH system produces GHG emissions, where an important role is played not only by the type of fuel [15] but also by the energy efficiency of the system [16]. In order to analyse the efficiency of the primary energy consumption, the Kaya identity equation was complemented with the efficiency component (PF/HC):

$$C = (C/PF)(PF/HC)(HC/Y)(Y/P)P, \qquad (2.1)$$

where C – amount of CO_2 emissions, tCO_2/year; HC – DH heat consumption, MWh/year; PF – consumption of primary energy by DH, MWh/year; Y – gross domestic product (GDP), EUR/year; P – number of inhabitants connected to the DH system.

In general, the formula (2.5) sums up those GHG emissions which are produced when firing different types of fossil fuel [14].

The suggested methodology provides the identification of independent variables, the alterations of which would have an impact on the changes of each Kaya equation component. The complemented Kaya equation is tested on the operational data of DH systems of Latvia.

2.3. Multi-criteria Analysis

Research of technical, economic, socioeconomic, environmental and institutional improvements at all stages of a DH system should be connected in a common system. Since the development scenarios of DH systems are characterized by a number of indicators in the empirical study, all these contradicting dimensions should be analysed together using multi-criteria decision analysis tools.

To determine the efficiency rating of the DH system, a multi-criteria model is developed. This method is widely applied for sustainable energy planning [17]. In order to evaluate the efficiency of different scenarios, a MADM or MCDM method based on TOPSIS [18] was used. TOPSIS procedure started with constructing of raw data matrix:

$$\begin{array}{c} \\ A_1 \\ A_2 \\ \vdots \\ A_i \\ \vdots \\ A_n \end{array} \begin{array}{c} \begin{array}{cccccc} b_1 & b_2 & \cdots & b_j & \cdots & b_n \end{array} \\ \begin{bmatrix} b_{11}^k & b_{12}^k & \cdots & b_{1j}^k & \cdots & b_{1n}^k \\ b_{21}^k & b_{22}^k & \cdots & b_{2j}^k & \cdots & b_{2n}^k \\ \vdots & \vdots & \cdots & \vdots & \cdots & \vdots \\ b_{i1}^k & b_{i2}^k & \cdots & b_{ij}^k & \cdots & b_{im}^k \\ \vdots & \vdots & \cdots & \vdots & \cdots & \vdots \\ b_{n1}^k & b_{n2}^k & \cdots & b_{nj}^k & \cdots & b_{nm}^k \end{bmatrix} \end{array} \quad (2.2)$$

Multi-criteria analyses were used to evaluate various DH system scenarios and to find the most suitable one for the transition towards 4GDH and for ranking DH companies according to their efficiency performance.

2.4. System Dynamics

The DH system is a complex system, which was studied using a SD framework. The SD method follows five steps, which start with problem formulation, continue with the creation of dynamic hypothesis, and only in the third step, the actual building of the model's structure starts [19]. When the model's structure is ready and accepted by the experts in the field, the model's testing and validation step follows.

In this Thesis, Latvian non-ETS DH system development scenarios were created by using the SD model.

2.4.1. Dynamic Hypotheses and Causal Loop Diagram

The main dynamic hypothesis, which is developed within the SD framework, is that 4GDH can be reached in near or distant future, depending on used policy instruments.

As the share of the used energy resource depends on the changes in the installed capacity, the installed technology capacities are selected as the main stocks for the model. The capacity of the natural gas boilers is selected as one of the stocks, as this fuel currently dominates in the DH of Latvia, but different renewable energy capacities are also selected. The value of the capacity variable is determined by the size of the installation and the depreciation rate changes. Technologies compete with each other. The selection of which technology will be installed in the following year is based on the economic benefit. The causal loop diagram consists of one reinforcing (R) and one balancing (B) loop. The positive loop is characterized by the replacement of gas technologies with renewable energy technologies (see

Fig. 2.2.). The negative loop is trying to slow down this transition. An important element is the distribution temperature, which in case of gas technology is higher but switching to renewable energy technologies, based on the 4GDH concept, distribution temperature is lower.

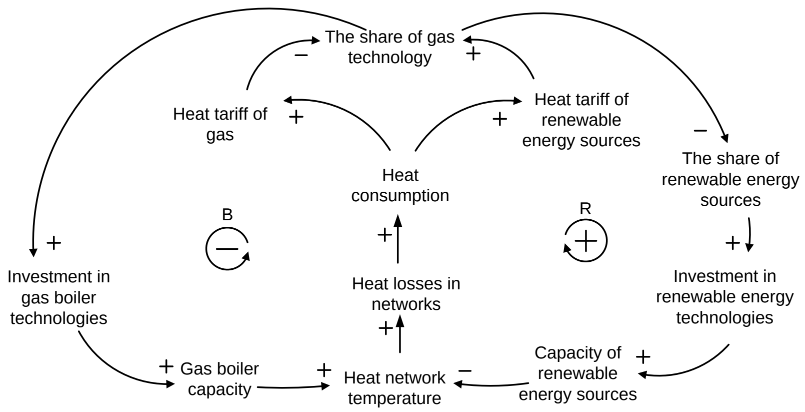

Fig. 2.2. Causal loop diagram for the development of 4GDH (R – reinforcing, B – balancing).

This means that heat losses and heat consumption decrease [20]. In case the positive loop is stronger than the negative loop, the share of renewable energy has a tendency to increase according to the principle of S shaped growth curve. As the negative loop tries to bring the system back to the balance, the increase furthered by the positive loop cannot continue endlessly, and at some point, the increase in the renewable energy capacity will slow down under the impact of the negative loop and the system will come to its state of balance.

2.4.2. Model's Structure

The development of the 4GDH model is performed in the program "Powersim Studio 8". Technology capacities are selected as the central elements of the model, i.e., natural gas boilers (GB) as they are currently the dominating fossil-based technology, and biomass boilers (BB) as current renewable energy technology, as well as the currently non-existent but perspective solar collectors (SC) and heat pumps (HP).

The model is built for the DH system with 1.75 TWh produced heat energy capacity, which corresponds to the total final heat produced at the boiler houses in Latvia during the year 2013. In order to secure such amount of the heat, 875 MW of natural gas and biomass technology capacity is required. The distribution of the fuel in the system is allocated accordingly to the situation of the DH in Latvia (natural gas 80 %, biomass 20 %), and the initial capacity values for gas boilers are 700 MW, but for biomass boilers – 175 MW. Considering the current situation of the DH in Latvia, solar collectors and heat pumps initially are not installed.

A scheme demonstrated in Fig. 2.3. is created, where the central stocks are the capacities of the respective technologies. The changes in the stock value are regulated by the inflow and outflow, and this can be described as [21]:

$$dN_i = +N_{Ni}dt - N_{di}dt, \qquad (2.3)$$

where dN – change in technology capacity, MW; N_N – installed capacity, MW/yr; N_d – depreciation of technology, MW/yr; dt – a step of simulation; i – type of technology.

The depreciation of technology depends on the installed (i) technology service life (τ_{sli}):

$$N_{di} = N_{Ni}/\tau_{sli} \qquad (2.4)$$

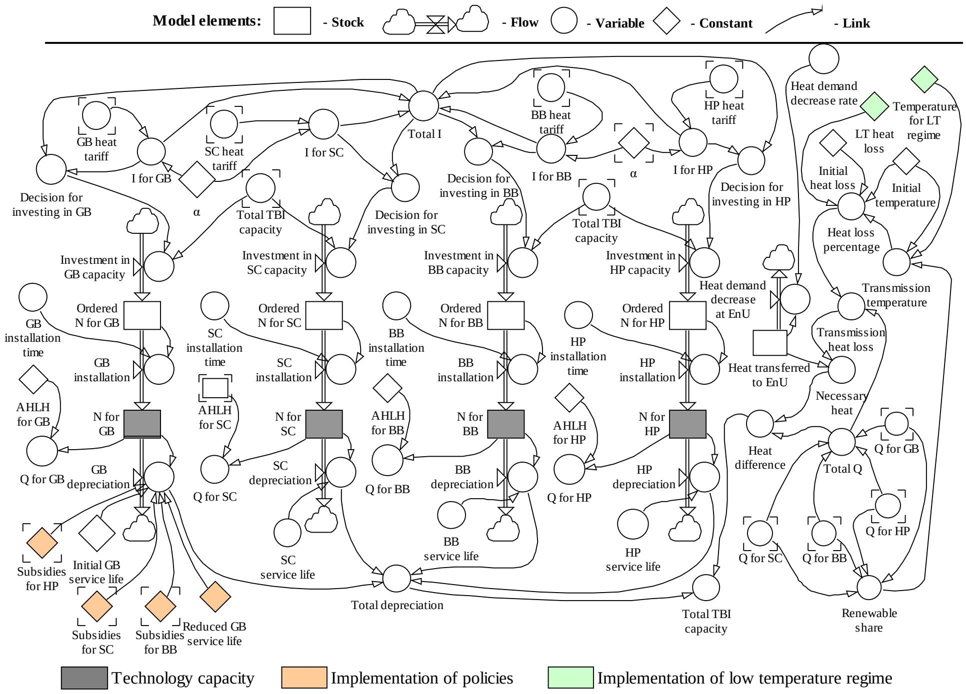

Fig. 2.3. Model for capacity substitution:

GB – gas boiler; BB – biomass boiler; SC – solar collectors; HP – heat pumps; LT – low temperature; AHLH – adjusted heat load hours; EnU – the end users; TBI – to-be-installed capacity; I – technology investment share; Q – heat produced.

The changes in stocks are based on how new technologies are installed after the old ones reach the end of their technical lifetime. The selection of which new technology will be installed is determined by comparing the heat energy tariffs of all four technologies at the time when change should happen.

The calculation of the heat energy tariff is based on the methodology developed by the Regulator [22]. The heat tariff according to this Methodology consists of three parts – production, transmission, and sales tariff [22] which was extended by inconvenience cost *R* (€/MWh):

$$T_i = T_{prodi} + T_{tri} + T_{3i} + R, \quad (2.5)$$

where T_i – heat tariff of the respective technology, €/MWh; T_{prod} – production tariff, €/MWh; T_{tr} – transmission tariff, €/MWh; T_3 – sales tariff, €/MWh; *R* – inconvenience cost, €/MWh; *i* – type of the selected technology.

The inconvenience costs characterize the technical, economical and psychological costs that the DH producers have and that hinder the transition to a new technological solution (in Latvian DH system these are solar collectors and heat pumps). The created model was structurally and behaviorally validated.

2.4.3. Scenario Analysis

After the validation of the model, the component of the temperature regime is added, as well as various policy instruments to research the behaviour of DH during transition to the 4GDH; for the summary of the scenarios see Table 2.2.

Table 2.2

Scenarios for multi-perspective decision-making

			Subsidies			Risk reduction			Efficiency increase		
			Bi[1]	SC[1]	HP[1]	Bi	SC	HP	Bi	SC	HP
1	A[2]	Without policy instruments	0	0	0	0	0	0	0	0	0
	B[2]										
	C[2]										
2	A	With all policy instruments	1	1	1	1	1	1	1	1	1
	B										
	C										
3		All policies for heat pump	0	0	1	0	0	1	0	0	1
4	D[3]	Subsidies for solar technology	0	1	0	0	0	0	0	0	0
	E[3]										
5		Risk reduction for solar technology	0	0	0	1	0	0	0	0	0
6		Efficiency increase for solar technology	0	0	0	0	0	0	0	1	0

Bi[1], SC[1], HP[1] – biomass (Bi), solar collectors (SC), heat pump (HP);
A[2], B[2], C[2] – temperature regime shift at the 60 % (A), 80 % (B), and 95 % (C) renewable energy share;
D[3], E[3] – amount of subsidies 15 % (D) and 25 % (E).

Three different policy instruments were added for faster introduction of renewable energy technologies into DH: subsidies for renewable energy technologies (grants subsidies at the amount of 25 % for investment costs to the renewable energy technologies); the risk reduction instrument which aims to reduce the risk component (inconvenience costs); and the policy instrument directed at the increase of the efficiency of renewable energy technologies.

2.4.4. Sensitivity Analysis

Sensitivity analysis was done for the developed SD model in order to determine the model's sensitivity to different input parameters and to learn which variables have the most significant impact on the results.

Sensitivity analysis was done for the system at different initial conditions by changing one input parameter at a time (one-at-a-time (OET) method). The following parameters were included into the OET sensitivity analysis: price of natural gas, biomass and electricity, costs of all four technologies, and costs of heat losses.

2.5. Decision Making: Multi-perspective Analysis Methodology

The scenarios created within the study and the results of the four main interlinked parts – empirical study, system dynamics modelling, multi-criteria and decision-making section – are summarized in the decision-makers section (see Fig. 2.4.). Then, all obtained results are examined together by the multi-perspective analysis framework.

The proposed methodology defines the initial data that characterize each stage of DH systems (see Modules 1, 2, 3, 4, and 5); these data are supplied to correlation analysis (Module 6). Using all initial data and the defined assumptions (Module 9) together with the independent variables (Module 7), a regression analysis is performed (Module 8). The results of the correlation and regression analysis are further used as the input for the development of the system dynamics model (Module 12).

The developed model is tested and validated (Modules 13 and 14) as well as supplemented with policy instruments (Module 16) that allow exploring a variety of the DH systems' development scenarios. If the model does not pass validation, it is improved and tested again (returned to Module 12). In the case of a valid model, the created development scenarios are transferred to the decision makers and supplemented by the calculations of additional economic indicators – Net Present Value (NPV), Internal Rate of Return (IRR), etc. (see Module 19).

Since the development scenarios of DH systems are characterized by a number of technological, economic, and ecological indicators, all these contradicting dimensions should be analysed together using multi-criteria decision analysis tools. One of such tools is TOPSIS method (Module 21), where the obtained results are ranked, and the most efficient scenario is ranked with the number closer to 1. Thus, the methodology allows guiding researchers and policy makers towards the selection of the benchmark for the scenarios that are the closest to the 4GDH concept (Module 22). Next, the development strategy for DH (Module 23) is presented to policy makers (Module 24).

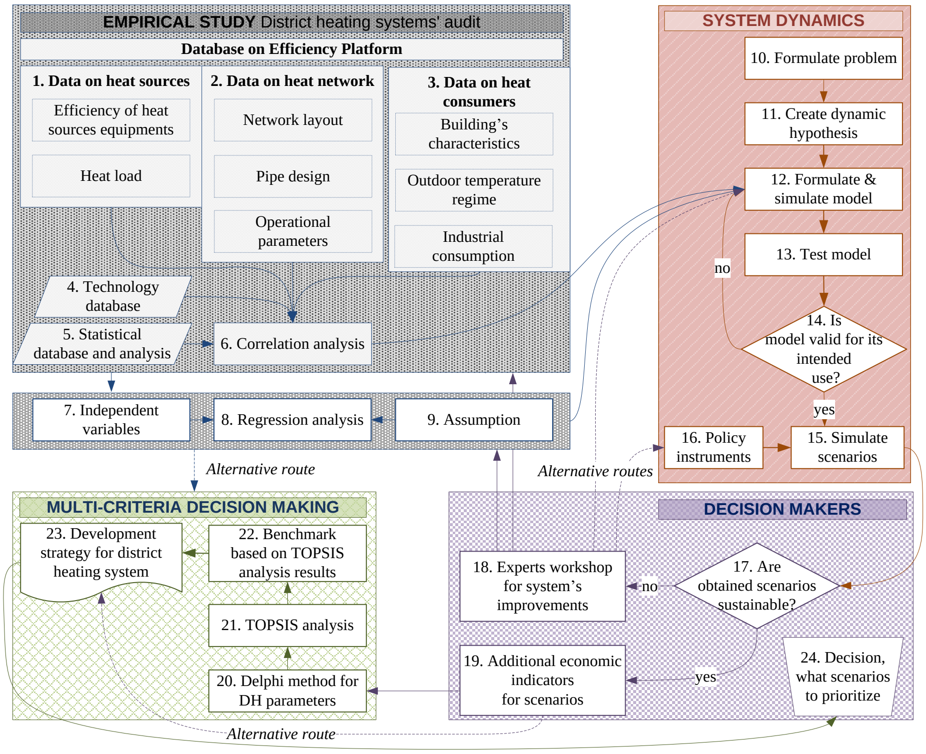

Fig. 2.4. Extended conceptual scheme for the multi-perspective methodology used to assess the transition to 4GDH systems using empirical study tools, system dynamics, multi-criteria decision making framework, and economic and policy analysis.

A vital part of the presented methodology is the feedback loops from the interviews and workshops with the decision makers. The main feedback mechanism is presented in the Module 17, where the initial input data, developed model and/or policy tools can be adjusted based on the requirements of the Directives, financial restrictions, or other relevant decision-making factors.

Strategic decision making, for the purposes of this Thesis, is the process of making short- and/or long-term decisions that allow the transition from a conventional DH system to the 4GDH system and achieve DH system emissions near to zero level. Optimal solution, which allows the DH transition to 4GDH, shows the best system design and minimizing DH system's costs (heat energy tariff). The most sustainable scenarios identify the necessity for the implementation of the policy instruments for energy system planning in order to achieve a low-carbon DH system, which is characterized with renewable energy sources, low-temperature distribution networks, and low-energy buildings in a common smart energy system.

3. RESULTS AND DISCUSSION

3.1. Empirical Study

The results of the empirical study are obtained by the application of several statistical analysis methodologies: regression analysis of DH production data, forecasting model time series, and decomposition analysis.

Furthermore, the results of the correlation and regression analysis are used as the input for the development of the system dynamics model.

3.1.1. Result of Regression Analysis of the Condensing Unit Production Data

The condensing economizer is a classic tubular heat exchanger used for heat transmission from hot heat-transfer agent (flue gas) to cool (heating network water). The economizer is installed in the boiler's KVGM-100 flue gas channel and is placed between the fan and the chimney.

The capacity of the condensing unit depends on outdoor temperature: the decrease in outdoor temperature creates a need for a higher capacity of the condensing unit. The empirical model of the capacity of the condensing unit versus outdoor temperature (see Fig. 3.1.) is expressed in the form of a linear regression equation and shows good correlation between the data and the model.

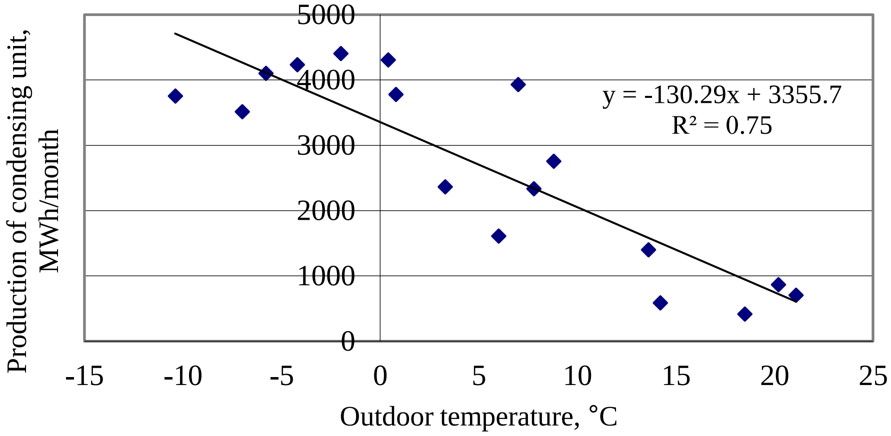

Fig. 3.1. Production of the condensing unit versus outdoor temperature.

Then, t coefficients which have to be within the borders $|t| > t_{tab}$ were estimated. The relevance $|t| > t_{tab}$ is valid in all cases. This means that all the parameters are significant and must be maintained in the equation. The created model explains 75.5 % of analysed heat produced by economizers. To increase the effectiveness of the economizers' work, the linear line has to be above the one that was established on the data from the industrial experiment.

3.1.2. Result of Time Series Forecasting

The STATGRAPHICS Forecasting (ARIMA (0, 1, 1) × (2, 0, 1) 12 time series) and regression analysis modelling tools were used to develop two possible forecasting curves showing the trend of wood fuel use in Latvia's capital, Riga, until the year 2020. The results obtained from both forecast models can be seen in Fig. 3.2. The model shows that it would be possible to produce around 600 GWh during the coldest months by 2020.

Both models demonstrate that the company could almost completely exclude fossil fuel use by 2020 if it sets targets that are even more ambitious.

The results show that technical improvement in heat source allows gaining economical effect and improving the environmental efficiency of the DH system, and all together, it allows gradually moving towards the 4GDH system.

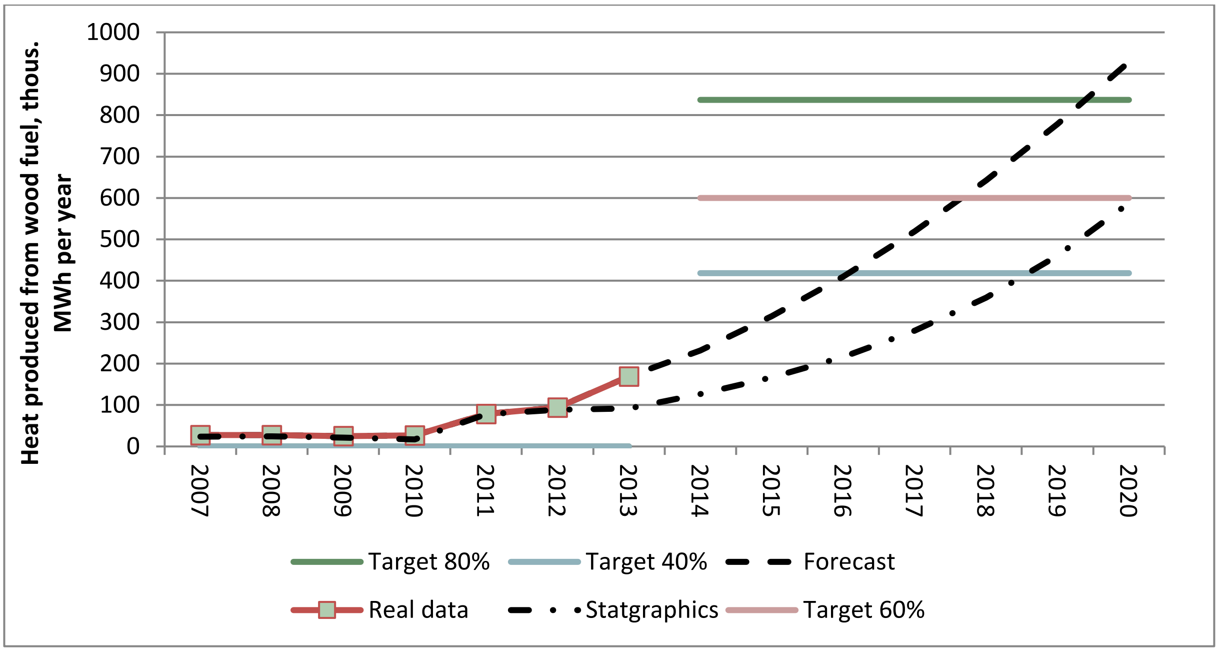

Fig. 3.2. Results of forecast models by using regression analysis and the ARIMA time series forecasting tool.

3.1.3. Results of Decomposition Analysis

The index decomposition analysis (Kaya identity equation) was developed for the analysis of CO_2 emission reduction in the DH system. The dynamics of the alterations in the components of Kaya equation were compared. All data were applied to the beginning of the research period – the year 2002, which does in fact illustrate the intensity of the changes in these components. The results are summarized in Fig. 3.3.

One of the Kaya equation components is the emission factor (C/PF) (see eq. 2.5) During the last years, the total emission factor of fossil fuel has reduced minimally in the DH systems of Latvia: by 6 % (see Fig. 3.6.). Substantial changes were experienced by the energy intensity factor (HC/Y), which decreased by 40 % until 2013. It is very important that over the last years, the intensity of primary energy consumption (PF/HC) has fallen. It represents an increased energy efficiency (HC/PF).

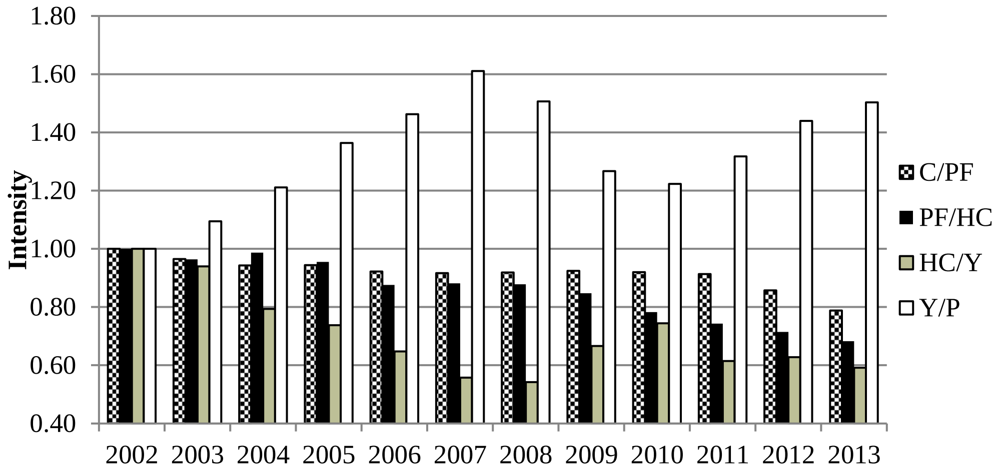

Fig. 3.3. Intensity of alterations into Kaya equation components.

Owing to the fact that Kaya equation was complemented with the equation (2.5), to which the energy efficiency component (PF/HC) is added, it is possible to analyse the impact on CO_2 emissions by the renewable sources of energy and the efficiency of heat production, transmission, and consumption. Over the last years, production of heat from renewable sources of energy has increased, and therefore the consumption of primary fossil fuel has decreased. The results show that increase in renewable energy sources improves the environmental efficiency of the DH system and allows gradually moving towards the 4GDH system.

3.2. Multi-criteria Analysis Results

In conducting the analysis of the energy efficiency ratings for DH companies, it is necessary to compare the technological indicators, economic indicators and expert opinions related to the three stages in heat supply: the heat source, heating networks, and the consumer. In order to perform this task, the multi-criteria decision-making method based on TOPSIS is used. With the help of TOPSIS, all companies were ranked according to how close they are to an ideal company. The proposed methodology was tested using performance data of the Latvian DH companies.

The results of the multi-criteria analysis are used to set benchmarks of the DH companies' performance. The DH company efficiency indicator determined by the TOPSIS method can fall between 0 and 1. The determined mean efficiency value is 0.557, and half of the companies fall above this mean level, while the other half fall below this level. Four efficiency zones have been developed in Fig. 3.4. Six DH companies are located in the highest zone (above 0.7). The performed analysis indicates that these companies have modernized their systems in recent years and have managed to preserve their relatively low heat energy tariff. In studying these companies in more detail, it has been established that they use wood fuel, which allows them to lower their production costs.

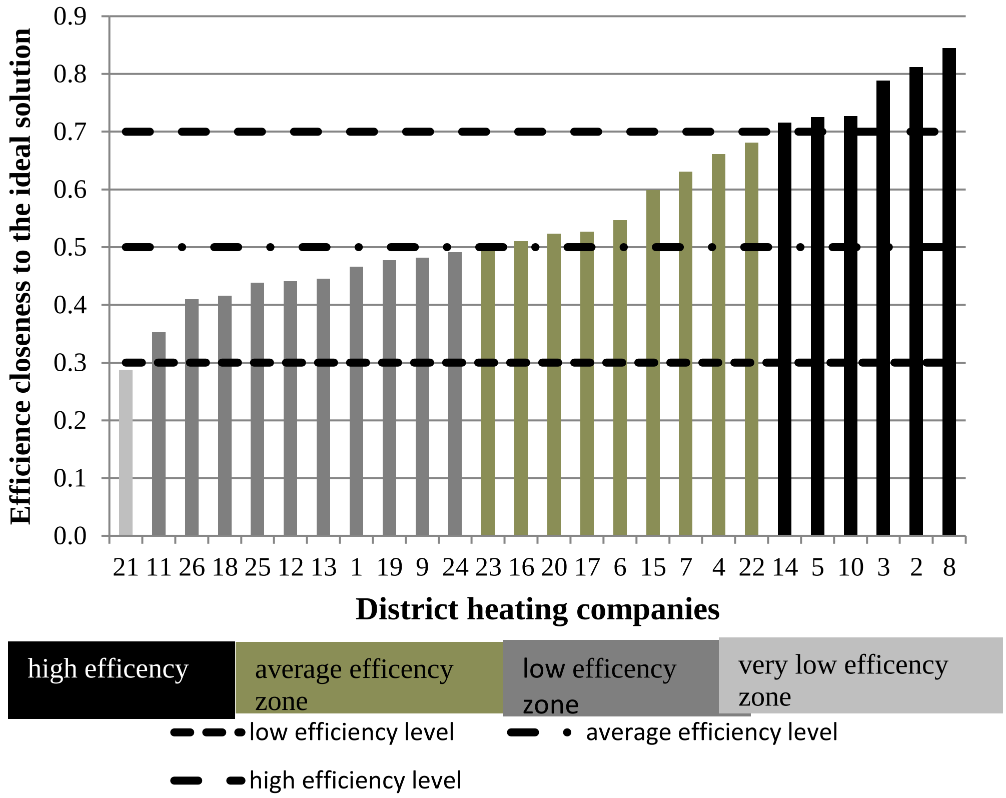

Fig. 3.4. DH company efficiency relative to their closeness to an ideal solution.

Another nine DH companies fall within the next efficiency zone. Their energy efficiency is above the mean. This means that these companies have performed partial modernization and the directors of the heat sources are working at improving their energy efficiency.

The largest number (10) of DH companies falls between the 0.5 and 0.3 efficiency levels and two of those companies are under the 0.4 level. The directors of these two companies, as well as those of the lowest ranking company (whose efficiency level of 0.3 is critical), will need to focus on solving the issue of efficiency in the nearest future. The companies with the lowest values should study and learn from those six companies with the highest values.

The multi-criteria methodology allows us to signal DH companies that are below the benchmark value regarding the need to restructure so that they may reach the level of a low-carbon business.

3.3. System Dynamics Modelling Results

3.3.1. Comparison of Hypothetic Scenarios with SD Model's Results

The main dynamic hypothesis, which is developed in the SD framework, is that 4GDH can be reached in near or distant future, depending on the used policy instruments. Renewable energy sources implementation is one of the important aspects for pathway towards the 4GDH system. Based on the historic data, three hypothetical DH development scenarios were elaborated before modelling: pessimistic, moderate, and optimistic (see Fig. 3.5.).

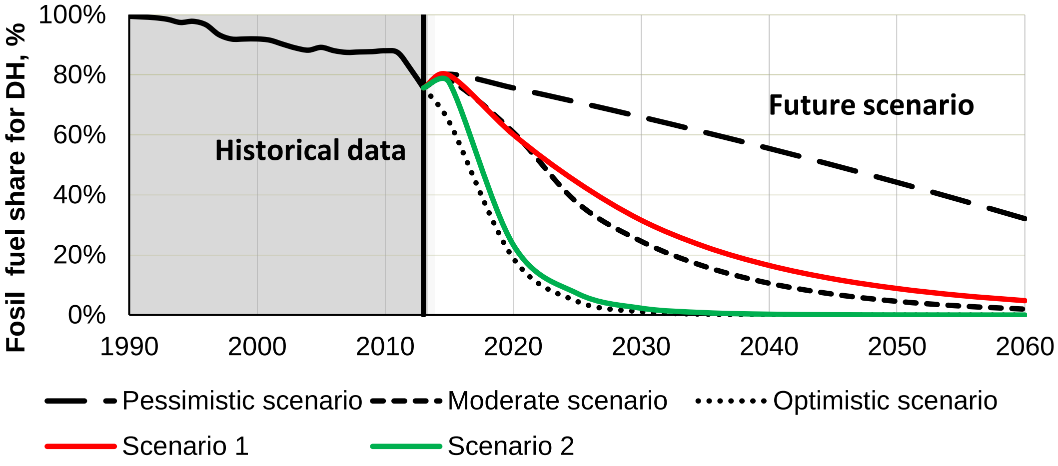

Fig. 3.5. The comparison of hypothetic – pessimistic, moderate, and optimistic – scenarios with the results obtained from the model, where Scenario 1 without any policy support and Scenario 2 by using all policy instruments for all technologies.

The pessimistic scenario predicts that transition from fossil resources to renewable energy could take place at the same speed as observed in the past decades. While the optimistic scenario foresees that the share of fossil resources could diminish at the faster pace observed over the couple of last years. The optimistic scenario corresponds to the situation when policy tools are used to expand renewable energy. This scenario could lead to 100 % renewable DH in Latvia by 2030, while in the case of the moderate scenario, 100 % renewable DH would become by 2060.

The results obtained from the model show that no policy instruments were used in DH (Scenario 1) moderate hypothetical scenario would be true. But when all policy instruments are used (Scenario 2), almost exactly follows the trend of the optimistic hypothetical scenario. Within the modelled scenarios, the systems' behaviour is mainly influenced by fuel price, technology costs, and electricity price. These results are based on the optimistic assumptions that fuel price will rise and technology costs will decrease. In case of contrary development, the results would be closer to the pessimistic scenario.

3.3.2. Scenario Analysis of Temperature Regime in Distribution Network

The low-temperature regime is an important component of the 4GDH system. The transition to low-temperature heating system provides for additional improvement of energy efficiency parameters: efficiency increase of condensing economizer, production of additional power at the CHP, emission reduction, and others [23]. Based on the crucial role of temperature regime, the created model of SD was also used to study the operation of transmission network at different temperature regimes six scenarios were examined (see Table 2.2), which reflects temperature decrease at the heat network (Scenarios 1A, 1B, 1C, 2A, 2B, and 2C).

The change in temperature regime affects the heat tariff in all scenarios (see Fig. 3.6). In the case of the scenario without policy support (Scenario 1), initially heat tariff increases, since the fossil fuel technologies dominate in the DH system. The transition to a lower temperature regime takes place only after the year 2026, when the share of renewable energy in the DH system reaches at least 60 % (Scenario 1A).

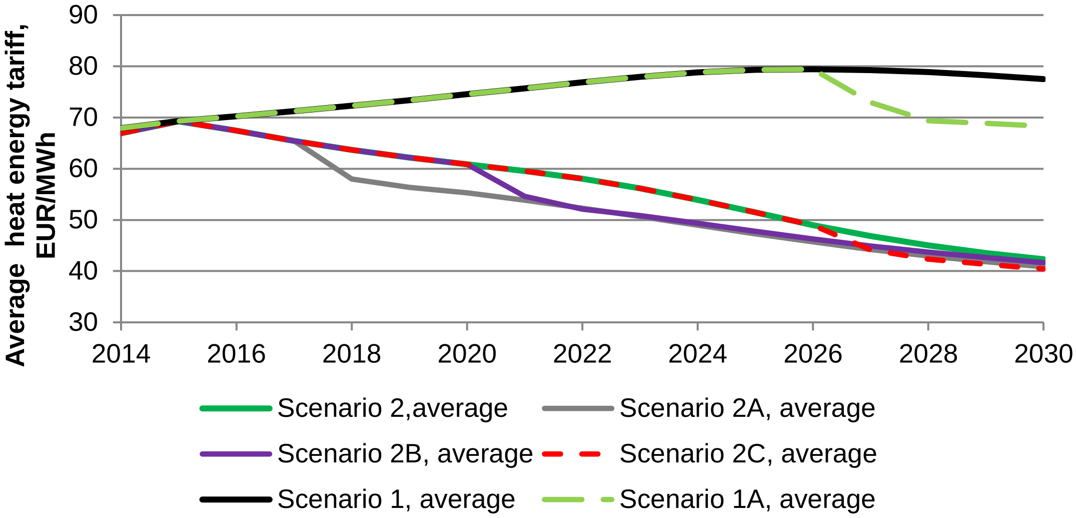

Fig. 3.6. Average heat tariff for studied temperature regime scenarios, where Scenario 1 without any policy support, and Scenario 2 by using all policy instruments for all technologies, A stands for temperature regime shift at 60 % renewable energy share in district heating, B stands for shift at 80 % of renewable energy share, and C stands for shift at 95 % renewable energy share.

In the case all policy instruments are used and DH system transits to a lower temperature regime when 60 % of the renewable energy share is reached in DH (Scenario 2A), the reduction in the heat tariff could be possible already in 2018.

If the temperature regime shift is made at a higher share of renewable energy in DH, for example, at 80 % in Scenario 2B or at 95 % in Scenario 2C instead of 60 % in Scenario 2A, the tariff reduction occurs later in the time scale and the decrease in the tariff is not as rapid.

Consequently, a timely shift to the lower temperature regime is more beneficial to the consumers, since this shift reduces the heat tariff sooner and more rapidly than the studied policy tools. An equally important argument is the optimal payment for heat energy for the consumers.

3.3.3. Forecast of CO_2 Emissions

During the transition to 4GDH, the reduction in CO_2 emissions is also one of the underlining goals. With the help of the developed model, the results on CO_2 emissions for Scenario 1 (no policy instruments used in DH) and Scenario 2 (all policy instruments used for all technologies in DH) were obtained (see Fig. 3.7.).

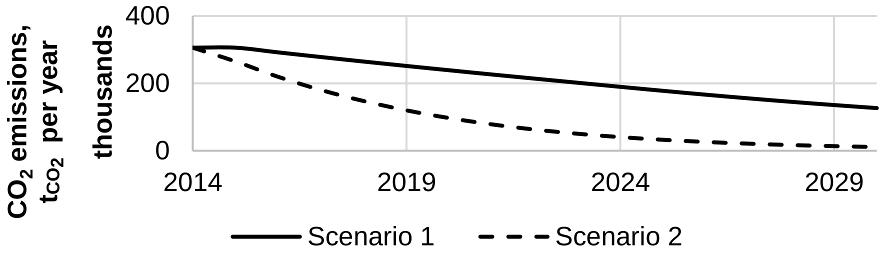

Fig. 3.7. CO_2 emissions created in the process of heat production under different scenarios.

Under Scenario 1, the technology exchange in DH takes place on the basis of business principles – heat production technology with the lowest tariff substitutes less profitable technology. At the start of simulation, natural gas technologies are substituted with the biomass-based technologies. However, around 2024, the capacities of biomass and natural gas technologies start to decrease. At that time, a stable place in DH is taken by the solar DH solution (solar collectors with accumulation). Therefore, under Scenario 1, CO_2 emissions gradually decrease (see Fig. 3.7.) by 59 % until 2030. Our results correspond to the research by Romagnoli *et al*. [21], where the transition from natural gas to biomass was modelled, but this work did not include the 4GDH concept.

3.3.4. Results of Sensitivity Analysis of Developed System Dynamics Model

The sensitivity analysis for the system dynamics model was carried out to model and examine a possibility of introducing the 4th generation district heating system in Latvia. All 4GDH conditions were taken into account. At the beginning, the analysis for a static system at base conditions A (80 % natural gas and 20 % biomass fuel) and at balance conditions B (25 % natural gas, 25 % biomass fuel, 25 % solar collectors, and 25 % heat pumps) were carried out with OET method, by changing one input parameter at a time. The results obtained from the model show that at the base conditions, natural gas price fluctuations (±30 %) is the most sensitive parameter and would change the heat tariff by ±18 %. Heat tariff is flexible against other parameters (natural gas technology price, biomass price, electricity price, biomass technology price).

At the balance conditions (25 % natural gas, 25 % biomass fuel, 25 % solar collectors, and 25 % heat pump), heat tariff sensitivity to changes in input parameters (±30 %) can be divided into three groups: sensitive, moderately sensitive, and flexible. The system is the most sensitive to solar collector price changes, moderately sensitive to changes in heat losses, natural gas price, heat pump technology price and electricity price, and flexible to changes in biomass price, biomass technology price and natural gas technology price.

3.4. Results of Multi-perspective Analysis

3.4.1. Scenarios for Multi-perspective Decision Making

Created non-ETS DH system SD model allows analysing several development scenarios in order to evaluate the most sustainable scenario for short- and long-term perspective. The most sustainable scenarios identify management policy (in state, municipality, or DH company level) in order to achieve a low-carbon DH system which is characterized with renewable energy sources, low-temperature distribution networks and low-energy buildings in the common smart energy system. The Latvian non-ETS DH system development scenarios were tested by using SD model. The relative amount of the produced heat was determined for all technological solutions included into the SD model (see Fig. 3.8.). Results were examined for Scenario 1, within which the DH develops without additional measures supporting any of the technological solutions (base scenario), and for Scenario 2, where all support mechanisms for the renewable energy are used.

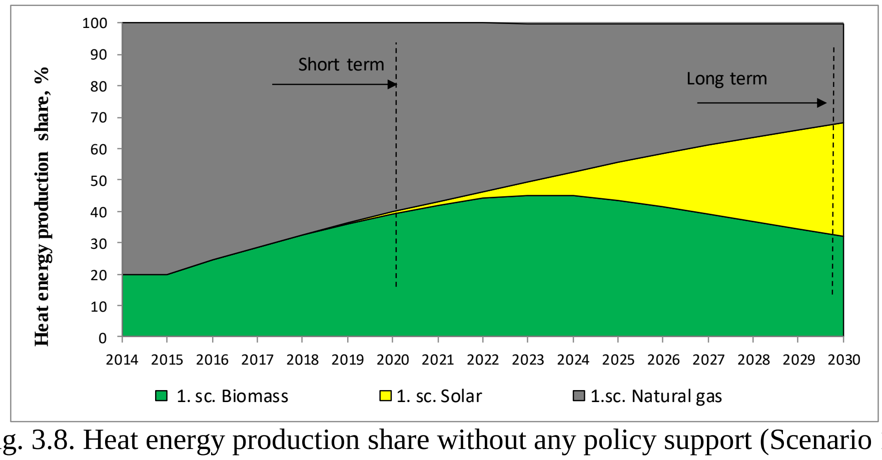

Fig. 3.8. Heat energy production share without any policy support (Scenario 1).

For Scenario 1, at the beginning of the period, 80 % of heat is produced from fossil fuel, but at the end, this share decreases to 31.6 %. At the end of the period (2030), the amount of the produced heat is rather similar for three technological solutions: natural gas – 31.6 %, biomass – 32.2 %, and solar collectors with accumulation – 36.0 %. Heat pumps (0.2 %) produce the remaining share (0.2 %) of heat.

The introduction of policy instruments promotes the integration of renewable energy into the DH system in short- and long-term perspective. At the end of the simulation period (2030), 97.7 % of heat is produced from renewable energy (Scenario 2) (see Fig. 3.9.).

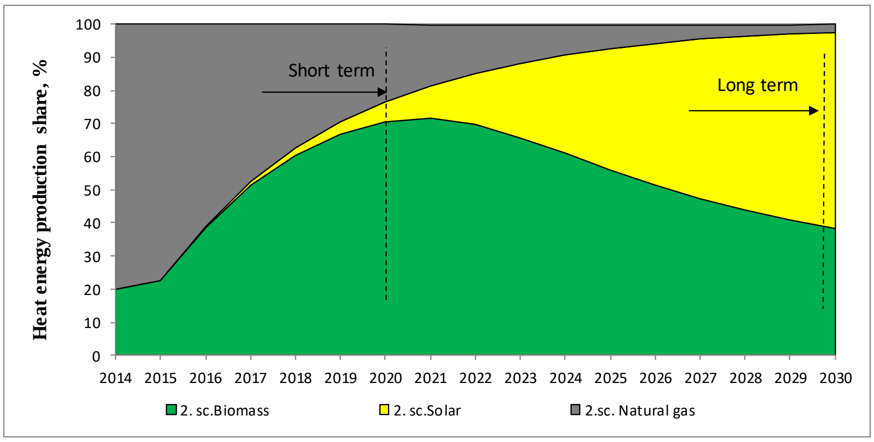

Fig. 3.9. Heat energy production share by using all policy instruments for all technologies (Scenario 2).

Even with policy instruments (Scenario 2), heat production with the heat pump technology is not economically feasible. Therefore, in the case the development of heat pump technologies it is strategically important, additional support would be required.

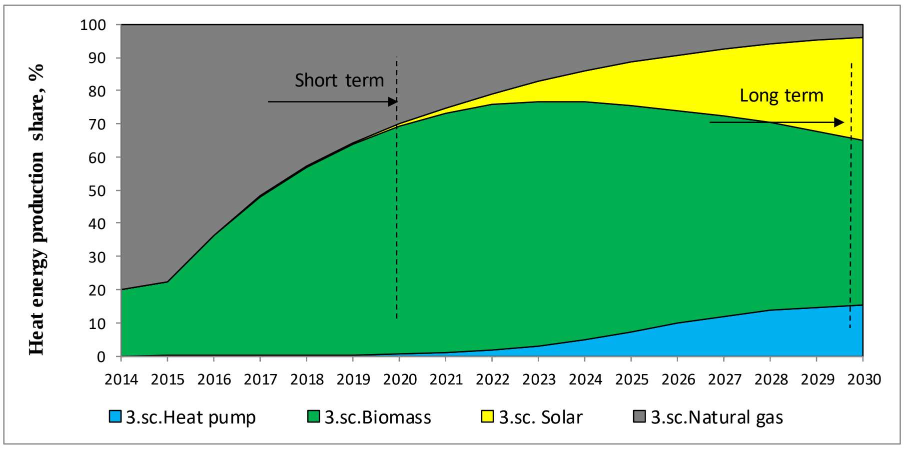

Fig. 3.10. Heat energy production share by using all policy instruments only for the heat pump technology (Scenario 3).

By using all policy instruments for the support of the heat pump technology only, the specific amount of heat produced by this technology, reaches 15.4 % by 2030 (see Fig. 3.10.). This reduces the share of renewable energy technologies (biomass accounts for 49.7 % and solar collectors with accumulation account for 31.0 % by 2030).

SD approach allows calculating the economic indicators for all scenarios in dynamics (investments cost, fuel and electricity cost, heat energy tariff, etc.) for the next investigation by multi-perspective analysis. In addition, the NPV, IRR and other economic indicators can be calculated for determining the optimal DH system's development solution.

3.4.2. Economic Feasibility Evaluation for Multi-perspective Decision Making

The coherent modernization approach allows simultaneously developing all stages of DH – heat source, distribution networks, and end-users. The research identifies a balance point between the implementation of energy efficiency measures at the source and at the heat consumers' side. Energy saving measures with various levels of efficiency were incorporated into the modelled scenarios: Scenario 1 – 22 % from the Base scenario; Scenario 2 – 42 %; and Scenario 3 – 51 %. By simulating all scenarios, heat source designs were created based on the share of technologies in 2050 (see Fig. 3.11.). The share of renewable energy sources (solar collectors with the accumulation and biomass) increases from 75 % in Scenario 1 to 93 % in Scenario 3, thus promoting the transition of the whole system towards 4GDH.

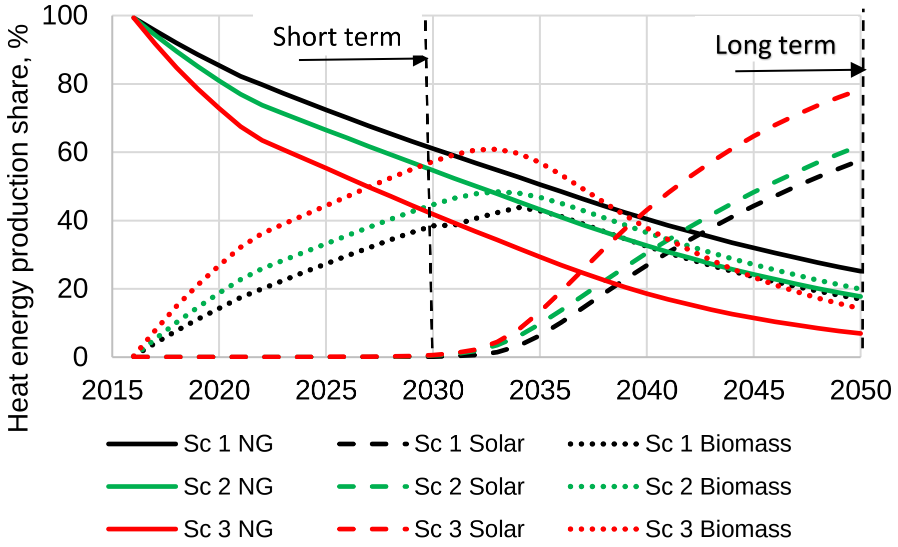

Fig. 3.11. The dynamics of heat energy production share for different scenarios.

In order to identify the optimum between heat saving measures at the consumer's side and in connection with heat source reconstruction, the research also concerns specific investment costs at both consumer and heat source sides.

Both lines in Fig. 3.12. that characterize the interrelated specific investment costs intersect at the specific heat consumption of 60 kWh/m^2, corresponding to Scenario 2, which can be considered as an optimal solution.

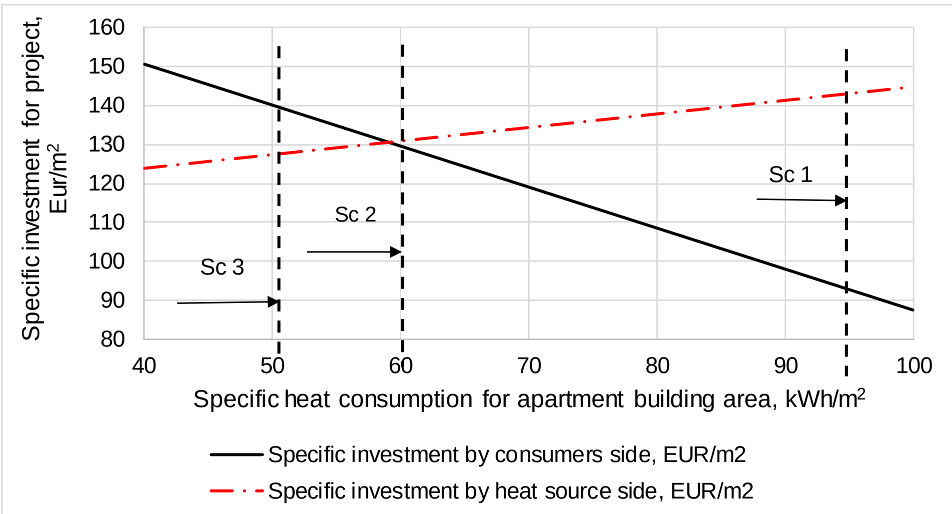

Fig. 3.12. Specific investment by the consumers and heat sources sides for the studied case.

Based on the above arguments, the reduction in the produced amount of heat by 42 %, which is ensured by both the implementation of energy savings measures at the end-user and the transition to 4GDH, is an optimal solution for the existing DH system.

CONCLUSIONS

1. This Thesis proposes the multi-perspective methodology for the assessment of DH systems' development scenarios in order to move towards the 4GDH systems; this proposed methodology combines empirical study tools, system dynamics, multi-criteria decision-making framework, and economy and policy analysis. Two of these parts, e.g., empirical study and multi-criteria decision making, are static. The third part is dynamic as it analyses the changing behaviour of a complex system by identifying and defining its elements and their interactions. The Decision makers' part is predictive and expend the insights to DH system's economic indicators by calculation NPV, IRR and other economic indicators. The developed methodology includes models based on the principle of parsimony, where the selection of more complex models is justified by the specific purpose of the model and the desired insights that this model should provide.
   The Thesis shows that the paradigm shift (4GDH), which is characterized with low-temperature heat sources, low-temperature distribution networks, and low-energy buildings in a common smart energy system, brings new challenges for all interested parties (DH companies, consumers, developers, policy makers, and other interested parties). This means that all DH system stages should be analysed together with integration in a common energy system.
2. The Thesis includes the evaluation and analysis of the technological, economic, socioeconomic, and environmental indicators, the improvement of which would allow gradual transition towards the 4GDH system. The complexity of the applied methodologies was developed over the time to match the growing complicatedness of studied research questions.

3. The results of empirical study are presented in the Thesis by the application of several statistical analysis methodologies: regression analysis, forecasting model time series, and decomposition analysis at the municipality and national level.
   The options of wood chip use in Latvia's capital, Riga, were analysed in the Thesis. The results show that the summary avoided emissions could reach 80 % until 2020.
   KAYA identity was added for the CO_2 emission study by the decomposition analysis of Latvian DH system. In the case of the optimistic scenario, CO_2 emissions would decrease by 29 % until 2020 as compared to 2012.
   The technical improvement at heat sources could be provided by the implementation of renewable energy sources. This would allow achieving economical effect by decreasing the heat energy tariff and improving the environmental performance of the DH system. However, in general, it allows gradually moving towards the 4GDH system.
   Unfortunately, the study of several DH stages and indicator improvements does not enable to identify priority for the development areas in order to move towards 4GDH. It is necessary to add more complicated methods: multi-criteria analysis, system dynamics, and, finally, multi-perspective analysis.
4. Within this Thesis, the DH system was analysed by using multi-criteria analysis. Multi-criteria decision-making framework allows providing holistic methodology in order to evaluate the most suitable solution that aids decision makers, DH system operators and developers to rank all development scenarios or to rank DH producers' performance.
   The obtained multi-criteria analysis results show that the most suitable DH system`s water temperature regime for standard buildings and the climatic conditions of the Baltic countries are 90/60 °C. But the most economically feasible scenario for energy-efficient buildings would be the temperature regime of 60/30 °C. The results of the multi-criteria analysis confirm that the scenario that is the closest to the ideal solution from the point of view of a DH company, sharply differs from the best scenario for the developers. The difference in scenario evaluation shows that additional motivation is required for building developers to adjust buildings to the low-temperature regime. It can be done by introducing the government support (grants, tax credits, etc.) that would promote the developer to shift to the low-temperature regime.
   The research of the DH system by using the multi-criteria analysis has one significant disadvantage – it is static. The developed methodology includes the models based on the principle of parsimony, where the selection of more complex models is justified by the specific purpose of the model. Moreover, in case of the DH system – the model should be dynamic.

5. The SD model was developed for DH system in Latvia and showed how 4GDH can be reached in near or distant future, depending on the used policy instruments and using various multi-

perspective scenarios. Following, the underlying conditions of the 4GDH concept were considered: low-temperature heat sources (renewable energy sources), low-temperature distribution networks, and decreasing heat energy consumption by end users. The transition to the 4GDH and the exchange of technology is based on the principle of economic advantage. In the optimistic scenario, the hypothesis was not supported that the 4GDH conditions could be reached in Latvia by 2020, but in the pessimistic scenario the hypothesis was proven that these conditions could be reached in Latvia by 2030. Based on the current pace of the development and considering the forecasted dynamics of the fuel and technology costs, the share of renewable energy reached 68.4 % at the end of the simulation period in 2030 (long-term perspective), thus allowing to reach the 4GDH system's conditions. Before 2024 (short-term perspective), the increase mainly in the share of biomass is forecasted, but after 2024, the share of the renewable energy is supplemented with solar collectors with accumulation. The results show that the DH system's development in the base scenario is not sustainable until 2024; therefore', multi-perspective policy instruments for decision-making should be implemented.

6. In order to facilitate the transition to renewable energy, three political instruments were included into the SD model: subsidies, risk reduction instrument, and efficiency increase instrument. Results show that at the end of the simulation period (long-term perspective), 97.7 % of the heat energy is produced from renewable energy (Scenario 2). In this Scenario, the 4GDH system's conditions are reached already in the short-term perspective.
   In the SD model, a transition to the low temperature regime was included (60/30) at the various shares of the renewable energy (60 %, 80 %, and 95 %). The change in temperature regime increases the efficiency of the renewable technologies but does not change the share of the renewable energy for the whole system.
   The use of renewable energy at DH has several barriers – relatively higher capital costs of technologies, lack of experience in installation, operation and maintenance, and lack of information. Therefore, by the expanding use of renewable technologies, these barriers are getting smaller. However, even with policy instruments (Scenario 2), heat production with heat pump technology is not economically feasible. Moreover, the Thesis shows that the main barrier is that a lot of new gas boilers have been already installed during the reconstruction of boiler houses in the past few years. To change the ratio between renewable energy and fossil energy in DH and to bring the system closer to the 4GDH system, it is necessary to make additional decisions about reducing the service life for gas combustion technologies.
   In addition, the sensitivity analysis results obtained from the model show that natural gas price is the most sensitive parameter, followed by natural gas technology price, biomass price, electricity price, and biomass technology price. Base scenario (Scenario 1) predicts that in the year 2030, the energy share produced by gas technologies would be 31.6 %, but by renewable technologies – 68.4 %. The sensitivity analysis indicates that in the case of the reduction in natural gas price (-25 %), the energy share produced with a gas technology could increase to 49.7 %, but in case of an increase (+25 %) could fall down to 29.7 %. These results should be taken into account when creating the DH development policy.
   The developed model has high practical potential as an important aid for policy makers to make the assessment of policy tools and to provide strategic actions in order to introduce 4GDH.

7. Economic feasibility analysis for the transition from a conventional DH system to the 4GDH system was performed. Energy saving measures with various levels of efficiency were incorporated into the analysis. The study evaluated energy saving measures and compared the specific investment costs for all scenarios according to their heat energy savings. At specific heat consumption of 60 kWh/m^2, an optimal solution is achieved, which is characterized by the lowest investment and by the lowest heat energy consumption by end users.
   This developed efficiency platform could be applied to other DH systems if corresponding initial data are added. The proposed methodology allows evaluating the opportunities to transition from the existing DH system to the 4GDH system, while maintaining the competitiveness of the DH system.

8. Although the model was based on Latvian specific technological substitution process, the developed multi-perspective framework could be applied to other DH systems. Future studies could be performed by adding to the SD model the behaviour of the DH system's consumers. The multi-

perspective analysis provides the methodology with combines empirical study tools, system dynamics, multi-criteria decision-making framework, economic and policy analysis. Decision makers need to concentrate the attention on strategic actions - governmental regulation, e.g., taxes, subsidies, changes in energy price etc. depending on prioritised scenario. The implementation of policy instruments for energy system planning allows achieving 4GDH system. In additional the NPV, IRR and other economic indicators was calculated for the determination the optimal DH system's design. Optimal solution for the development of the DH system that allows transition towards the 4GDH, shows the best design of the system minimizes the cost of the DH system and, that is very important, ensures optimal payment for heat energy for consumers.

The macroeconomic evaluation of the scenarios is outside the scope of this Thesis. This can be the topic for further research.

Based on the requirements of the Directives, financial restriction or other relevant decision-making factors the initial input data, developed model and/or policy tools can be adjusted to reach the compromise

The presented framework allows evaluating various DH development scenarios from the point of view of all involved parties – DH system operators, developers, final consumers, policymakers etc. Various involved parties will have different priorities, but the final decision based on multi-perspective methodology should be made in order to move the DH system towards the 4GDH system.

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