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

Ginta CIMDIŅA
Doctoral Student of the Study Programme “Environmental Science”

SCALING-UP FROM A SINGLE ENERGY PRODUCTION UNIT TO STATE ENERGY SECTOR

Summary of the Doctoral Thesis

Scientific supervisor
Dr. habil. sc. ing., Professor
DAGNIJA BLUMBERGA

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DOCTORAL THESIS PROPOSED TO RIGA TECHNICAL UNIVERSITY FOR THE PROMOTION TO THE SCIENTIFIC DEGREE OF DOCTOR OF ENVIRONMENTAL EGINEERING

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 ....at …………, at the Faculty of Power and Electrical Engineering of Riga Technical University, 12/1 Azenes Street, Room 115.

OFFICAL REVIEWERS

Dr. hab. chem. Maris Klavins,
University of Latvia

Dr. sc. ing. Edgars Vigants,
Riga Technical University

Dr. sc. ing. Andres Siirde,
Tallinn Technological University

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.

Ginta Cimdiņa ……………………………….. (signature)

Date ………………………..

The present Doctoral Thesis has been written in English and contains: introduction, 3 chapters, conclusions, bibliography with 62 reference sources; it has been illustrated by 26 figures and 5 tables. The volume of the Thesis is 169 pages including 13 appendices.

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Topicality of the Doctoral Thesis

Energy use is the fundamental building block of our society, both today and in the future. To achieve the milestones of sustainable development, energy systems should be viewed as one of the vital elements among water and food security.

Energy systems consist of various elements, with the starting point at energy production units. These units are linked together with energy distribution networks, where networks are part of the local energy plans. And as the final stage of agglomeration, the state energy sector is formed.

Therefore to have a well-functioning and sustainable state energy sector, each of the underlining elements should function with the maximum efficiency at each given moment in time. To ensure maximum efficiency and study possible improvement, the scaling-up framework is presented in the present research.

This approach is based on the research of four individual domains: energy production units, energy distribution networks, local energy plans and low energy strategy.

The Aim and Tasks of the Doctoral Thesis

The aim of the present Doctoral Thesis is to transfer and approbate the framework of scaling-up methodology from a single energy production unit to the state energy sector in Latvia.

The following tasks have been set to achieve the aim:

1. to study combined heat and power production unit with the use of energy, exergy, emergy, regression and correlation analysis;
2. to study the district heating network with the use of multiple-criteria decision analysis and to model future development scenarios of this district heating network;
3. to study municipal energy plans using a time series forecasting tool and a climate change indicator;
4. to study the low carbon strategy using the archetype "Distraction" and to propose methodologies for the development of low carbon strategy.

Hypothesis of the Doctoral Thesis

In order to reach the low carbon strategy, the framework of scaling-up should be used to ensure that each of the energy system elements functions with the maximum efficiency at each given moment in time.

Methodology of Research

In order to test the hypothesis, various types of research methodologies were used (see Fig. 1).

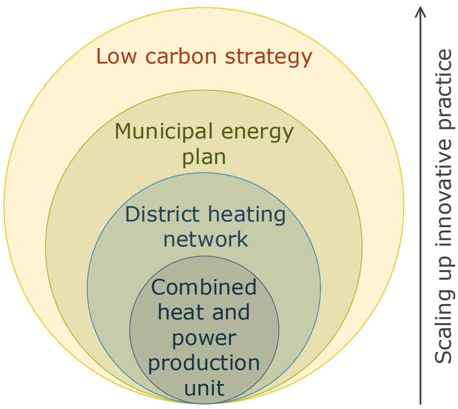

Fig. 1. Applied methodologies for scaling-up innovative practices in the energy sector using four domains.

The scaling-up framework means that the starting point is combined heat and power production unit and their operation, next step of aggregation is a district heating network followed by a municipal energy plan and finally leading to a low carbon strategy.

Each methodology presented in this Thesis was applied to separate sectors; nevertheless, some of the methodologies could also be used for other levels of the system.

The presented framework can primarily be applied to energy systems and energy sectors, but its use is not limited and can be applied to other fields of economy as well. Moreover, the presented framework can be used both for scientific research purposes and by policy makers.

Scientific Significance of the Doctoral Thesis

A complex study on the possibilities to achieve the targets of low carbon society in the energy sector is presented through the framework of scaling-up methodology. The novelty of the research lays in the application of various methodologies for various levels of the governance in order to achieve one common target a low carbon society.

To the author's knowledge, it is for the first time when the scaling-up framework has been presented for all levels of energy systems, starting from a single energy production unit up to the state energy sector. The novelty of this methodology is in its application to study four individual domains: the combined heat and power production unit, district heating network, municipal energy plan and low carbon strategy. The Thesis presents various methodologies suitable for use in these defined domains, thus outlining the presented scaling-up framework.

The framework of scaling-up demonstrates 14 distinct methodologies applied to the energy sector. Firstly, the scaling-up methodology itself is presented and discussed. Secondly, each domain of research is outlined by the remaining methodologies: where 1) the domain of combined heat and power production unit is studied using the energy, exergy, emergy, regression and correlation analysis; 2) the domain of district heating network is studied using the multiple-criteria decision analysis and modelled for future development scenarios; 3) the domain of municipal energy plans is studied using a time series forecasting tool and a climate change indicator; and 4) the domain of low carbon strategy is studied using the archetype "Distraction" and the algorithms are developed to reach a low carbon strategy. The methodologies are validated in various case studies in Latvia and are presented in the Thesis.

Practical Significance of the Doctoral Thesis

Studies on the energy systems are needed to ensure a rapid convergence to a low carbon society. The proposed framework of scaling-up methodology has wide application, starting from a local level up to a national level.

The present research allows for the successful, innovative practices developed and tested on the lower level of aggregation to be then transferred to the upper levels of aggregation, thus leading to the scaling-up effect of innovative practices.

In terms of particular study domains, the operators of combined heat and power production units can explore possibilities to reach higher energy production efficiency and obtain better models for the identification of the areas for possible improvements. The operators and owners of district heating systems can model various development scenarios and guide the decision making process. Municipalities are presented with the forecasting tools and the calculation method for the assessment of climate change mitigation using various alternatives. Finally, the government officials can use the archetype "Distraction" and various algorithms to explore possible setbacks and reach the stated targets for a low carbon society.

The framework under discussion can primarily be applied to energy systems and energy sectors, but its use is not limited to those stated and can be applied to other fields of economy as well. Moreover, the presented framework can be used both for scientific research purposes and by policy makers.

Structure and Description of the Doctoral Thesis

The Doctoral Thesis is based on the thematically unified 13 scientific publications. Those publications are 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 scaling-up methodology from a single energy production unit to the state energy sector in Latvia.

The present Doctoral Thesis consists of an introduction and three chapters:

1. literature review;
2. research methodologies;
3. results and discussion thereof.

In the introduction, the aim of the Thesis and underlying tasks are formulated, followed by the definition of the Thesis structure and a short description of the approbation of the research results by means of the publications and participation in the international scientific conferences.

Chapter 1 provides an overview of the research issues present in the four defined study domains. Chapter 2 describes the methodologies used in the scaling-up framework. The results obtained from the application of proposed methodologies are presented in Chapter 3. Finally, conclusions are given at the end of the Thesis.

An Overview of the Author’s Studies on Scaling-up from a Single Energy Production Unit to the State Energy Sector

Short Description of the Solutions Used

The efforts of the European Union (EU) to reduce the impact on climate change are going in two directions. The first direction is related to an increase in the proportion of renewable energy resources. The second direction is related to an increase in energy efficiency. These two directions are also clearly visible in energy production systems.

In this Thesis, the energy system is considered from the perspective of a scaling-up approach — starting from local heat production units and going towards a bigger scale of distribution network, municipality and finally ending up at the state energy sector (see Fig. 2).

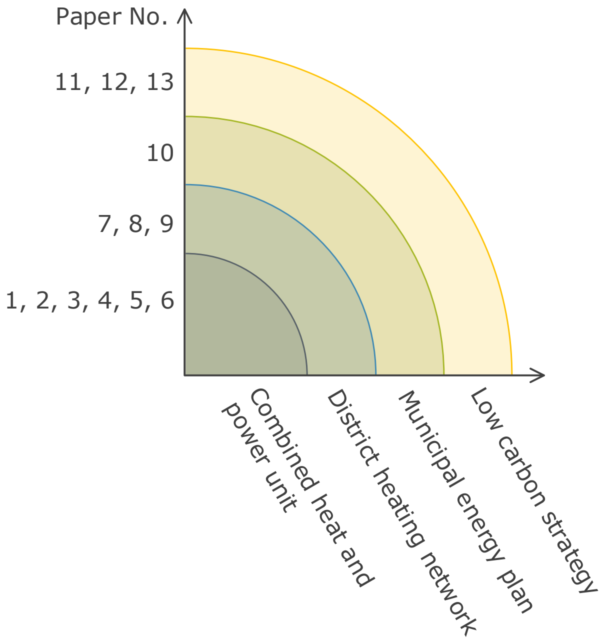

Fig. 2. The publications used in the scaling-up methodology (the full title of publication corresponds to the number given in Table 1).

All domains under consideration have a common target to move towards the low carbon strategy, but each domain fulfils its own specific function and is studied using the best-fit methodology. Nevertheless, these elements are interconnected since the malfunctioning of one component will affect the whole system.

Table 1. Scientific Publications used in the Thesis to Study the Framework of Scaling-up from a Single Energy Production Unit to the State Energy Sector

Studied domain	No.	Title of publication
Combined heat and power (CHP) production unit	1	Sustainable Development of Biomass CHP in Latvia
	2	Modelling of Biomass Cogeneration Plant Efficiency
	3	Energy and Exergy Analysis of Wood-based CHP. Case Study
	4	Review-based Emergy Analysis of Energy Production
	5	Emergy Analysis of Biomass CHP. Case Study
	6	Analysis of Wood Fuel CHP Operational Experience
District heating (DH) network	7	Sustainable Development of Renewable Energy Resources. Biomass Cogeneration Plant
	8	Development of District Heating Systems — Cogeneration Versus Energy Efficiency of End User
	9	The Role of the Latvian District Heating System in the Development of Sustainable Energy Supply
Municipal energy plan	10	Analysis of Wood Fuel Use Development in Riga
Low carbon strategy	11	Potential for Bioenergy Development in Latvia: Future Trend Analysis
	12	The Natural Gas Addiction and Wood Energy Role in Latvia Today and Future
	13	Green Energy Strategy 2050 for Latvia: A Pathway towards a Low Carbon Society

In the present Doctoral Thesis, the author refers to these 13 major publications — Paper No. 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12 and 13, which correspond to the articles given in Table 1.

Combined Heat and Power Production Unit as a Study Domain

One of the ways to use energy production units in sustainable way in the short term is to substitute fossil fuels with biomass. Currently, bio-energy usage in the world makes around 10 % of total primary energy supply; therefore, the potential to expand use of bioresources is vast[1].

The second direction to reach climate goals is to promote cogeneration or combined heat and power production (CHP). The highest potential for CHP was also found in the countries around the Baltic Sea[2]. Therefore, Paper No. 1 studied the sustainable development of biomass CHP plants in Latvia.

[1] Haberl H., Beringer T., Bhattacharya S.C., Erb K.H., Hoogwijk M. The global technical potential of bio-energy in 2050 considering sustainability constraints, *Curr Opin Environ Sustain*, 2010; 2(5–6): 394–403.

[2] Çakir U., Çomakli K., Yüksel F. The role of cogeneration systems in sustainability of energy, *Energ Convers Manage*, 2012; 63: 196–202.

It is not sufficient to install CHP plants and use renewables, the analysis of operational performance also is vital. Thus, Paper No. 2 determines the vital factors of the operation performance in biomass cogeneration power by presenting quantitative equations.

Biomass CHP plants can be assessed using indicators; traditional assessment methods of energy and mass flows and economic analysis do not provide an integral assessment. In this case, emergy and energy analysis could serve as an integral assessment method[3]. Therefore, Paper No. 3 presents the exergy analysis of a CHP plant, which shows the vital points of exergy destruction and might be used for the improvement of operations. The emergy analysis for biomass CHP plant is developed in Paper No. 4 and the case study is given in Paper No. 5.

Under electricity market liberalisation, the price for electricity is time-variable and creates an economically favourable offer for the plant, if the plant is able to operate dynamically with the variable generation of electrical energy[4]. Therefore, Paper No. 6 analyses the operation conditions for a biomass cogeneration plant under dynamic market conditions.

District Heating Network as a Study Domain

The transition from local, separate high efficiency and sustainable energy supply solution to the community based level supply solutions can have various underlying challenges. Firstly, a choice among CHP plants of different size and capacity should be made. Secondly, one must choose among different investment priorities taking into account whether the investment in energy efficiency should be made at the power plant, distribution grid or energy end consumers. Also the integration of biomass CHP solutions for district heating (DH) system is subject to an analysis.

Various researchers have addressed the problem on the correct sizing and capacity of the CHP plant within the DH system. Two radically contradictory solutions when choosing the installed capacity of CHP plant are studied in Paper No. 7: 1) compliance with the base load of the DH system; and 2) compliance with the optimal heat load of the DH system during the whole year.

Moreover, the effective use of energy sources in production units is tightly related to final energy consumption. Since energy efficiency measures lead to reduced energy demand, the production units (especially in the case of district heating) need to be reorganised by considering relocated load distribution and integration of renewable energy sources[5]. Therefore, the aim of Paper No. 8 is to find the optimal solution in case heat load decreases in the district heating system.

From the short-term point of view, an increase in the share of biomass in DH systems would economically be one of the most optimal paths in changing the country's energy balance in favour of renewable energy sources (RES). However, in the longer run, the integration of intermittent renewable energy technologies on a large scale

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[3] Brown M.T., Ulgiati S. Emergy analysis and environmental accounting, *Ency Energy*, 2004: 329–354.

[4] Mitra S., Sun L., Grossmann I.E. Optimal scheduling of industrial combined heat and power plants under time-sensitive electricity prices, *Energy*, 2013; 54: 194–211.

[5] Gładysz P., Ziębik A. Complex analysis of the optimal coefficient of the share of cogeneration in district heating systems, *Energy*, 2013; 62: 12–22.

should be considered. However, this solution requires flexible consumers who are able to adapt their consumption to the supply from those sources. DH systems to a certain extent are able to serve a flexible consumer and to participate in the solution of any mismatch between supply and demand from RES. Thus, the aim of Paper No. 9 is to determine to what extent a district heating system can serve a flexible user in the energy system of Latvia.

Municipal Energy Plan as a Study Domain

When using biomass for energy production, the question of resource sustainability is usually on the list of issues to consider. In Latvia, forests cover around 50 % of the territory. While the total growing stock accounts for 631 million m^3, the average forest processing rate is 12 million m^3 per year[6]. The research by Dubrovskis[7] concludes that available biomass potential in Latvia is around 25–30 TWh per year and the annual logging rate complies with the basic principles of sustainable development. Moreover, the price of biomass in Latvia is around two times lower than the price of natural gas. Despite these facts, Latvia is not currently among the countries with the highest biomass share in its energy balance.

This fact leads to the conclusion that the operators of the heat production units and district heating networks by themselves cannot lead the sector for sustainable solutions quickly enough. Municipal-level support is critical at the initial phases of development. Therefore, the aim of Paper No. 10 is to analyse the use of wood fuel for district heating in Riga municipality. The study forecasts the share of wood fuel in the thermal energy balance of the municipality. The hypothesis of the research is that 25 % of the total heat energy consumption of Riga municipality can be supplied using biomass by 2020.

Low Carbon Strategy as a Study Domain

In order to be able to define Latvia's national path for the transition to a low carbon strategy, the potential for various resources should be stated. Therefore, the aim of Paper No. 11 is to develop Latvia's national path for the transition to a low carbon strategy, where the potential for various resources is stated. This strategy is presented from technical, environmental and economic points of view.

Transition from a fossil fuel economy to a renewable energy economy is a complex process and requires a long-term development strategy and a serious approach to its implementation.

Therefore, Paper No. 12 analyses strategies for restricting Latvia's dependence on fossil fuel imports in a line with an increasing challenge to follow the leading EU Member States in greening the energy sector.

[6] CSB, Latvian Central Statistical Bureau database.

[7] Dubrovskis D. Forest resources in Latvia, *5th Latvian Green Energy Forum*, September 7, 2011, Riga, Latvia.

Currently Sweden[8] and Denmark[9] are aiming for 100 % renewable energy sources in their energy strategies by 2050. Also various studies were carried out to investigate the transition to 100 % renewable energy systems at the municipality and city levels. Although case studies do not provide a common methodology, they outline a vision of future energy systems, where reduction in fossil fuel consumption is possible. Therefore, Paper No. 13 presents the methodology underpinning the development of the Green Energy Strategy 2050 for Latvia.

Summary of the Literature Review

Based on the literature analysis carried out, it can be concluded that in order to aim for a low carbon society the underlining elements of the system — municipality, district heating network and energy production units — should be functioning to reach the same targets. Therefore, the present Thesis presents the scaling-up framework for the state energy sector. To author's knowledge, this is the first Thesis presenting this framework for a case study in the energy sector. The focus of the research is to present various methodologies suitable for use in various domains of a scaling-up framework.

Approbation of the Research Results

The research results have been approbated in 10 international scientific conferences (6 in SCOPUS database and 6 in ISI Web of Science database) and published as 14 full-length articles (10 in SCOPUS database and 9 in ISI Web of Science database) and 2 abstracts in international scientific journals and conference proceedings.

Reports at international scientific conferences

1. Cimdina G., Prodanuks T., Veidenbergs I., Blumberga D. Sustainable Development of Biomass CHP in Latvia // International Scientific Conference of Environmental and Climate Technologies CONECT 2015, 14–16 October 2015, Riga, Latvia.

2. Prodanuks T., Cimdina G., Veidenbergs I., Blumberga D., Karklina K., Baranenko D. Emergy Analysis of Biomass CHP. Case Study // International Scientific Conference of Environmental and Climate Technologies CONECT 2015, 14–16 October 2015, Riga, Latvia.

3. Karklina K., Cimdina G., Veidenbergs I., Blumberga D. Energy and Exergy Analysis of Wood-Based CHP. Case study // International Scientific Conference

[8] Joelsson J, Gustavsson L. Swedish biomass strategies to reduce CO_2 emission and oil use in an EU context, *Energy*, 2012; 43: 448–468.

[9] Parajuli R. Looking into the Danish energy system: Lesson to be learned by other communities, *Renew Sust Energ Rev*, 2012; 16: 2191–2199.

of Environmental and Climate Technologies CONECT 2015, 14–16 October 2015, Riga, Latvia.

4. Cimdiņa G., Prodaņuks T., Veidenbergs I., Blumberga D. Review-Based Emergy Analysis of Energy Production // Environment. Technology. Resources: Proceedings of the 10^{th} International Scientific and Practical Conference 18–20 June 2015, Rezekne, Latvia.

5. Cimdina G., Blumberga D., Veidenbergs I. Analysis of Wood Fuel CHP Operational Experience // International Scientific Conference of Environmental and Climate Technologies CONECT 2014, 14–16 October 2014, Riga, Latvia.

6. Cimdiņa G., Blumberga D., Veidenbergs I. Why Wood Fuel CHP is a Sustainable Solution. Analysis of Operation Experience // International Scientific Conference of Environmental and Climate Technologies CONECT 2014, 14–16 October 2014, Riga, Latvia.

7. Blumberga D., Cimdiņa G., Timma L., Blumberga A., Rošā M. Green Energy Strategy 2050 for Latvia: a Pathway Towards a Low Carbon Society // 17^{th} Conference on Process Integration, Modelling and Optimisation for Energy Saving and Pollution Reduction PRES 2014, 23–27 August 2014, Prague, Czech Republic.

8. Cimdina G., Slisane Dz., Ziemele J., Vitolins V., Vigants G., Blumberga D. Sustainable Development of Renewable Energy Resources. Biomass Cogeneration Plant // The 9^{th} International Conference "Environmental Engineering", 22–23 May 2014, Vilnius, Lithuania.

9. Cimdiņa G., Veidenbergs I., Kamenders A., Ziemele J., Pakere I., Blumberga A., Blumberga D. Modelling of Biomass Cogeneration Plant Efficiency // 5^{th} International Conference "Biosystems Engineering 2014", 8–9 May 2014, Tartu, Estonia.

10. Ziemele J., Pakere I., Talcis N., Cimdiņa G., Vīgants Ģ., Veidenbergs I., Blumberga D. Analysis of Wood Fuel Use Development in Riga // 5^{th} International Conference "Biosystems Engineering 2014", 8–9 May 2014, Tartu, Estonia.

11. Cimdiņa G., Blumberga A., Veidenbergs I., Blumberga D., Barisa A. The Natural Gas Addiction and Wood Energy Role in Latvia Today and Future // Recent Advances in Mechanics, Fluids, Heat, Elasticity and Electromagnetic Fields: the 2013 International Conference on Mechanics, Fluids, Heat, Elasticity and Electromagnetic Fields (MFHEEF 2013), 28–30 September 2013, Venice, Italy.

12. Barisa A., Cimdina G., Romagnoli F., Blumberga D. Potential for Bioenergy Development in Latvia: Future Trend Analysis // 4^{th} International Conference "Biosystems Engineering 2013", 9–10 May 2013, Tartu, Estonia.

13. Cimdina G., Blumberga D. Jelgavas biomasas koģenerācijas stacijas siltumnīcefekta gāzu samazinājuma prognoze // Latvijas Universitātes 71. zinātniskā konference „Ģeogrāfija. Ģeoloģija. Vides zinātne.” (in Latvian), 1st February 2013, Riga, Latvia.

14. Blumberga D., Bazbauers G., Blumberga A., Cimdina G., Rochas C. Development of District Heating Systems – Cogeneration versus Energy Efficiency of End User // The 13th International Symposium on District Heating and Cooling, 3–4 September 2012, Copenhagen, Denmark.

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1. Cimdina G., Prodanuks T., Veidenbergs I., Blumberga D. Sustainable Development of Biomass CHP in Latvia // Energy Procedia (ISSN: 1876-6102) – 2016 – Article in Press.

2. Prodanuks T., Cimdina G., Veidenbergs I., Blumberga D., Karklina K., Baranenko D. Emergy Analysis of Biomass CHP. Case Study // Energy Procedia (ISSN: 1876-6102) – 2016 – Article in Press.

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4. Cimdina G., Timma L., Veidenbergs I., Blumberga D. Methodologies Used for Scaling-up from a Single Energy Production Unit to State Energy Sector // Environmental and Climate Technologies (ISSN 1691-5208) – 2015 – Vol. 15 – pp. 5-21. doi:10.1515/rtuect-2015-0002.

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10. Cimdiņa G., Veidenbergs I., Kamenders A., Ziemele J., Pakere I., Blumberga A., Blumberga D. Modelling of Biomass Cogeneration Plant Efficiency // Agronomy Research (ISSN: 1406894X) – 2014 – Vol. 12 (2) – pp. 455–468.

11. Ziemele J., Pakere I., Talcis N., Cimdiņa G., Vīgants Ģ., Veidenbergs I., Blumberga D. Analysis of Wood Fuel Use Development in Riga // Agronomy Research (ISSN: 1406894X) – 2014 – Vol. 12 (2) – pp. 645–654.

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1 RESEARCH METHODS

1.1 Combined Heat and Power Production Unit as a Study Domain

The methodology for obtaining various indicatives values of the combined heat and power (CHP) plant is given, next the statistical analysis model — correlation and regression analysis for the plant follows.

1.1.1 Energy Analysis

Energy analysis is used to assess energy conversion efficiency. The main purpose of this analysis is to obtain information about the efficiency and losses for various parts of the plant and various operation modes. This information can be further used to identify non-optimal working conditions and make improvements (see Paper No. 1 and Paper No. 3 for more details, where this methodology is used).

1.1.2 Exergy Analysis

Exergy analysis shows points of exergy degradation in a system and allows making a quantitative assessment of energy quality changes. Therefore, the main purpose of exergy analysis is to identify the “bottle-necks” in the CHP plant and to perform possible improvements to reduce the degradation of exergy (see Paper No. 1 and Paper No. 3 for more details, where this methodology is used).

1.1.3 Emergy Analysis

Emergy is the availability of the energy (exergy) of one kind that is used up in transformations directly and indirectly to make a product or service. Several emergy indicators were used to analyse the system and to compare with other systems: environmental sustainability index, emergy sustainability index, emergy yield ratio and environmental loading ratio (see Paper No. 4 and Paper No. 5 for more details).

The emergy analysis is in the development phase; therefore, data availability for various flows can be a limitation and uncertainty cause. Nevertheless in terms of composite indicator for the evaluation of the systems performance, the emergy analysis is a competitive tool to use.

1.1.4 Correlation Analysis

Correlation analysis is aimed at establishing whether there is a correlation between the dependent variable and the analysed independent variable describing the operation of the CHP plant. In case of single factor mathematic models, the Pearson’s equation (see Equation (1)) is used for its estimations (see Paper No. 2 for more details, where this methodology is used).

$$X^2 = \sum_{i=1}^{h} \frac{[n_i - G(n_i)]^2}{G(n_i)} = \sum_{i=1}^{h} \frac{[n_i - ng_i]^2}{ng_i} \qquad (1)$$

In the Pearson's test statistic, the function X^2 is squared deviation of the observed counts from their expected values, $G(n_i)$ for $i = 1, 2, \dots h$ weighted by the reciprocal of their expected values, where n_i is cell count and g_i parameters of observations.

Regression equation was verified based upon the following indices: autocorrelation, multicolinearity and heteroscedasticity.

The result of the correlation analysis can be further used as a basis of information for other methodologies.

1.1.5 Regression Analysis

The regression analysis explains the importance of the stochastic link by functional relationships. The aim of the regression analysis was to obtain an empirical equation that would provide a quantitative description of the change in the specific fuel consumption of the CHP plant depending on statistically important operational indices of this plant; and therefore the obtained equation would serve as the basis for forecasting and evaluating the specific fuel consumption of this CHP plant (see Paper No. 2 for more details, where this methodology is used).

The evaluation of the adequacy of the regression equation is performed by means of the dispersion analysis by applying the Fisher's criterion.

1.2 District Heating Network as a Study Domain

The methodology for comparing alternative solutions is given, followed by the model for the alternative operation modes and the model of district heating (DH) with the integration of renewables.

1.2.1 Multiple-criteria Decision Analysis Methodology

The methodology was developed to allow making a comparison of various alternative solutions, where the efficiency of the use of primary energy resources was analysed. The criteria that are used for the multiple-criteria analysis are energy efficiency, operational costs, investment costs, load coefficient (see Paper No. 7 for more details, where this methodology is used).

The proposed methodology uses the Technique of Order Preference by Similarity (TOPSIS) for an analysis. To start the TOPSIS analysis, data must be arranged in the form of a decision making matrix and then normalized and weighted (see Equation matrix (2)).

$$\begin{array}{c} \\ A_1 \\ A_2 \\ \vdots \\ A_i \\ \vdots \\ A_n \end{array} \begin{array}{c} \begin{array}{cccccc} w_1b_1 & w_2b_2 & \cdots & w_jb_j & \cdots & w_nb_n \end{array} \\ \begin{bmatrix} w_1b_{11}^k & w_2b_{12}^k & \cdots & w_jb_{1j}^k & \cdots & w_nb_{1n}^k \\ w_1b_{21}^k & w_2b_{22}^k & \cdots & w_jb_{2j}^k & \cdots & w_nb_{2n}^k \\ \vdots & \vdots & \cdots & \vdots & \cdots & \vdots \\ w_1b_{i1}^k & w_2b_{i2}^k & \cdots & w_jb_{ij}^k & \cdots & w_nb_{im}^k \\ \vdots & \vdots & \cdots & \vdots & \cdots & \vdots \\ w_1b_{n1}^k & w_2b_{n2}^k & \cdots & w_jb_{nj}^k & \cdots & w_nb_{nm}^k \end{bmatrix} \end{array}, \qquad (2)$$

here n evaluation criteria are given as x_j and m alternatives as A_i. Normalized data are weighted by multiplying data with the criterion weights w_j.

After normalization, positive and negative ideal solutions are defined, followed by the calculation of the separation measure of each alternative from overall positive ideal and negative ideal solutions. The last step in calculation is to rate alternatives.

1.2.2 The Model of Alternative Operational Loads

Sustainable development of heat supply system depends on load development; therefore, it is needed to analyse a situation when heat consumption is reduced based on energy efficiency measures or because of climate change. Therefore, the model for the alternative operation modes of a CHP is presented in the situation when the load of this plant diminishes.

The model assumes that heat load in the future is covered by competing plants, and operation of these plants is established by three technical parameters: power-to-heat ratio of cogeneration plants, efficiency and share of renewable energy in the energy balance. These three parameters have to be maximised for the whole year period (see Paper No. 8 for more details, where this methodology is used).

All alternatives are justified from economic, environmental and climate change aspects and correspond to the base requirement, i.e. operation in the cogeneration mode.

1.2.3 The Generic Model of District Heating System

Sustainable district heating system means that more renewable resources will be integrated into the network. Nevertheless, such resources as wind and solar energy have intermittent patterns and, therefore, are subject to underlying optimisation questions.

The energy system analysis model "EnergyPLAN" developed at Aalborg University in Denmark was chosen as the modelling tool to solve this modelling problem. The aim of this generic model is to study the role of the DH system in advancing more sustainable energy supply systems, in particular integration of wind power plant (see Paper No. 9 for more details, where this methodology is used).

The model assumes time delays before large capacities of wind power plants can be added to the energy system, and the decrease in district heat consumption due to energy efficiency measures. The opposite trend is expected regarding electricity consumption — demand will most likely go up along with the expansion of economy.

Moreover, the role of heat storage is included in the model; it is to accumulate the excess heat produced by heat pumps during surplus wind power production periods, as well as to allow using extra CHP capacity to replace condensing power production when such opportunities arise.

1.3 Municipal Energy Plan as a Study Domain

The methodology using time series and climate indicator is presented for the application at the level of municipal energy plan.

1.3.1 Time Series Forecasting

For the forecasting model, time series based on the ARIMA model was chosen. The selected time period was 1 month and the seasonality — 12 months. The model was used to forecast the amount of heat energy at the municipality level (see Paper No. 10 for more details, where this methodology is used).

The general form of the model can be expressed in terms of the backwards operator β that operates on the time index of a data value. Using this operator, the model takes the form given in Equation (3).

$$(1-\beta-\beta^2-\dots\beta^p)(1-\beta^s-\beta^{2s}-\dots\beta^{Ps})\cdot$$
$$\cdot(1-\beta)^d(1-\beta^s)^D(Y_{t-\mu})=$$
$$=(1-\beta-\beta^2-\dots\beta^q)(1-\beta^s-\beta^{2s}-\dots\beta^{Qs})\alpha_t\,, \tag{3}$$

where a_t is a random error or shock to the system at time t, and μ represents the process mean for the stationary series. A residual autocorrelation function with a confidence level of 95 % is proposed to test the forecast model, where the residual autocorrelation at lag k measures the strength of the correlation between residuals k time period apart. The residual lag k autocorrelation is calculated using Equation (4).

$$\mathrm{r_k}=\frac{\sum_{t=1}^{n-k}(e_t-\bar{e})(e_{t+k}-\bar{e})}{\sum_{i=1}^{n}(e_t-\bar{e})^2}\,, \tag{4}$$

where t is the time period, e_t is one period ahead of forecasting, n is the sample size (number of observations used to fit the model), $t + k$ is the forecasting time.

1.3.2 Climate Change Indicator Calculation

The indicator of the avoided greenhouse gas emissions (t CO_2 per year) is proposed to be used in this model (see Paper No. 10 for more details, where this methodology is used).

1.4 Low Carbon Strategy as a Study Domain

The methodology using the algorithm for scenario evaluation, system archetype “distraction”, four-step management system and the methodology for green energy strategy are presented.

1.4.1 Algorithm for Scenario Evaluation

To define Latvia’s national path for the transition to a low carbon strategy, the potential for various resources is modelled. The evaluation is performed using historical data, scientific literature and indicators. The assessment is performed from the point of view of technological, economic and environmental aspects (see Paper No. 11, where this methodology is used).

The first step of the algorithm estimates the current biomass availability for energy production in the region. The estimates are done based on data about the current patterns and future development trends of land use, production yield of energy crop, and availability of the residue from forestry and agriculture.

Next, the algorithm estimates the technological potential for each of scenarios taking into account the available technologies for biomass conversion and energy demand. The tariffs of energy production using biomass and natural gas based technologies are compared to find the best scenario; this scenario should also align with the targets defined in the national renewable energy strategy.

1.4.2 System Archetype "Distraction"

It is hard to think in the long term when facing a short-term problem — energy consumption increase. There is great temptation to solve this problem using the simplest solution — importing more energy. The more attention is paid to a short-term solution, the less it is dedicated to the long term — the use of RES.

From the perspective of systemic thinking, this problem has been described by Senge[10] through the archetype "Distraction". The system archetype is schematically given in Fig. 3.

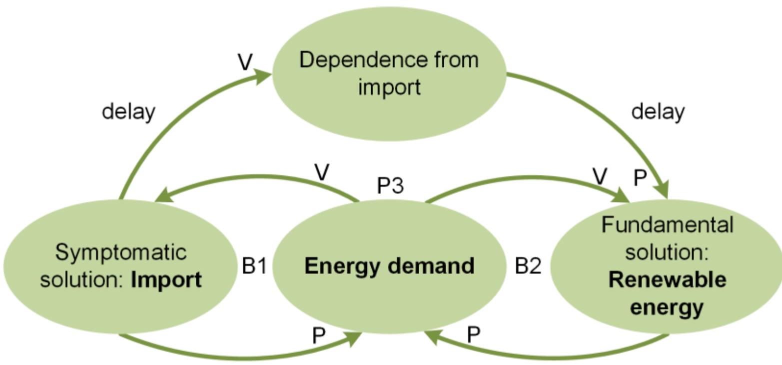

Fig. 3. System archetype "Distraction" (P — contrary processes, V — equal processes, B1, B2 — balancing loops, P3 — balancing loop).

This archetype reflects the effect of energy sector dependence and short-term planning on the situation in the energy sector in the long term. The main idea behind this archetype is that in case a symptomatic or short-term solution is used at least once, the implementation of fundamental or long-term solution is postponed (see Paper No. 12 for more details, where this methodology is used).

The example shows a short-term solution, which delays implementation of a long-term solution, such as the immediate need to renovate existing DH systems in a municipality, which is done immediately without considering additional investments, and a switch to renewable energy resources at the same time would produce better results in the long-term although might immediately cost the municipality more financial, technical resources.

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[10] Senge P. The Fifth Discipline. The Art and Practice of the Learning Organization, *Doubleday Business 1st Ed.*, 1990; 432.

1.4.3 Four-step Management System

To accomplish the transfer of the national economy from fossil to renewable energy resources, it is necessary to define directions, objectives and principles for such transformation.

Module 1. Tracks and directions determine how to meet the commitment of the country and which the priority sectors are:

- Track 1: Transition to more energy-efficient energy consumption and use of renewable energy sources.
- Track 2: Integration of new solutions in the energy sector and transport system.
- Track 3: Research, development and demonstration.

Module 2. Principles comprise financial, environmental, climate, socio-economic and management aspects. These principles include cost efficiency of the measures, minimal impact on public funding, renewed competitiveness, flexibility principle, full-bodied use of international cooperation, securing an energy supply system, support to centralised principle in heating supply, flexibility of energy industry system, market model, business model, gradual approach, sustainable development model, level mark model, assessment model.

Module 3. Calculations should be made taking into account learning and cost curves of the technologies. All of this emphasises the need for a flexible strategy, which ends with opportunities for technology development. Problems relevant to energy supply safety and impact on climate change can also be resolved in different ways.

Module 4. Selections of scenarios are affected by a variety of factors: distribution among different renewable energy sources, technology parameters, economic indicators, etc. In the period up to 2020, the main emphasis must be placed on a more complete use of biomass, without neglecting the use of wind energy after 2020 and the use of solar energy primarily in multi-apartment houses, thus ensuring hot water supply (see Paper No. 12 for more details, where this methodology is used).

1.4.4 Methodology for Green Energy Strategy

This methodology is based on the analysis of the current situation and the energy demand to determine the potential of energy generation and consumption (see Paper No. 13 for more details, where this methodology is used).

The proposed strategy contains at least three parallel paths: (1) the transition to energy-efficient consumption and use of renewable energy resources; (2) the integration of new solutions in the energy sector and transportation system; (3) growth of the green energy supply systems based on research and demonstration.

2 RESULTS AND ANALYSIS OF THE STUDY

This section contains the results for the application of scaling-up methodology in the domains of CHP plant, DH network, municipal energy plan and low carbon strategy.

2.1 Combined Heat and Power Production Unit as a Study Domain

The results of energy, exergy and emergy analysis are given followed by the correlation and regression analysis for the CHP plant.

2.1.1 Results of Energy and Exergy Analysis

Energy and exergy analysis method was used to assess irreversibility at the CHP plant. The detailed breakdown of the energy losses are given in the Sankey diagram (see Fig. 4).

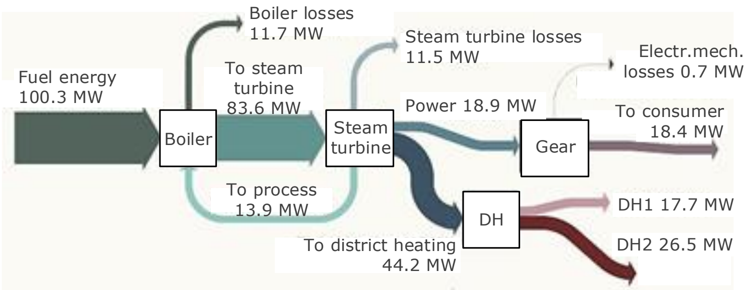

Fig. 4. Sankey diagram of energy flow in the CHP plant.

The obtained Sankey diagram shows the efficiency of the CHP plant and losses at this plant. In similar manner, the Grassmann diagram shows the detailed breakdown of the exergy losses (see Fig. 5). The results of exergy analysis show 64 % of irreversibility occurring in the boiler.

When both energy and exergy analyses are compared, the results show that energy losses in the boiler, associated with heat losses in flue gases and other losses in the furnace, are comparable with those in the steam turbine (Fig. 4), but the values are relatively small comparing to the exergy destruction (Fig. 5).

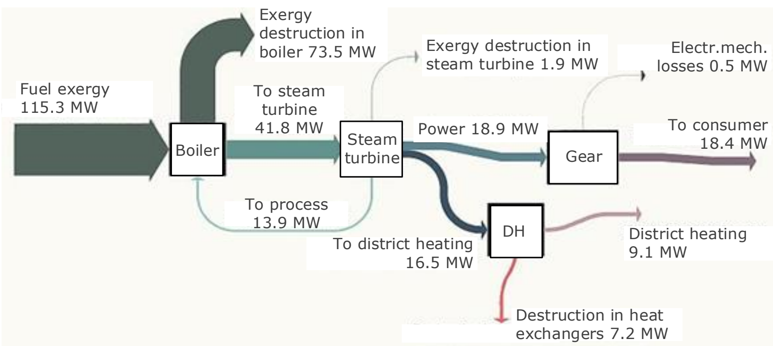

Fig. 5. Grassmann diagram of exergy flow CHP plant.

The results show that the energetic efficiency of the CHP plant is 62 % and exergetic 24 %. The explanation for these different results is that in the beginning the input energy and exergy values are similar (input energy is of high quality), but the output flows, which consist of produced heat and power, are both of different exergetic qualities; therefore, different results are obtained (see Paper No. 1 and Paper No. 3 for more details). These obtained results can be further used to identify "bottle-necks" and make improvements.

2.1.2 Results of Emergy Analysis

As given in Section 2.1.1, the obtained results in terms of energy and exergy analysis differ because of various outputs (heat or electricity generated), but also may differ when various energy production processes and technologies are compared. Therefore, to achieve a more complete analysis, the emergy analysis is used. Paper No. 4 presents the general framework of emergy analysis at the CHP plants and Paper No. 5 presents the analysis of the case study of the CHP plant using biomass.

Firstly, the diagram of emergy flow for the CHP plant was created (see Fig. 6). Outside the rectangle (in Fig. 6) all inputs are shown, inside the rectangle all components of the system and flows between these components are given. Three outputs: electricity, heat and ashes are given with the black arrows.

Next emergy table for the studied system was developed. The aim of this emergy table is to link up all compounds of the system and use the obtained values for further analysis (see Table 2).

Table 2. The Comparison of Emergy Indicators[11], where *ED* — Empower Density, *EYR* — Emergy Yield Ratio, *ELR* — Environmental Loading Ratio, *ESI* — Emergy Sustainability Index, *R* — the Share of Renewable Resources

Case study (nominal capacity, MW)	*ED*, seJ/m^2	*EYR*	*ELR*	*ESI*	*R*, %
Biomass CHP plant (77)	$3.89 \cdot 10^{16}$	2.11	0.92	2.29	52.0
Wind power plant (2.5)	$1.19 \cdot 10^{12}$	7.47	0.15	48.3	86.6
Geothermal power plant (20)	$1.56 \cdot 10^{14}$	4.81	0.44	11.0	69.7
Hydroelectric power station (81)	$1.59 \cdot 10^{13}$	7.65	0.45	16.9	68.8
Methane power plant (171)	$2.61 \cdot 10^{15}$	6.60	18.1	0.56	7.8
Oil power plant (1280)	$2.48 \cdot 10^{15}$	4.21	14.2	0.30	6.6

[11] Sha S., Hurme M. Emergy evaluation of combined heat and power plant processes, *Appl Therm Eng*, 2012; 43: 67–74.

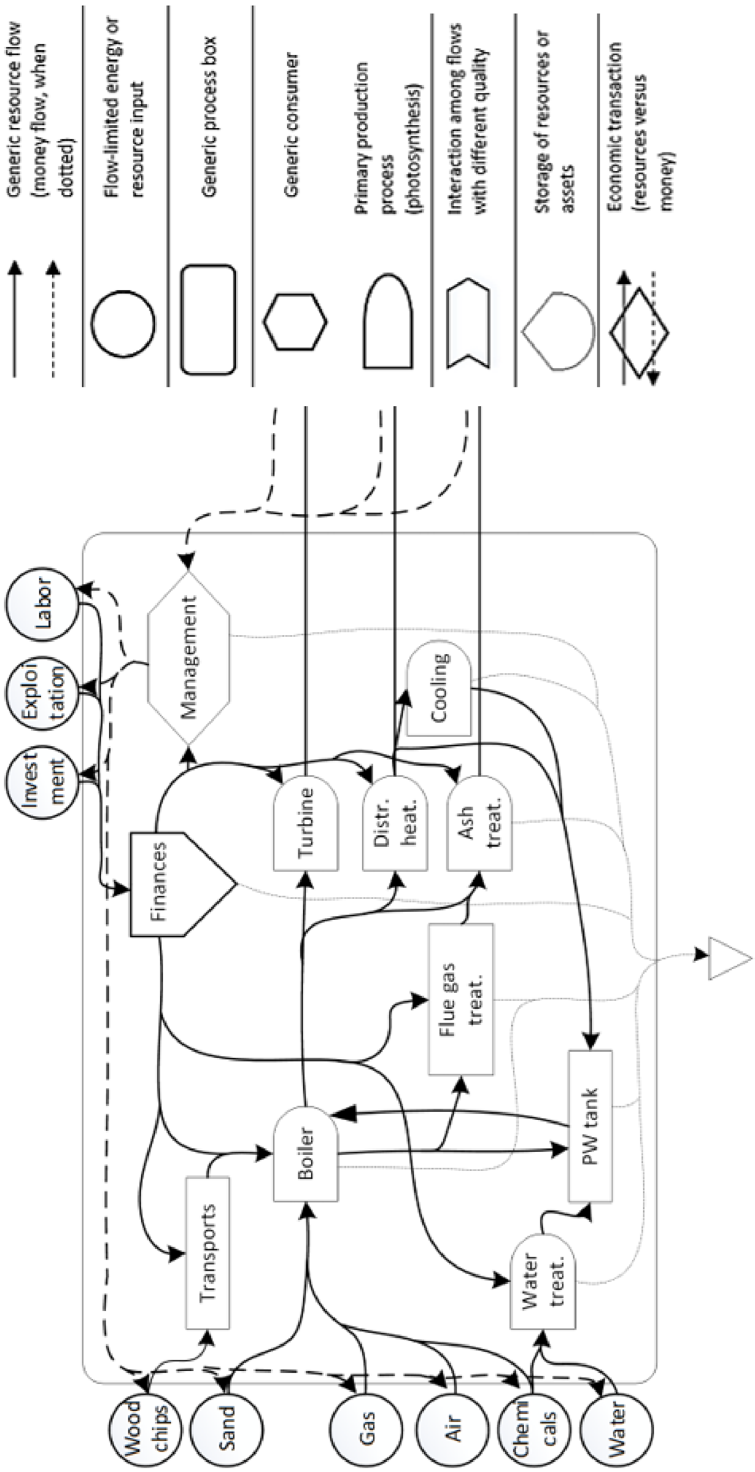

Fig. 6. The diagram of emergy flow for studied biomass CHP plant.

The interpretation of these parameters is as follows: in case the environmental loading ratio *ELR* converges to zero, the stress to the environment due to production is reduced. In case the emergy sustainability index *ESI* is < 1 than the studied system is not sustainable[12] (see Paper No. 1 and Paper No. 3 for more details).

2.1.3 Results of Correlation Analysis

The correlation analysis was aimed at establishing whether there is a correlation between the dependent variable and the analysed independent variable describing the operation of the CHP plant.

The relationship between the specific fuel consumption and outdoor temperature was studied (see Fig. 7).

The obtained value of the correlation coefficient is rather low, since there is a dispersion of data, leading to the conclusion that there is a considerable impact of other factors. The impact of other factors can be established by means of a multi-factor regression analysis.

The change in return water temperature in the function of the outdoor temperature was also studied (see Fig. 8). The value of the coefficient of determination as determined by the analysis R^2 = 93 %. The relationship between the variables is non-linear.

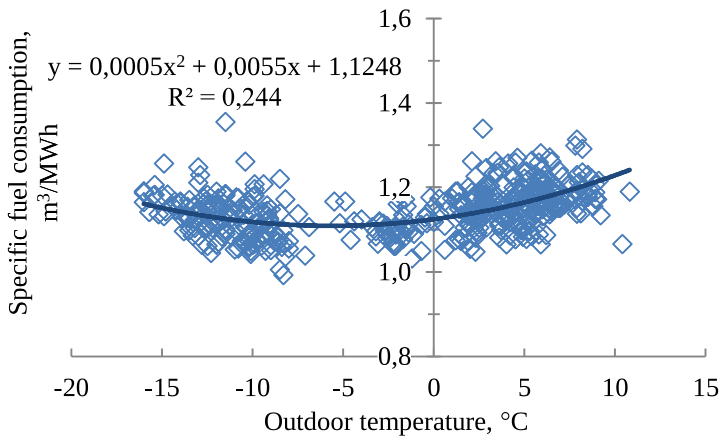

Fig. 7. The change of the specific fuel consumption in the function of outdoor temperature.

As a result of the correlation analysis, it is obtained that within further multi-factor regression analysis the change of the specific fuel consumption of the CHP plant b_{ch} (dependent variable) could be described by four independent factors (see Equation (5)).

[12] Brown M.T., Ulgiati S. Emergy evaluations and environmental loading of electricity production systems, *J Clean Prod*, 2002; 10: 321–334.

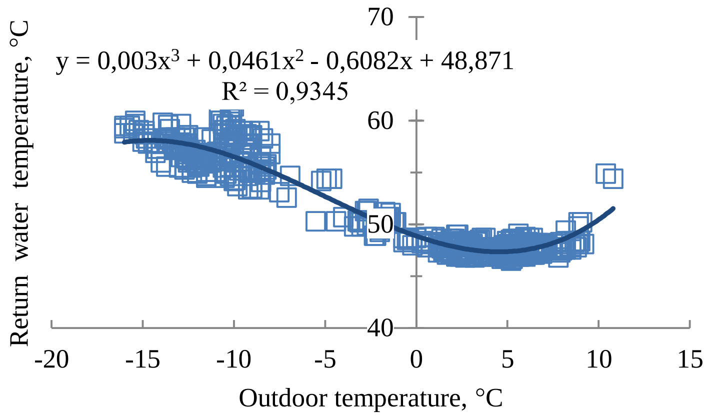

Fig. 8. The change in return water temperature in the function of the outdoor temperature.

$$b_{ch} = f\left(\frac{N_b}{B};\frac{N_{el}}{B};\frac{Q_{th}}{B};T_{out}\right), \tag{5}$$

where N_b/B is the boiler efficiency, N_{el}/B is the power generation efficiency, Q_{th}/B is the heat production efficiency and T_{out} is the outdoor temperature. The correlation analysis makes further regression analysis easier as the set of factors that need to be included in the multi-factor regression equation was established.

2.1.4 Results of Regression Analysis

The regression equation was obtained, where Equation (6) determined the change in the specific fuel consumption, b_{ch}.

$$b_{ch} = 2.3 - 2.3\cdot 10^{-2}\frac{N_b}{B} - 1.4\frac{N_{el}}{B} - 1.3\frac{Q_{th}}{B} - 3.9\cdot 10^{-3}T_{out} \tag{6}$$

The value of R^2 = 99 % and the F-value = 26392.0 for Equation (6). The values of the dispersion analysis are presented in Table 3. Since the table value of Fisher's criterion, F_{tab} = 1.19, the relationship $F > F_{tab}$ means that the obtained equation is valid in the range:

N_b/B the boiler efficiency [0.89; 1.15] MWh/m^3;
N_{el}/B the power generation efficiency [0.21; 0.32] MWh/m^3;
Q_{th}/B the heat production efficiency [0.51; 0.69] MWh/m^3;
T_{out} the outdoor temperature [+ 9.0; – 15.2] °C.

Table 3. The Results of Dispersion Analysis

Coefficient	t-statistics	P-value
For the boiler efficiency, b_1	– 3.2590	0.0012
For the power generation efficiency, b_2	– 88.061	< 0.0001
For the heat production efficiency, b_3	– 128.491	< 0.0001
For the outdoor temperature, b_4	– 1.6221	0.1004
Constant, b_0	530.37	< 0.0001

Results in Table 3 show that the outdoor air temperature can be discarded from the equation. Nevertheless this parameter T_{out} is important in terms of physical processes taking place in the CHP plant, and therefore kept in the equation. The assessment of the percentage difference shows that the rate change of the specific fuel consumption from the real values lies in the margin of 7.5 %. Therefore, the model can adequately describe the situation (see Paper No. 2 for more details).

2.2 District Heating Network as a Study Domain

Firstly, the results for the comparison of various alternative solutions in a district heating system are given, followed by the results for the alternative operation modes of the CHP plant when the load of this plant diminishes, and finally the results of the generic model for the DH system with the integration of renewable energy resources are given.

2.2.1 Results of Multiple-criteria Decision Analysis Methodology

The methodology of multiple-criteria decision analysis was used to compare various alternative solutions, where the development options for energy sources for Jelgava city DH supply system was analysed. Three different wood chip steam cycle cogeneration alternatives are proposed: 1) small-scale CHP plant; 2) large-scale CHP 1 plant in condensing regime; 3) large-scale CHP 2 plant in cogeneration regime.

The data were normalized and followed the methodology outlined in Section 1.2.1. The results of TOPSIS analysis are given in Fig. 9.

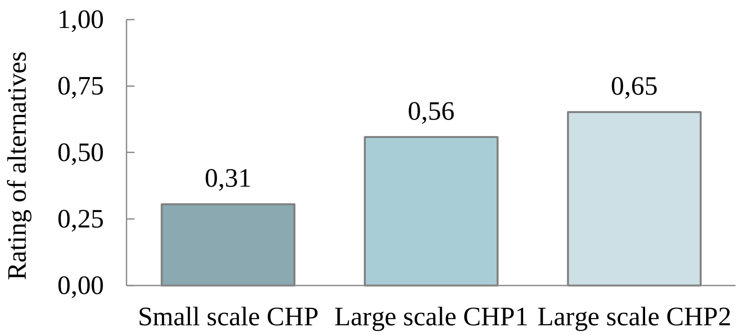

Fig. 9. Rating of selected alternatives.

The alternative with the highest rating should be selected. High capacity CHP plants operating in the cogeneration mode represent the best scenario with the highest rating. According to the analysis of Jelgava city heat supply system, the operation of the CHP plant in the cogeneration mode is also better compared to the alternative of installing a small scale CHP plant (see Paper No. 7 for more details).

2.2.2 Results of the Model for Alternative Operational Loads

The model of the CHP plant operation modes was developed when the heat load diminished. Four scenarios were analysed: basic scenario, where the current operation of the CHP plant continued as usual; (1) scenario, where CHP plants operated for 3000 hours a year; thus, the cogeneration capacity would be used effectively.

Next two scenarios use heat storage systems, for the storage of surplus heat produced by the CHP plant during a low demand period; later this stored heat covers the peak load when the capacity of the CHP plant is not sufficient. Therefore (2) scenario includes situation, where the heat load is covered by Riga TEC 2/1 using heat storage systems and the station could operate effectively for 5000 hours per year; and (3) scenario, where natural gas is replaced by wood fuel in Riga TEC 1 and heat storage is installed. The other natural gas-fired plants are kept idle or operate in condensation mode (see Paper No. 8 for more details).

The comparison of these scenarios is presented in Fig. 10.

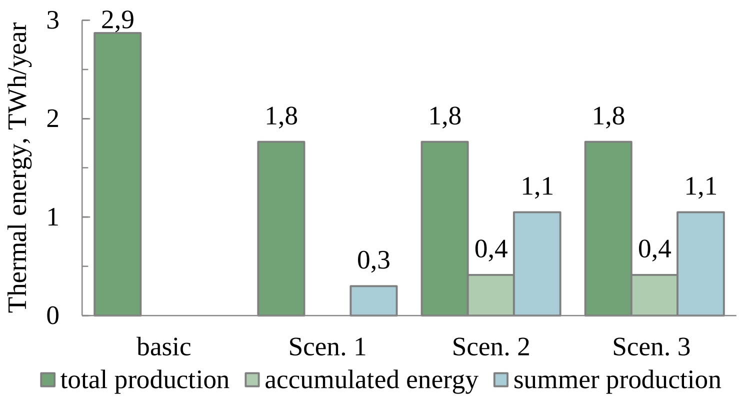

Fig. 10. Thermal energy production and accumulation.

Results show that Scenario 3 allows completely using the installed capacity of the CHP plant. The new phase of Riga TEC 2 could operate less than 3000 hours per year in partial cogeneration regime to cover peak loads instead of boilers. Such an inefficient approach is not practised by a power station. Financial evaluation of the scenarios shows that Scenario 3 would also have the lowest costs of electricity (see Paper No. 8 for more details).

2.2.3 Results of the Generic Model of District Heating System

The model for the integration of renewable resources in the district heating network is analysed. The use of heat pumps reduces electricity production and net export (see Fig. 11) due to the cut-back of the CHP plant production and an increased domestic electricity production.

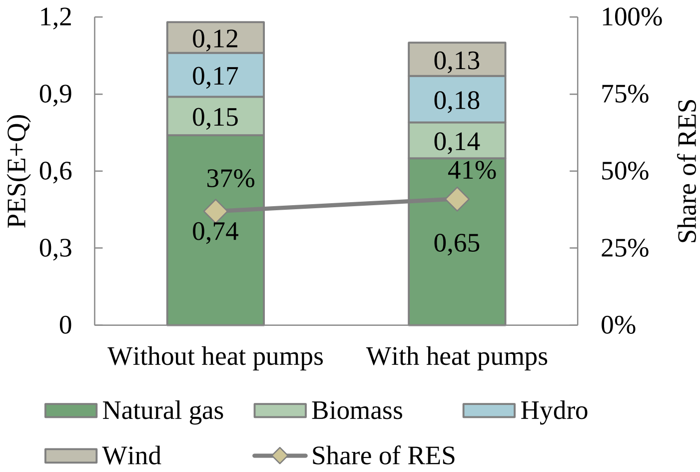

Fig. 11. Use of heat pumps decreases the share of natural gas and increases the share of the renewable energy sources (RES) for heat (Q) and electricity (E) production. Due to the replacement of CHP plants and boiler production with wind power plants, total primary energy consumption (PES) per unit of energy (heat plus electricity) decreases. Biomass includes wood fuel and biogas.

The use of heat pumps increases the share of both renewable energy sources — wind power plants and hydro power plants. Since energy production in CHP plants is partly replaced by wind power plants, and a large part of the production in CHP plants is based on natural gas, the share of renewable energy sources in the total energy (heat and electricity) is larger in the system with heat pumps. With heat pumps, the share of natural gas in district heat and electricity production decreases from 63 % to 59 %, while the share of RES (biomass includes wood fuel and biogas) goes up (see Paper No. 9 for more details).

2.3 Municipal Energy Plan as a Study Domain

In this section, the results using time series and climate indicator are presented for the application at the level of municipal energy plan.

2.3.1 Results of Time Series Forecasting

The ARIMA (0,1,1)×(2,0,1)12 time series forecasting model was developed using monthly data about heat produced from wood fuel. The model shows that it would be possible to produce around 600 GWh during the coldest months by 2020 (see Figure 12).

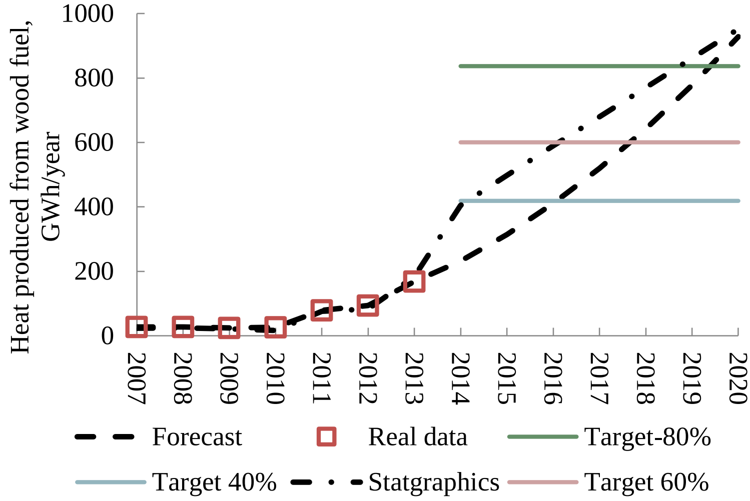

Fig. 12. The comparison of the results from forecast models using the regression analysis and ARIMA time series forecasting tool.

Results show that there is a small difference between the forecasting models. According to the regression analysis, it would be possible to produce 40 % of the total heat with wood chips by 2016. The Statgraphics model (time series) shows that the same amount (40 %) of heat from wood fuel can be produced by 2015. Both models show that the company could almost completely exclude fossil fuels by 2020 if it sets even more ambitious targets (see Paper No. 10 for more details).

2.3.2 Results of Climate Indicator Calculation

The indicator of the avoided greenhouse gas emissions was proposed to be used together with the ARIMA model. Use of wood fuel results is a significant reduction of CO_2 emissions. The avoided CO_2 emissions in the 13-year period (from 2007 to 2020) were calculated by assuming that the industry would substitute the use of natural gas. The total reduction of CO_2 emissions for different scenarios can be seen in Table 4.

Table 4. The Sum of Avoided CO_2 Emissions for Different Scenarios

Scenario	Avoided CO_2 emissions, 1000 t	Produced heat, GWh
Historical 2007 to 2013	99	439
Target 40 % (2007–2020)	576	2568
Target 60 % (2007–2020)	782	3484
Target 80 % (2007–2020)	959	4275

Table 4 shows that around 100 thousand tons of CO_2 emissions were avoided from 2007 to 2013 by introducing wood fuelled boiler houses instead of using natural gas fuelled ones.

Almost tenfold reduction in the greenhouse gas emissions will be achieved if the target of 80 % heat from wood fuel is reached by 2020. The sum of avoided emissions in the analysed period would be around 1 million tons CO_2 if 80 % of the heat were produced by wood chips (see Paper No. 10 for more details).

2.4 Low Carbon Strategy as a Study Domain

In this section, the results using the algorithm for scenario evaluation, system archetype "Distraction", four-step management system and methodology for green energy strategy are presented.

2.4.1 Results of Algorithm for Scenario Evaluation

Four scenarios were built to analyse the potential of biomass fuels in Latvia: base scenario; (1) scenario that assumed the utilisation of locally available forest biomass; (2) scenario that added growing of energy cultures on available agricultural lands and; (3) scenario that included the utilisation of available organic residues for biogas production (see Paper No. 11 for more details). The results for scenarios are given in Fig. 13.

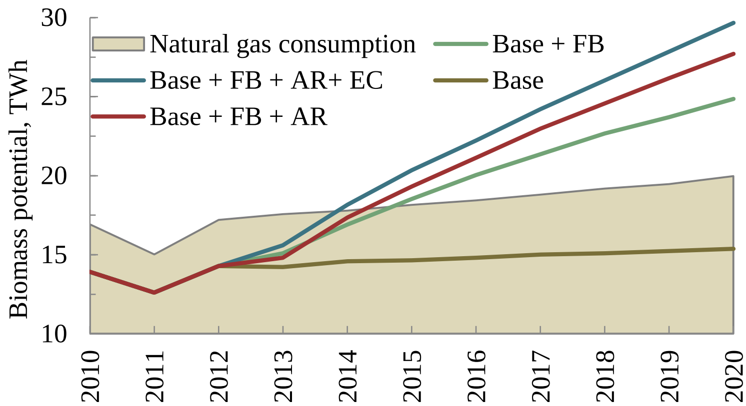

Fig. 13. Evaluation of biomass potential in Latvia (Base — biomass consumption in business as usual scenario, FB — biomass potential from forestry, AR — biomass potential from agricultural residues, EC — biomass potential from energy crops)

In the base scenario, natural gas dominates. Meanwhile in other scenarios biomass allows replacing natural gas already in 2015. The largest biomass potential is associated with the use of the residues from forest logging and by-products of timber processing. Total bioenergy potential in 2020 approved to be twice bigger than the current rate of biomass utilisation.

2.4.2 Results of System Archetype "Distraction"

To understand the restrictions in wood fuel use in the energy sector in Latvia and develop a baseline upon which a future vision is built, statistical data for the time period of 4 years were analysed.

Data on annual primary energy consumption and energy end-use present a maximum value in 2010 followed by a decline afterwards. However, the import of primary energy increased dramatically (by 21.6 %) in 2011 in comparison with the previous year. Reasons for the observed decrease in energy consumption in 2011 could be several. The most commonly agreed reason for this trend is the improvements in energy efficiency introduced within the energy sector.

Figure 14 illustrates the relationship between the primary energy consumption and the efficiency of primary energy use during the period 2008–2011.

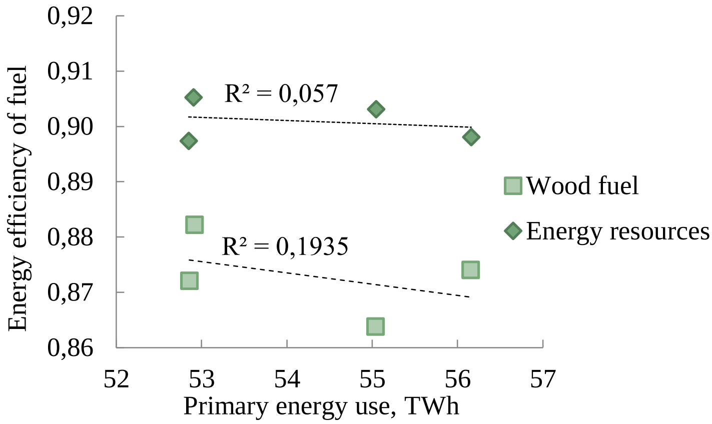

Fig. 14. The relation between primary energy consumption and energy efficiency of fuel use.

Data in Fig. 14 show a weak correlation between the primary energy consumption and efficiency of primary energy use. The results indicate that the reduction in primary energy consumption is not caused by a more efficient use of energy resources. Such tendencies state that the development of energy sector goes contrary to governmental statements (see Paper No. 12 for more details).

2.4.3 Results of Four-step Management System

The forecast on wood fuel production amounts, the share of wood fuel in primary energy consumption and energy end-use are presented in Fig. 15.

Data present the scenario of future development with a gradual growth in wood energy consumption. Based on statistical data on historical wood energy consumption pattern, the share of wood fuel in primary energy consumption for the last four years was determined.

The difference in the shape of curves for the share of wood fuel in primary energy and energy end-use originates from changes in the amounts of supply and energy efficiency of wood fuel use.

Mathematical modelling of the wood fuel share is based on green growth calculation data and results of the assessment of historical wood fuel share. A gradual step-by-step increase over the next years will allow reaching 43 % of wood fuel share in energy end-use balance of Latvia (see Paper No. 12 for more details).

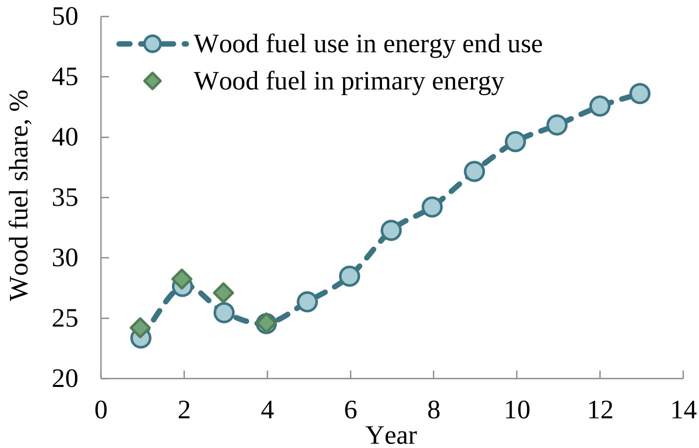

Fig. 15. Historical data and the forecast of wood fuel share.

2.4.4 Results of Green Energy Strategy

Projected energy demand in the baseline scenario increases heat energy consumption until 2050, while in the scenario of energy efficiency an increase is marginal and after 2016 a reduction follows (Fig. 16).

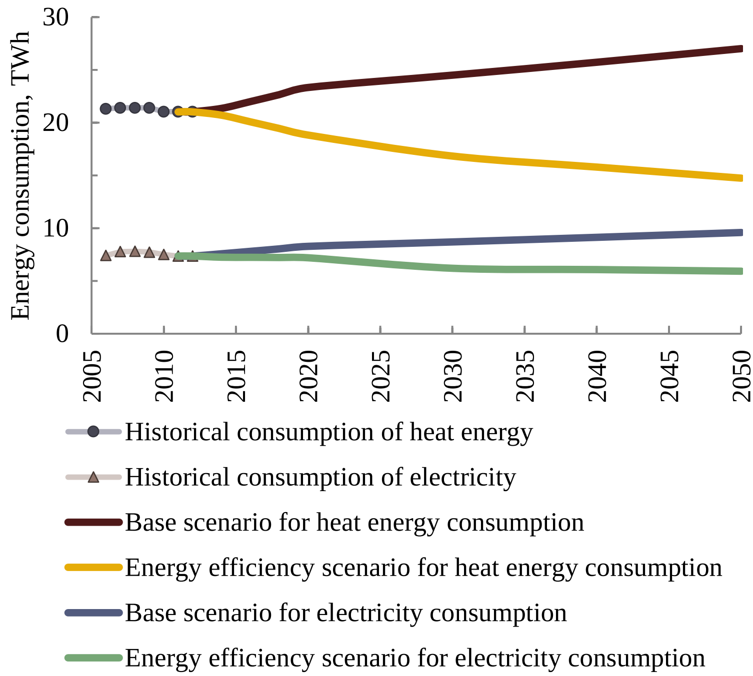

Fig. 16. Total final consumption of electrical and heat energy for baseline and energy efficiency scenarios.

The decrease in heat energy consumption is explained with energy efficiency measures in all sectors, especially in households and services. The final consumption of electricity grows in both scenarios. A growth rate slows down in the energy efficiency scenario by 2015 because the average consumption level of the EU-15 in 2004 is reached in households and services. Electricity consumption in industry is projected to increase gradually by 2020.

GHG emission projections by 2050 are illustrated in Fig. 17.

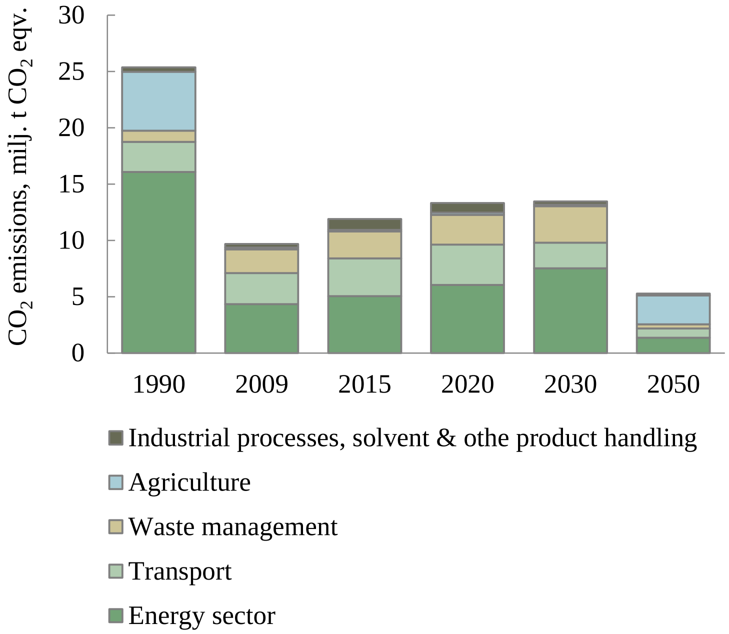

Fig. 17. Historical patterns and forecast of greenhouse gas emissions for various pathways of green energy strategy for Latvia.

Lower greenhouse gas emissions in 2020 and 2050 are explained by the transition of the energy sector to energy-efficient end-use and the use of renewable energy resources. In the period of 2013–2020 as well as up to 2050, the gradual decrease in the use of the fossil fuel will allow reaching the 20 % greenhouse gas emission level in the energy sector in comparison with 1990 (see Paper No. 13 for more details).

Conclusions

To have a well-functioning and sustainable state energy sector, each of the underlining elements should also function with maximum efficiency and each within a given moment of the time. To ensure maximum efficiency and study possible improvement, the scaling-up framework has been presented in the present research. The scaling-up framework has been applied for a case study — the state energy sector.

The scaling-up framework means that the starting point is a combined heat and power production unit and its operation, the next step of aggregation is a district heating network, followed by a municipal energy plan and finally leading to a low carbon strategy.

In the proposed framework, the author argues that the successful, innovative practices that are developed and tested on a lower level of aggregation can be then transferred to upper levels of aggregation, thus leading to a scaling-up effect of innovative practices.

The focus of the research is to present various methodologies suitable for use in various domains of scaling-up framework. The present research summarises 12 various methodologies used in the energy sector, by dividing these methodologies among the various levels of aggregation in the scaling-up framework.

Each methodology presented in the research is applied to separate sectors; nevertheless, some methodologies can also be used for other levels of the system.

The presented framework can be primarily applied to energy systems and energy sectors, but its use is not limited and can be applied to other fields of economy as well. Moreover, the presented framework can also be used for scientific research purposes as well as by policy makers.

Further, conclusions specific to the studied domains are given.

Combined Heat and Power Unit

The method of energy and exergy analysis was used to assess irreversibility at the CHP plant. Energy analysis was used to assess energy conversion efficiency. Exergy analysis was used to study exergy degradation in a system and make a quantitative assessment of energy quality changes. The results showed that the energetic efficiency of the CHP plant was 62 % and exergetic 24 %. The results of exergy analysis showed 64 % of irreversibility occurring in the boiler. This analysis revealed losses for various parts of the plant and various operation modes. This information can be further used to identify non-optimal working conditions and make improvements.

Emergy analysis was used as a composite indicator for the evaluation of the system performance. Several emergy indicators were calculated to analyse the CHP plant and to compare this plant with other systems: environmental sustainability index, emergy sustainability index, emergy yield ratio and environmental loading ratio. During the analysis, the diagram of emergy flow for the CHP plant was obtained. This diagram included all inputs, outputs and internal components of the system, as well as all flows between these components. The emergy table for the studied system was developed where all compounds of the system were linked together numerically. The results of the emergy indicators showed emergy sustainability index of 2.29, emergy yield ratio of 2.11 and environmental loading ratio of 0.92.

The correlation analysis was used to establish a correlation between the dependent variable and the analysed independent variable describing the operation of the CHP plant. In case of single factor mathematic models, the Pearson's equation was used for estimations. Regression equations were verified based upon the following indices: autocorrelation, multicolinearity and heteroscedasticity. As a result of the correlation analysis, it was obtained that within further multi-factor regression analysis the change of the specific fuel consumption of the CHP plant could be described by four independent factors: (1) the boiler efficiency; (2) the power generation efficiency, (3) the heat production efficiency and (4) the outdoor temperature. The result of the correlation analysis was further used as a basis for other methodologies.

The regression analysis was used to obtain an empirical equation that would provide a quantitative description of the change in the specific fuel consumption of the CHP plant depending on statistically important operational indices of this plant. The results showed the value of the coefficient of determination as R^2 = 99 %. The assessment of the percentage difference showed that the rate changes of specific fuel consumption from the real values were in the margin of 7.5 %. The evaluation of the adequacy of the regression equation was performed by means of the dispersion analysis by applying Fisher's criterion, where the tested values passed threshold requirements and, therefore, the obtained equation was concluded valid. The obtained equation served as a basis for the forecasting and evaluating of the specific fuel consumption of the CHP plant.

District Heating Network

The methodology of multiple-criteria decision analysis was used to compare various alternative solutions, where the development options for energy sources for Jelgava city DH supply system were analysed. Three different wood chip steam cycle cogeneration alternatives were proposed: (1) small-scale CHP plant; (2) large-scale CHP 1 plant in condensing regime; (3) large-scale CHP 2 plant in cogeneration regime. The criteria used for the analysis were energy efficiency, operational costs, investment costs, load coefficient. The results showed that high capacity CHP plants operating in the cogeneration mode represented the best scenario. According to the analysis of Jelgava city heat supply system, the operation of the CHP plant in the cogeneration mode was also better compared to the alternative of installing a small-scale CHP plant.

CHP's operation modes were modelled for the situation when heat load diminished. Four scenarios were analysed: basic scenario, where the current operation of the CHP plant continues as usual; (1) scenario, where CHP plants operated for 3000 hours a year, thus the cogeneration capacity would be used effectively; (2) scenario that included a situation, where the heat load was covered by Riga TEC 2/1 using heat storage systems and the station could operate effectively for 5000 hours per year; and (3) scenario, where natural gas was replaced by wood fuel in Riga TEC 1 and heat storage was installed. The results showed that scenario 3 allowed completely using the installed capacity of the CHP plant. Financial evaluation of the scenarios showed that scenario 3 would also have the lowest costs of electricity.

The model for the integration of intermittent renewable resources in the district heating network was developed, in particular to study the integration of wind power plant and heat pumps. The results showed that the use of heat pumps for excess electricity accumulation reduced electricity production and net export, and increased the share of renewable energy sources. Since energy production in CHP plants is partly replaced by wind power plants and a large part of the production in CHP plants is based on natural gas, the share of renewable energy sources in the total energy (heat and electricity) is larger in the system with heat pumps. With heat pumps, the share of natural gas in district heat and electricity production decreases from 63 % to 59 %.

Municipal Energy Plan

The ARIMA time series model was used to forecast the amount of heat energy at the municipality level. The results showed that it would be possible to produce around 600 GWh of heat energy from biomass during the coldest months by 2020. The comparison of regression model with ARIMA model was also performed. Both models showed that the company providing district heating at the municipally level could almost completely exclude fossil fuel use by 2020 if it set even more ambitious targets.

The indicator of the avoided greenhouse gas emissions was proposed to be used together with the ARIMA model. The scenarios for avoided CO_2 emissions in the 13-year period (from 2007 to 2020) were calculated by assuming that the industry will substitute the use of natural gas. The results showed that around 100 thousand tons of CO_2 emissions were avoided from 2007 to 2013 by introducing wood fuelled boiler houses instead of using natural gas fuelled. An almost tenfold reduction in greenhouse gas emissions will be achieved if the target of 80 % heat from wood fuel is reached by 2020. The sum of avoided emissions in the analysed period would be around 1 million tons CO_2 if 80 % of the heat were produced by wood chips.

Low Carbon Strategy

To define Latvia's national path for the transition to a low carbon strategy, the potential for biomass was modelled. Four scenarios were built to analyse the potential of biomass fuel in Latvia: base scenario; (1) scenario that assumed the utilisation of locally available forest biomass; (2) scenario that added growing of energy cultures on available agricultural lands and; (3) scenario that included the utilisation of available organic residues for biogas production. In the base scenario, natural gas dominated. Meanwhile in other scenarios biomass allows replacing natural gas already in 2015. The largest biomass potential is associated with the use of the residues from forest logging and by-products of timber processing. Total bioenergy potential in 2020 approved to be twice bigger than the current rate of biomass utilisation.

From the perspective of systemic thinking, this problem of dependence from energy import was explained through the archetype "Distraction". This archetype reflects the effect of energy sector dependence and short-term planning of the situation in the energy sector in the long term. The main idea behind this archetype is that in case a symptomatic or short-term solution is used at least once, the implementation of a fundamental or long-term solution is postponed. The example shows a short-term solution, which delays implementation of long-term solution, such as the immediate need to renovate existing DH systems in a municipality, which is done immediately without considering additional investments and a switch to RES at the same time would produce better results in the long term although might immediately cost the municipality more financial, technical resources. The analysis of statistical data showed a weak correlation between the primary energy consumption and efficiency of primary energy use. The results indicated that the reduction in primary energy consumption was not caused by a more efficient use of energy resources. Such tendencies stated that the development of energy sector went contrary to governmental statements.

The directions, objectives and principles for transition to a low carbon strategy was defined using a four-step management system, where the first step was to set by tracks and directions, the second step was to define principles with financial, environmental, climate, socio-economic and management aspects, the third step was to preform calculations taking into account learning and cost curves of the technologies and finally the selection of scenario was done based on a variety of factors. Using this proposed management system the mathematical modelling of the wood fuel share in Latvia was performed. The results showed that a gradual step-by-step increase over the next years would allow reaching 43 % of wood fuel share in energy end-use balance of Latvia.

The model for green energy strategy was based on three parallel paths: (1) the transition to energy-efficient consumption and use of RES; (2) the integration of new solutions in the energy sector and transportation system; (3) growth of the green energy supply systems based on research and demonstration. The results showed that the projected energy demand in the baseline scenario would increase heat energy consumption until 2050, while in the scenario of energy efficiency an increase was marginal and after 2016 reduction would follow. In the period of 2013–2020 as well as up to 2050, the gradual decrease in the use of fossil fuel will allow reaching 20 % greenhouse gas emission level in the energy sector in comparison with 1990. Lower greenhouse gas emissions in 2020 and 2050 are explained by the transition of the energy sector to energy-efficient end-use and the use of renewable energy resources.