RIGA TECHNICAL UNIVERSITY
Faculty of Engineering Economics and Management
Institute of International Business and Customs
Chair of International Business, Transport Economics and Logistics

Māris Balodis

Doctoral study program "Management and Economics"

Optimisation Models for Securing Energy Supply Towards Sustainable Economic Development of Latvia

Summary of the Doctoral Thesis

Field: Management Science
Sub-field: Business Administration

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DOCTORAL THESIS

PROPOSED TO RIGA TECHNICAL UNIVERSITY FOR THE PROMOTION TO THE SCIENTIFIC DEGREE OF DOCTOR OF ECONOMICS

To be granted the scientific degree of Doctor of Economics, the present Doctoral Thesis will be defended at a public session of RTU Promotion Council "RTU P-09" on 9 December 2016, at 12.00 o'clock, Riga Technical University, Faculty of Engineering Economics and Management, 6 Kalnciema Street, Room 309.

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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 Economics (Dr. oec.) is my own and does not contain any unacknowledged material from any source. I confirm that this Thesis has not been submitted to any other university for the promotion to other scientific degree.

Maris Balodis ____________________

The Doctoral Thesis has been written in Latvian. It consists of introduction, 4 chapters, conclusions and recommendations, bibliography, 8 appendices. The Thesis has been illustrated by 62 figures and 26 tables. The total volume of the Doctoral Thesis is 177 pages. The bibliography contains 130 reference sources.

The Doctoral Thesis and Summary are available at the Scientific Library of Riga Technical University, 10 Azenes Street.

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CONTENTS

GENERAL DESCRIPTION OF THE RESEARCH

Topicality of the Thesis

Economy needs considerable amount of resources for growth. The demand in energy resources depends on the development of economy, changes in its structure and the technologies employed.

Up-to-date forecasting and planning tools for the management of energy supply system are needed in order to ensure adequate and uninterrupted energy supply that complies with the requirements in respect to a secure supply system and environment. Models of various types occupy a special place among these tools. Energy system models are important instruments allowing analysing, forecasting, planning and optimally adjusting complex interactions between power engineering and environment, changes in technologies and energy consumption.

During the past decade the targets and measures in respect of energy supply have not been compatible with the actual technological capabilities, costs and price conjuncture in respect of energy resources. All these factors have had an adverse impact on the economies in the European Union. Solutions towards balanced development and reduction in the prices on energy resources are being sought, at the same time considering the factors having an impact on the environment. To strengthen the competitiveness of the energy sector without altering the previously adopted strategies for climate change mitigation is a complex task.

At present, there are a variety of opinions in respect of the use of renewable energy sources (RES) and the support structures thereto. Relevant generating sources are needed for balancing and provisioning of production resources that are hard to forecast. The EU member states are looking for solutions how to bring investment to power generation plants running on fossil fuels so that they could provide the balancing and provisioning services to power plants fuelled by RES.

Simultaneously, the energy market organisation is evolving and market area is expanding. With the establishment of new power transmission grid connections with Finland, Sweden and Poland, more electricity import and export possibilities open both for Latvia and the entire Baltic region. This also results in more volatile market prices in the region. These price fluctuations become even more pronounced along with the implementation of RES projects with changing and hard to predict outputs. This, in its turn, determines the necessity for changing the technological processes in the energy system management and power generation portfolio.

Many of these issues can be addressed employing a set of mathematical modelling instruments. Thus, energy systems models can be helpful for resolving the issues of environmental impact on the structure and costs of energy supply, the effect of expanding power market on the development of long-term capacities, optimum production capacities and the development of fuel supply infrastructure depending on price conjuncture of resources and demand. This is the reason why the total number of available and applicable models has notably increased during the recent years, and a question arises which of the models is the most appropriate for a specific purpose or situation.

Scientific literature describes and characterises models of various types. Models are classified according to their type of use, methodology, geographic area (region, state) and the specifics of the region or state concerned. There are the so-called "bottom-up" or engineering models and "top-down" or macroeconomic models. They comprise a variety of methodological groups: stochastic and deterministic models, agent and multi-agent models, fuzzy logic models and interval-valued mathematical programming models, cost-output spreadsheet models etc. As to the European Union states, hybrid modelling systems are commonly used for forecasting the demand and supply of energy. Macroeconomic energy models usually look at the economy as a whole on a national or a regional level. They include general technological descriptions without providing adequate guidance for the capabilities of technological progress.

The optimisation methods employed for long-term forecasting, analysis and designing scenarios in respect of power supply in Latvia are based on the analysis of voluminous data and a detailed evaluation of different consumption and delivery structures in the case of various scenarios. However, on several occasions the changes in the impact factors and economic situation have outrun the adjustments introduced to the evaluations. This dictates the necessity of simultaneous use of various methods and models in specific circumstances, and more often than not also the ones offering a lesser degree of detail and accuracy, yet allowing a quicker evaluation of the optimisation results of development scenarios. This is crucial in the cases when there are time constraints for taking decisions on strategic projects that have a material effect on a number of sectors in national economy or energy supply services.

The objective of the energy supply system modelling is to evaluate this energy supply system and analyse the information about the interrelationship between the key elements in the energy supply, costs and prices in particular. Literature refers to a large number of such models, including calculation methods, yet often failing to give an idea about their applicability. Due to this fact, the feasibility of some models may not always be transparent to policy makers and infrastructure investors. The real-life use of a number of models has been limited due to their inability to provide a revision of the programme structure and to update results in reasonably short time periods.

Aim of the Doctoral Thesis

The aim of the Doctoral Thesis is to develop and approbate models for energy supply, focusing on optimisation of long-term planning in power engineering and securing the sustainable development of Latvia in terms of use of energy resources. The analysis of sustainable development focuses on electricity and heat generation sectors and primary energy sources required for their operation.

Tasks of the Research

To achieve the aim of the research, the following tasks have been set:

1. To analyse the energy supply system in Latvia and its specifics, energy security and technological, economic and management aspects of energy supply.
2. To study the energy system models available globally, their applicability, modelling methods, computer software, algorithms, the manner of use for the purpose of planning and forecasting the development of energy systems, and for analysing and evaluating the efficiency of performance.
3. To develop models, their modifications and algorithms for making calculations in the situation characteristic of Latvia.
4. To collect the required statistical, regulatory framework, expert opinion and other information for implementation of the models.
5. To perform calculations using the models, by drawing up development scenarios and imitating the effect of various factors and changes in resources, capacities, etc.

Object of the Research

The object of the research is energy supply system in Latvia, comprising interrelated elements of power supply and district heating system. During the approbation process of the model developed as part of the Doctoral Thesis, the object of the research has been narrowed to a body of objects involved in district heating and cogeneration.

Subject of the Research

The subject of the research is models for energy supply analysis, planning, forecasting and optimisation as well as their applicability for evaluating the securing of energy resources over longer horizons.

Methodological Foundation of the Thesis

The theoretical and methodological foundation of the research is based on scientific papers, theoretical and practical findings in respect of modelling the development of energy supply systems offered by both foreign (Herbst, A., Kemfert, C., Schade, W., Forrester, J. W., Kremers, E. Timilsina, R. G., Wallace, S. W., Fleten, S. E., Zeng, Y., Schulz, V., Stehfest, H., Bernal-Agustín, J. L. Martinsen, D., etc.) and Latvian authors (Žīgurs A., Kuņickis, M., Gerhards, J., Sauhats, A., Junghāns, G., Linkevičs, O., etc.).

Informative Basis of the Research

The information provided by the Central Statistical Bureau of the Republic of Latvia, published and non-published information by JSC Latvenergo, *Eurostat* data, information materials by the World Energy Council, reports, publications and materials by Latvian and foreign research institutes and public authorities have been used in the research. In order to provide the legal framework, the European Union and Latvian national laws and regulations have served as information sources for the research, together with planning documents, development policy documents, etc.

The materials from scientific conferences and workshops, scientific literature available in *Web of Science, Scopus, ScienceDirect, Ebrary* as well as other electronic databases have also been used.

Research Methods

General theoretical research methods have been analysed and employed in the research, including induction and deduction, analysis and synthesis, systemic approach, along with specific methods, e.g., mathematical modelling, system dynamics, correlation regression, analysis of scenarios, strategic decision making, classification, the evaluation of balance sheets and expert evaluation, content analysis.

Scientific Novelty of the Research

The novelty of the Doctoral Thesis is as follows:

1. The models currently used globally for planning the development of power engineering and ensuring the management processes have been critically evaluated, and their limitations and possibilities of use in the Latvian situation have been identified.
2. The energy supply planning models applied in Latvia have been analysed, and their application, the obtained forecast results and their relevance to the existing situation have been compared.
3. System dynamics, optimisation and statistical models and algorithms for securing energy supply have been developed, considering the topical processes in the energy sector at national and regional levels.
4. Principles and proposals have been drawn up in respect of:
   - analysis of interaction between electricity supply and district heating and its influence on the national indicators of the efficiency and the securing of energy supply;
   - enhancement of the optimisation methods used up to now in the energy sector, by assessing the integration of RES in electricity and heat generation.
5. Moreover, as a result of regional level analysis, development scenarios for power generation capacities have been obtained for a specific conjuncture of external factors (EU legislation, price of imported resources, behaviour of companies in the neighbouring countries in a single market area).

Approbation and Practical Use of the Research Results

The results of the Doctoral Thesis have both theoretical significance and practical applicability for improving the management of the energy supply sector and the attaining of energy efficiency targets.

The research results have been reported at the international scientific conferences both in Latvia and abroad:

- *16th IEEE International Conference on Environment and Electrical Engineering*, Florence, Italy, 7–10 June 2016;
- *9th International Scientific Conference on Business and Management,* Vilnius, Lithuania, 12–13 May, 2016;
- *IEEE 5th Internationaln Conference on Power Engineeting, Energy and Electrical Drives (POWERENG)*, Riga, Latvia, 11–13 May, 2015;

- *REHVA Annual Meeting and the Conference on Advanced HVAC and Natural Gas Technologies*, Riga, Latvia, 6–9 May, 2015;
- *56th International Riga Technical University Conference "Scientific Conference on Economics and Entrepreneurship"*, Riga, Latvia, 14–16 October, 2015;
- 55th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON), 14 October, 2014.

The research results have been approbated at JSC Latvenergo drawing up long-term development programmes and strategies for medium term.

The research results have been used for developing practical proposals in respect of forecasts for electricity balance in the documents produced by the Ministry of Economics "Latvijas Enerģētikas ilgtermiņa stratēģija 2030 – konkurētspējīga enerģētika sabiedrībai" (2012) and "Enerģētikas attīstības pamatnostādnes 2014.–2020. gadam" (2014). The research data obtained by the author of the Doctoral Thesis have been used in the document "Analyses of Energy Supply Options and Security of Energy Supply in the Baltic States" (IAEA, 2007).

The results of the Doctoral Thesis have been used taking part jointly with RTU experts in the project about the optimisation of the operation of the hydroelectric power plants and combined heat and power plants run by JSC Latvenergo; as well as in the State Research Programme 5.2. "EKOSOC-LV" sub-project 5.2.1. "To investigate the competitiveness of the Latvian companies in export markets and to provide recommendations for strengthening thereof" (registration No. 02.2-09/13).

Hypothesis

Innovative application of various hybrid models in power engineering allows for a comprehensive and sufficiently accurate optimisation of the use of energy resources both in an individual spatial unit (a city) and on a regional scale with the purpose to ensure sustainable development.

Thesis Statements

1. The developed set of modelling instruments is a basis for optimal resource management in energy supply and its sustainable development, taking account the provisions of the EU legal acts in respect of efficiency, use of renewable energy sources and security of energy supply.
2. Development and implementation of an adequate model allows improving the energy supply optimisation results.

3. In order to ensure efficient and sustainable operation of energy supply companies, it is possible to create an efficient decision-making mechanism in sub-sectors by using the results obtained via modelling.

Publications

The research results of the author of the Doctoral Thesis have been presented in 25 scientific publications, including 11 internationally recognised peer-reviewed scientific publications.

Publications in scientific journals:

1. Balodis, M., Skribans, V., Ivanova, P. Development of a System Dynamics Model for Evaluation of the Impact of Integration of Renewable Energy Sources on the Operational Efficiency of Energy Supply Facilities: Theoretical Background. Ekonomika un uzņēmējdarbība. No. 18, 2016, pp. 4–12. ISSN 2256-0386. e-ISSN 2256-0394. Available at: doi:10.1515/eb-2016-0001.
2. Kuņickis, M., Balodis, M., Sarma, U., Cers, A., Linkevics, O. Efficient Use of Cogeneration and Fuel Diversification. Latvian Journal of Physics and Technical Sciences, No. 6, Vol. 52, 2015, pp. 38–47. ISSN 0868-8257.
3. Balodis, M., Gavars, V., Andersons, J. Analytical Treatment of Forecasts of Electric Energy Consumption in Latvia. Latvian Journal of Physics and Technical Sciences, Institute of Physical Energetics, Riga, No. 3, Vol. 51, 2014, pp. 3–14. ISSN 0868-8257.

Publications in peer-reviewed scientific proceedings:

4. Skribans, V., Balodis, M. Development of the Latvian Energy Sector Competitiveness System Dynamic Model. 9th International Scientific Conference on Business and Management: Proceedings, Vilnius, Lithuania, 12–13 May, 2016. Vilnius: VGTU Press, pp. 1–10. eISSN 2029-929X, eISBN 978-609-457-921-9.
5. Ivanova, P., Sauhats, A., Linkevics, O., Balodis, M. Combined Heat and Power Plants Towards Efficient and Flexible Operation. 16 IEEE International Conference on Environment and Electrical Engineering, Florence, Italy, 7–10 June, 2016.
6. Kuņickis, M., Balodis, M., Linkevičs, O., Ivanova, P. Flexibility Options of Riga CHP-2 Plant Operation under Conditions of Open Electricity Market. IEEE 5th International Conference on Power Engineering, Energy and Electrical Drives (POWERENG),

Latvia, Riga, 11–13 May 2015. Riga: Riga Technical University, 2015, pp. 548–553 ISBN 978-1-4799-9978-1. Available at: doi:10.1109/PowerEng.2015.7266375

7. Žīgurs, Ā., Kuņickis, M., Linkevičs, O., Stuklis, I., Ivanova, P., Balodis, M. Evaluation of Exhaust Gas Condensing Economizer Installation at Riga CHP Plants. Proceedings of REHVA Annual Conference 2015, Latvia, Riga, 6–9 May 2015. Riga: RTU Press, 2015, pp. 474–154 ISBN 978-9934-10-685-9. e-ISBN 978-9934-10-717-7. Available at: doi:10.7250/rehvaconf.2015.021
8. Sauhats, A., Linkevičs, O., Varfolomejeva, R., Žalostība, D., Kuņickis, M., Balodis, M. Towards Smart Control and Optimization of the Small-Scale Power System. IEEE 5th International Conference on Power Engineering, Energy and Electrical Drives: Proceedings, Latvia, Riga, 11–13 May 2015. Riga: RTU, 2015, pp. 440–446. ISBN 978-1-4799-9978-1.
9. Sauhats, A., Varfolomejeva, R., Linkevičs, O., Petričenko, R., Kuņickis, M., Balodis, M. Analysis and Prediction of Electricity Consumption Using Smart Meter Data. IEEE 5th International Conference on Power Engineering, Energy and Electrical Drives (POWERENG): Proceedings, Latvia, Riga, 11–13 May 2015. Riga: Riga Technical University, 2015, pp. 17–22 ISBN 978-1-4673-7203-9. e-ISBN 978-1-4799-9978-1. e-ISSN 2155-5532. Available at: doi:10.1109/PowerEng.2015.7266290
10. Balodis, M., Ekmanis, J., Žīgurs, Ā., Kuņickis, M., Zeltiņš, N., Gavars, V. The Latvian Electricity Supply Trilemma. The 12th WEC Central & Eastern Europe Regional Energy Forum (FOREN 2014) "Tomorrow's Energy: From Vision to Reality", Romania, Bucharest, 22–26 June 2014. Bucharest: World Energy Council (WEC), Romanian National Committee, 2014, pp. 1–8.
11. Linkevičs, O., Mahņitko, A., Mjadjuta, K., Balodis, M. Modelling of Wind, Hydroelectric and Thermal Power Plant Coordinated Dispatch in Latvian Power System. 55th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON): Proceedings, Latvia, Riga, 14 October 2014. Riga: RTU Press, 2014, pp. 167–171 ISBN 978-1-4799-7460-3. e-ISBN 978-1-4799-7462-7. Available at: doi:10.1109/RTUCON.2014.6998218

Other scientific publications:

1. Balodis M., Krickis O., Ivanova P. N-Ergie siltuma akumulācijas realizācija Nirnbergas centralizētajā siltumapgādē. Enerģija un Pasaule, No. 3 (98), 2016, pp. 40–44.

2. Balodis, M., Linkevičs, O., Ivanova, P., Gavars, V. Latvijas primāro energoresursu patēriņš: vēsturiskās izmaiņas un prognozes. Enerģija un Pasaule, No. 5, 2015, pp. 15–19, ISSN 1407-5911.
3. Kuņickis, M., Balodis, M., Ķiene, S. ENTSO-E jaunie tīkla kodeksi un jaunas prasības ģeneratoriem. Enerģija un Pasaule, No. 3 (92), 2015, pp. 36–39.
4. Balodis, M., Počs, R., Kuņickis, M. Elektroapgādes attīstības optimizācija ilgtspējīgai valsts ekonomiskai attīstībai. Enerģija un Pasaule, 2015, No. 5, pp. 30–35, ISSN 1407-5911.
5. Linkevičs, O., Balodis, M., Ivanova, P. Stokholmas siltumapgādes sistēmas attīstības tendences. Enerģija un Pasaule, No. 3, 2014, pp. 52–61, ISSN 1407-5911.
6. Kuņickis, M., Balodis, M., Linkevičs, O., Stuklis, I. ES enerģētikas politikas krustceļš. Enerģija un Pasaule, No. 3, 2014, pp. 19–23, ISSN 1407-5911.
7. Balodis, M., Stuklis, I., Vesperis, E. Eiropas Parlamenta un Padomes energoefektivitātes direktīvas 2012/27/ES ieviešana. Enerģija un Pasaule, No. 5, 2014, pp. 10–13, ISSN 1407-5911.
8. Kuņickis, M., Balodis, M. AER – energoapgādes ieguvumi un problēmas. Enerģija un Pasaule, No. 5, 2013, pp. 32–36, ISSN 1407-5911.
9. Balodis, M., Vesperis, E. Elektroenerģētika topošajā Eiropas Savienības Energoefektivitātes direktīvā. Enerģija un Pasaule, No. 6, 2011, pp. 44–48, ISSN 1407-5911.
10. Balodis M., Gavars V., Linkevičs O. Elektrības patēriņš strauji pieaug. Enerģija & Pasaule, No. 4 (45), Riga, 2007, pp. 54–56.
11. Balodis M., Gavars V., Linkevičs O. ES Direktīva par elektroenerģijas piegādes drošumu un investīcijām tā nodrošināšanai. Enerģija & Pasaule No. 1 (36), Riga, 2006, pp. 16–18.
12. Linkevičs O., Klāvs G., Gavars V., Balodis M., Andersons J. Baltijas valstu energoresursu apgāde līdz 2025. gadam. Enerģija & Pasaule No. 4 (33), Riga, 2005, pp. 32–35.
13. Balodis M,, Gavars V. Latvenergo energosistēma nākošajos desmit gados. Enerģētika & Sabiedrība, No. 25, Riga, 2003, pp. 6–8.
14. Gavars V., Andersons J., Balodis M. Latvijas elektroenerģētika Eiropas skatījumā. Enerģētika & Sabiedrība No. 25, 2003, pp. 42–44.

Submitted for publishing:

1. Zeltinš, N., Kuņickis, M., Balodis, M., Sarma, U., Linkevičs, O. Latvian Energy Trilemma Index in the Light of Contradiction between the Energy Efficiency and Renewable Energy Targets. 23rd World Energy Council "Embracing New Frontiers", Istanbul, Turkey, 9–13 October 2016.

Awards and Excellence of Scientific Research

1. Certificate (No. BM/16137) for participation at the Plenary Meeting of 9th International Scientific Conference "Business and Management'2016" with paper "Development of the Latvian Energy Sector Competitiveness System Dynamic Model", Vilnius, Lithuania, 12–13 May 2016.

Scope and Structure of the Doctoral Thesis

The Doctoral Thesis is an independent original scientific research project carried out and developed in the Latvian language. The total volume of the Thesis is 150 pages, excluding appendices.

The Thesis consists of introduction, four chapters, conclusions and recommendations, list of references and 8 appendices. The content of the research is illustrated by 67 figures and 26 tables.

The content of the Doctoral Thesis is as follows:

Chapter 1 provides the description of the energy supply system in Latvia, considering the consumption breakdown of primary energy sources, infrastructure for resource delivery, topical changes in the regional power market and aspects of district heating system.

Chapter 2 deals with the theoretical analysis of optimisation methods and models, as well as evaluates the strengths and weaknesses of the employed optimisation models, considering a wide range of the issues and tasks to be addressed. The evaluation is performed taking into account the results of content analysis. The possibilities for further enhancement of the models have been suggested.

Chapter 3 demonstrates an algorithm for evaluating the efficiency of energy supply and a relevant hybrid model with several sub-blocks, based on the proposals formulated in the analysis and using the econometric and system dynamics methods.

Chapter 4 is dedicated to the approbation of the developed hybrid model; demand forecasts have been drawn up; the effects of complex factors on the overall efficiency of energy supply system, electricity supply balance sheet and the gains or losses for final consumers have also been analysed. The diversification of fuels used for district heating has been assessed, together with its effect on the use of cogeneration and the effectiveness of production.

The results of energy models for long-term planning that are put in practice in Latvia have been analysed and compared.

KEY SCIENTIFIC FINDINGS

1. DESCRIPTION OF THE ENERGY SUPPLY SYSTEM IN LATVIA

Chapter One: 28 pages, 18 figures and 14 tables.

The author has performed the analysis of the consumption structure of primary energy sources in Latvia. The availability of primary sources and their price have a significant effect on final energy consumption. The author has compiled historical primary energy consumption data, making use of the information provided by the Central Statistical Bureau and other entities. Figure 1 demonstrates a detailed breakdown of the consumption of primary energy sources. The consumption in Latvia has been compared with that of other countries.

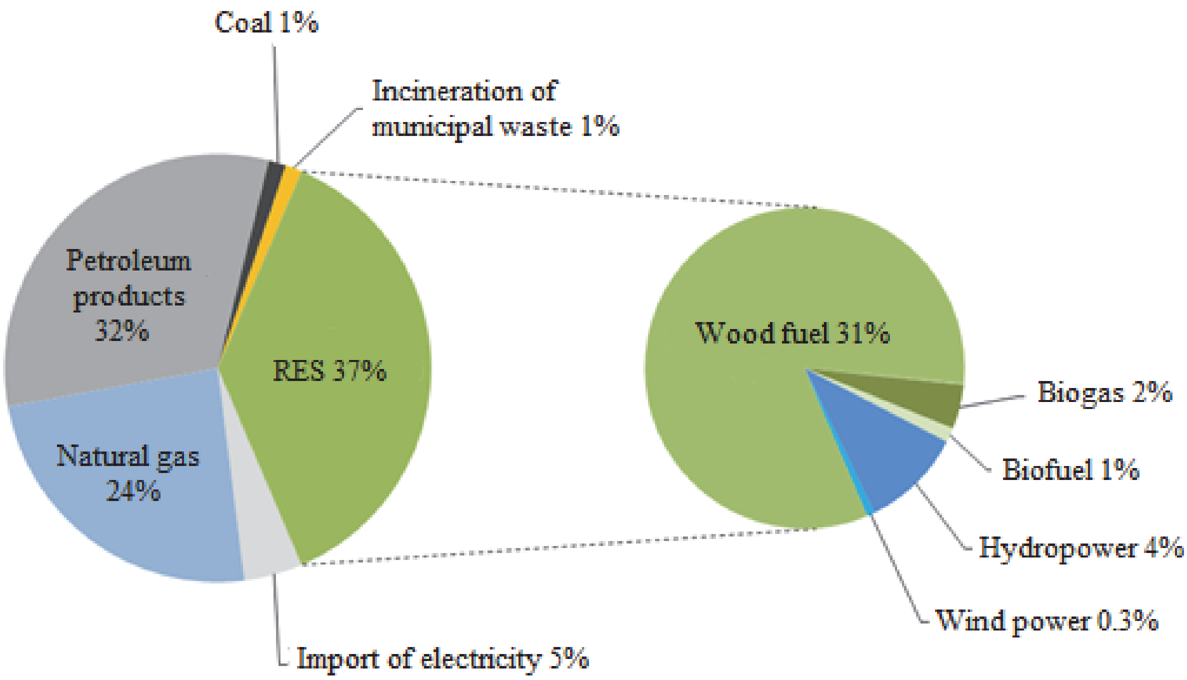


Fig. 1. Consumption of primary energy sources in Latvia in 2014 [1].

Energy consumption is materially affected by the transformation sector – its technological advancement and efficiency when transforming primary energy sources into a form that is usable by the end consumers.

RES most commonly are used for decentralised heating for family houses and small-size objects. High proportion of natural gas for power generation can be explained by high combustion temperature of this fuel, allowing reaching a high efficiency factor in Carnot cycle and generating electricity that is competitive in global markets.

In Latvia, the consumption of primary energy sources has remained virtually unchanged during the past decade: 188.7 PJ in 2004 and 188.1 PJ in 2014.

Most of heat energy (58 %) is obtained from RES (Fig. 2), while the remaining part is generated from the fossil energy source having the least hazardous emissions – natural gas.

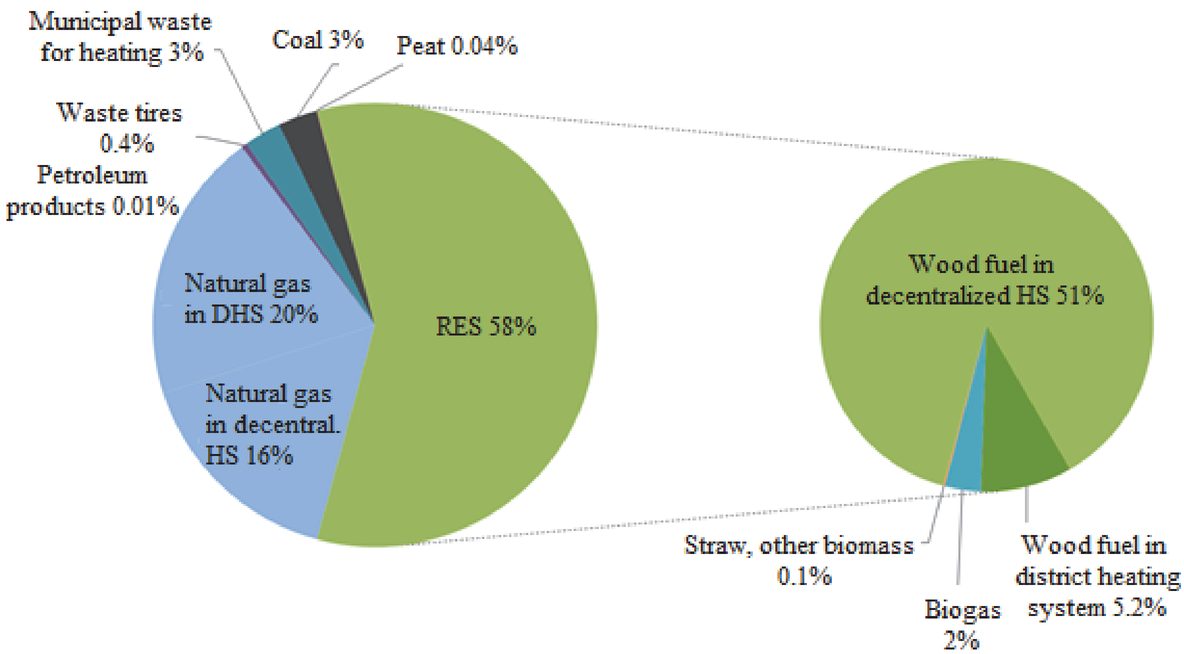


Fig. 2. Breakdown of the consumption of energy sources in 2014 in final consumption of heat energy 86.5 PJ (24.0 TWh) [1].

Heat in Latvia is supplied through district heating (CSS) (25 %) and decentralised heating (75 %), including local and individual heating. Local heating plants (SC) and boiler houses (KM) deliver heat to approximately 5 % of users. In 2014, in Latvia there were 311 boiler houses in operation (total heat output 1.54 TWh) and 134 cogeneration plants (total heat output 5.05 TWh). Out of this, in 2014 2.24 TWh heat energy was generated by JSC Latvenergo plants. As to district heating in Riga, in 2014 the aggregated output by the major plants was 2596 MWth. JSC Rīgas siltums in the financial year 2013/2014 delivered 2.7 TWH or 76 % of the heat energy necessary for Riga. Figure 3 demonstrates the dynamics of heat output volumes by Riga CHP-1 and Riga CHP-2.

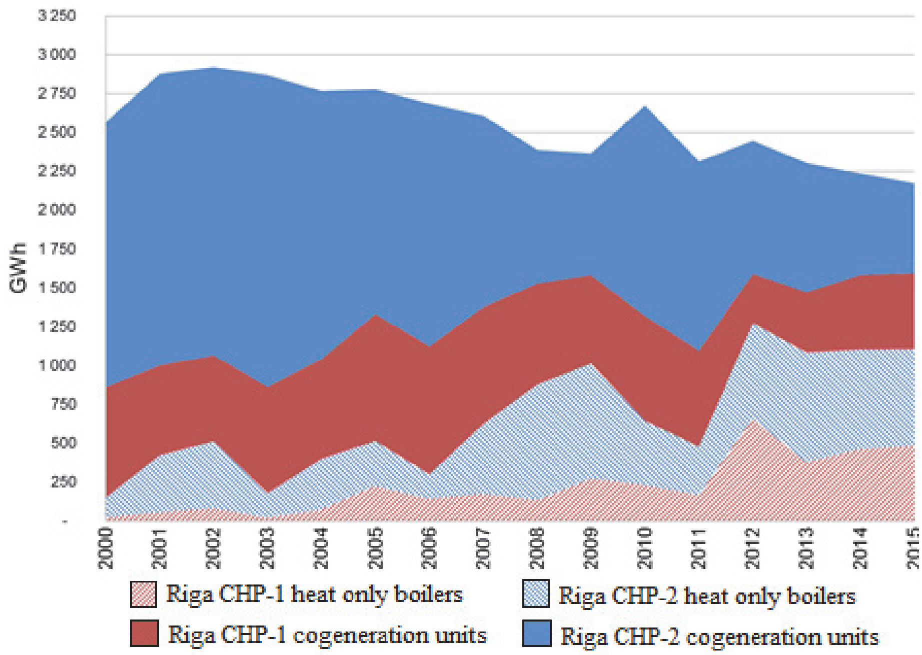


Fig. 3. Heat generation in Riga CHP (by the author; based on [2]).

One can conclude from Fig. 3 that Riga CHP is able to flexibly shift between technological processes: heat can be generated either in a cogeneration cycle or in boilers depending on external factors (price of natural gas, outdoor temperature, option to generate power in a cogeneration mode owing to the market prices of electricity, etc.).

In Latvia, the major part of local final consumption of electricity is produced from renewable energy sources (Fig. 4). In 2014, the share of fossil sources in final consumption of electricity was 33 % (2.18 TWh).

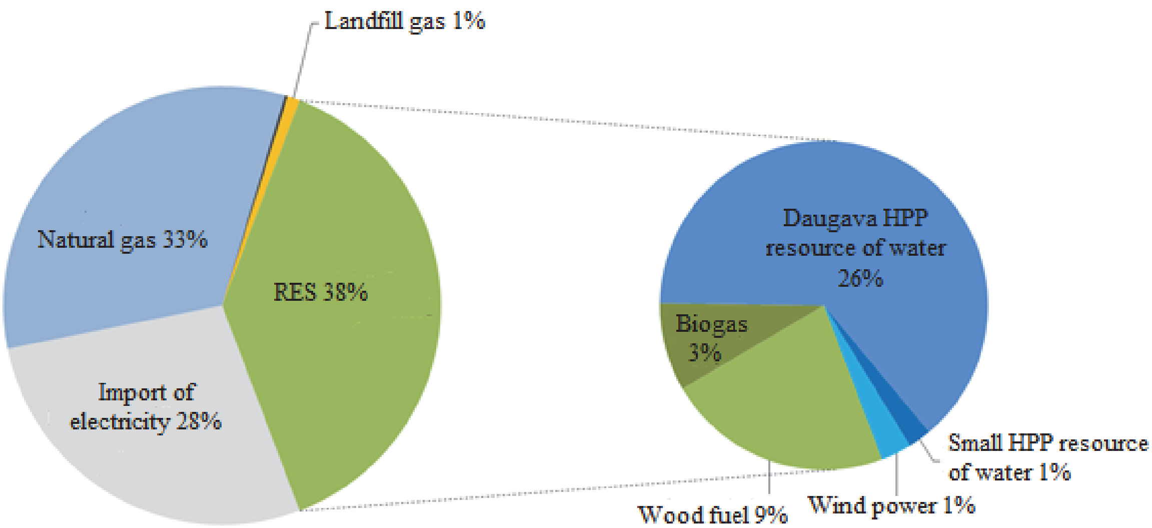


Fig. 4. Breakdown of the consumption of energy sources in 2014 in final consumption of electricity (6.58 TWh) [1].

Industry as well as other sectors of economy are major consumers of energy sources. The consumption of natural gas in industry and construction is 11 %. Transport sector consumes 75 % of the imported petroleum products. To reduce the environmental pollution (especially in cities) and decrease or sometimes even replace the vehicles driven by internal combustion engines in the future, the use of electric vehicles will be promoted in Latvia under "Electromobility Development Plan 2014–2016".

In 2014, 390 power plants were operated in Latvia to ensure the supply of electricity. The complex of JSC Latvenergo power plants was the major contributor of electricity (see Fig. 5).

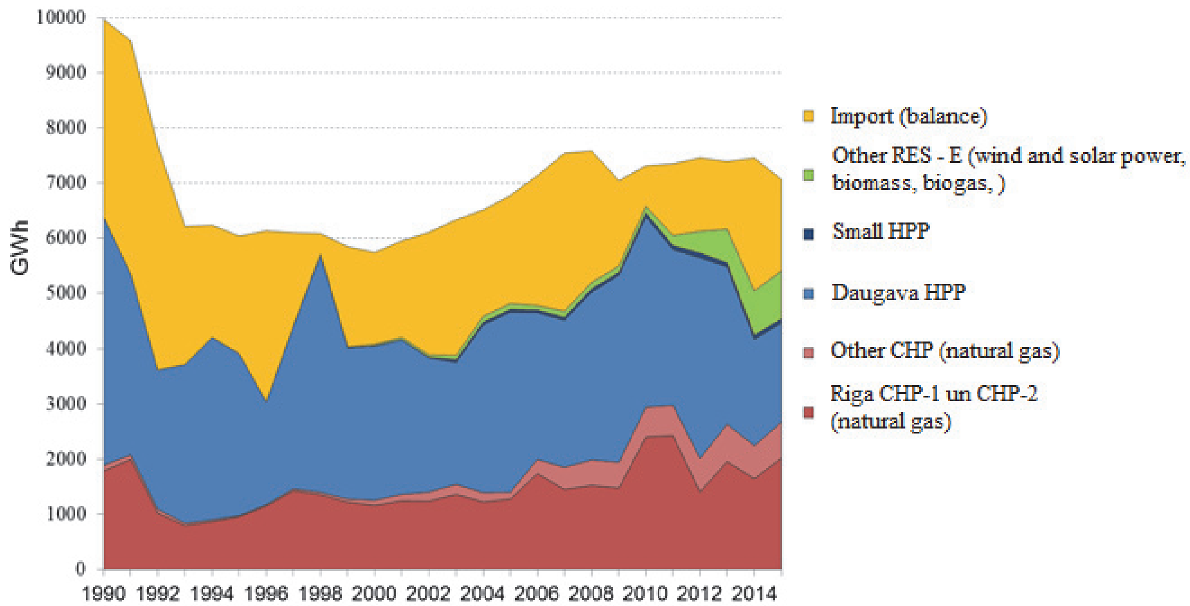


Fig. 5. Historical demand and generation of electric power in Latvia [20], [21].

The cascade of hydroelectric power plants on the Daugava River generates the highest electric power output volumes, which, though, are subject to fluctuations depending on the water flow. The hydroelectric power plants on the Daugava River mainly ensure power generation during the peak hours. Their water basins are of capacities allowing adjustments within one week. The available capacities of cogeneration plants for power generation depend on the demanded volumes of heat. The rest of the demand is met by the small power plants fuelled by RES, cogeneration plants in a condensing mode, as well as by the imported electricity. Table 1 demonstrates power generation in Latvia.

Table 1.

Provision of Electricity Supply in Latvia in 2014 [20], [21]

Power plants	Rated capacity, MW	Available capacity, MW	Electricity generated, GWh
CHPs in Riga	806	640	2335
Other CHPs	120	110	594
Hydroelectric power plants on the Daugava	1570	200	2809
Other power plants fuelled by renewable energy sources	75	40	243

The eight leading power plants in Latvia generated altogether 3.7 TWh or 74 % of domestically generated electricity in 2014. Power plants in Latvia with rated capacity under 4 MW generated altogether 1.28 TWh or 26 % of domestically generated electricity in 2014. They sell electricity in accordance with the Cabinet Regulation No.262 *Regulations Regarding the Production of Electricity Using Renewable Energy Resources and the Procedures for the Determination of the Price* as of 16 March 2010.

Electrical power engineering has a negligible environmental impact in Latvia. About 80 % of required electricity in Latvia is generated from renewable energy sources and in advanced cogeneration power plants using the combined gas-steam cycle (CCGT).

The aggregate annual electricity consumption in the Baltic States (Estonia, Latvia, Lithuania) is about 24 TWh. The peak of electricity output in the Baltic States is about 4600 MW in winter and about 2800 on average. The aggregate annual electricity consumption in Scandinavia is about 400 TWh, which is 16 times higher than in the Baltics [3]. Aggregate rated capacity of the power plants in the Baltic States is about 9300 MW. Majority (about 4000 MW) is contributed by natural gas-fuelled power plants (mainly in Lithuania), about 2000 MW is contributed by oil shale-fuelled power plants in Estonia, and about 1700 MW is contributed by hydroelectric power plants (mainly in Latvia).

In 2014, the electricity foreign trade volume in the Baltic region was 7 TWh, which was close to 30 % of aggregate consumption in the Baltic States. The trading volumes with Scandinavia and Russia were equal in size that year.

The author of the Doctoral Thesis has performed a quantitative as well as qualitative analysis in respect of power generation costs. Production costs and the costs of energy resources are the key parameters determining whether one or another type of energy generating technologies will be selected; likewise, they determine the methods of delivery and volumes consumed. As a rule, the production costs of energy resources and prices are also the key criteria in various types of models when performing optimisation etc. calculations and substantiating the choice of the development direction for various energy supply systems.

The comparison of production costs for various technologies is based on the 2014 and 2015 data [4]. These data have been compared with average prices on the NordPool market starting from January 2015 [5]. The comparison is presented in Fig. 6. When analysing the production costs of electricity, average cost price over the lifetime of the plant has been used. The cost per energy unit in long range has been calculated using this method, based on the assumptions of average adjusted impact factors (taxes, fuel price, price of CO_2 quotas, regulatory enactments) and applying various operation parameters (capacity utilisation levels, etc.) in the analysis.

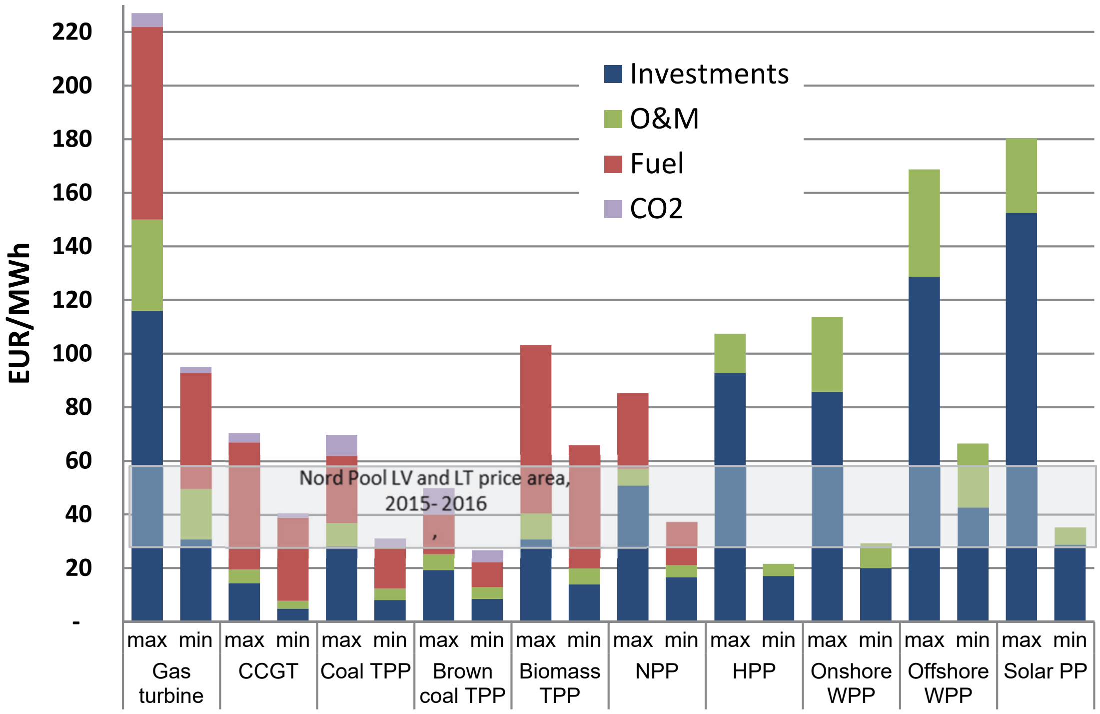


Fig. 6. Production costs for various technologies (optimum load) [4], [5].

Based on the cost prices calculated for various technologies, a chart has been created, which describes the competitive power of various technologies (Fig. 7).

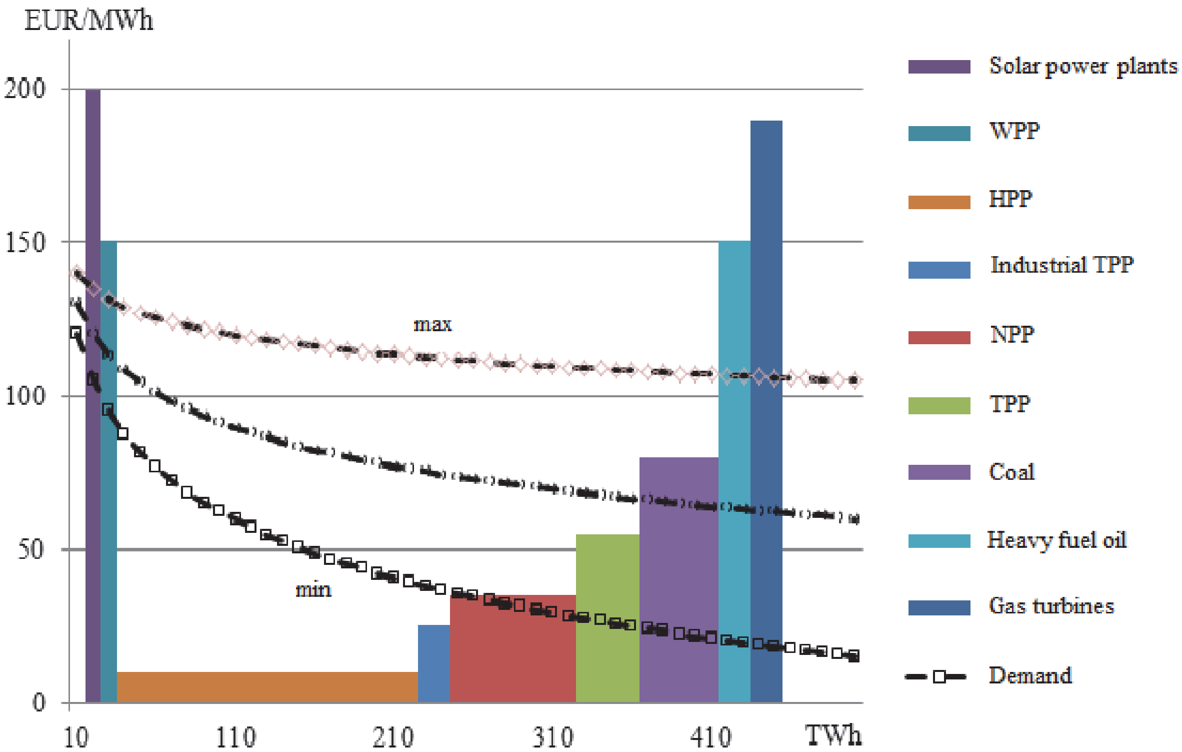


Fig. 7. Competitive power of the production technologies in the region (by the author).

Figure 7 suggests that technologies having lower production costs are subject to a higher capacity utilisation level and win a bigger market share. When the demand in electricity is low, power plants having high production costs utilise their capacities at very low levels. RES technologies, such as wind and solar power plants, occupy a special niche in the market, because more often than not they enjoy mandatory procurement (irrespective of their competitiveness).

Starting with 2012, the generation in a cogeneration mode has dropped, while the use of water boilers is increasing (Fig. 8). This is largely due to lower electricity prices on Nord Pool, as well as the increasing prices of natural gas during the reporting period (a threefold increase compared to 2004). Reduced natural gas prices would result in higher capacity utilisation rates at Riga CHP-1 and CHP-2.

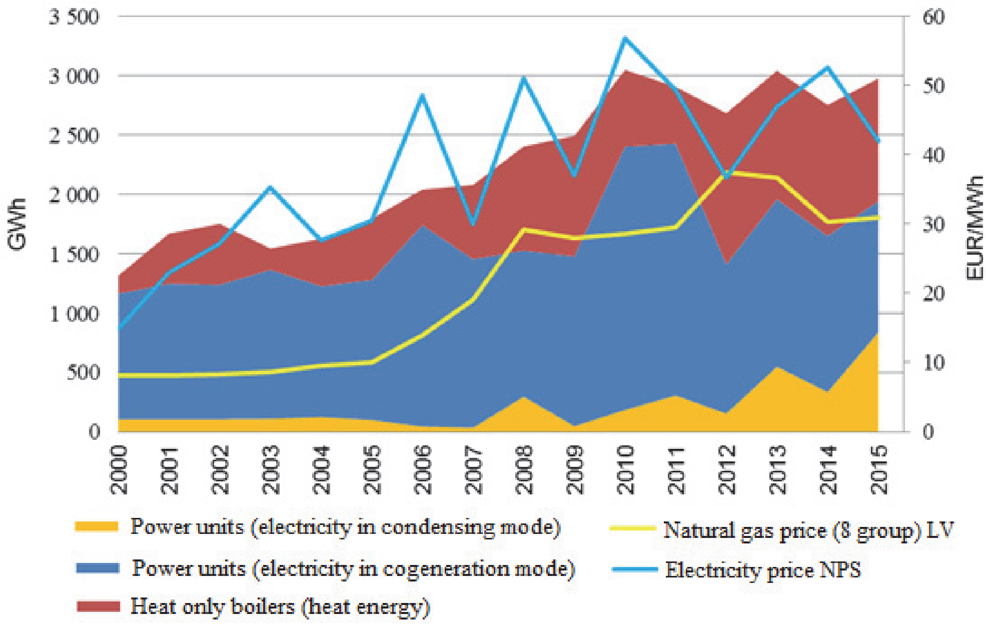


Fig. 8. Power generation and prices of energy sources (by the author; based on [2] and [5]).

There is a close correlation between the cost price of energy generating technologies and the market price of electricity and heat. Thus, the fall of electricity wholesale prices was due to cheaper electricity imports from Scandinavia and the operation of Riga CHP in a cogeneration mode. In Latvia, it used to be Riga CHP-2 that determined the price, because it happened to be the bid with the highest price in the Latvian and Lithuanian price area that was executed. Had these capacities not been available, the price in this area would have been significantly higher (Fig. 9).

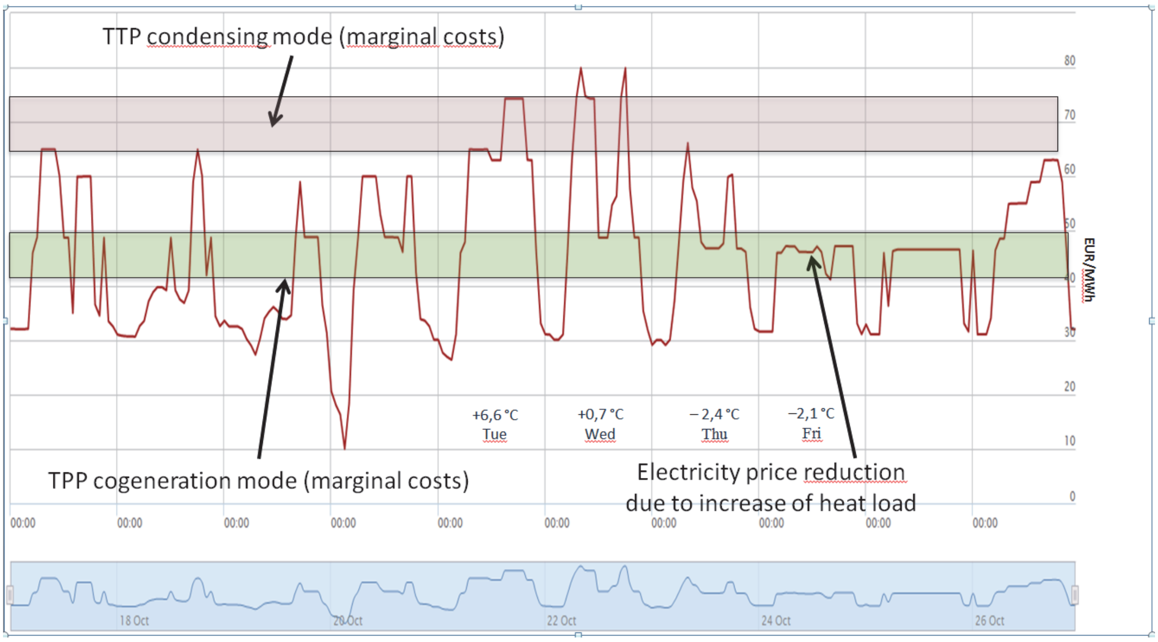


Fig. 9. The effect of the cogeneration plant (Riga CHP-2) on the market price (by the author according to [5]).

The correlation between the major cost item – the price of fossil fuel – and the market price of generated electricity has been provided in Fig. 10. With the drop of the prices for these fuels after 2013, the prices of electricity on the Nordpool Spot market went down correspondingly.

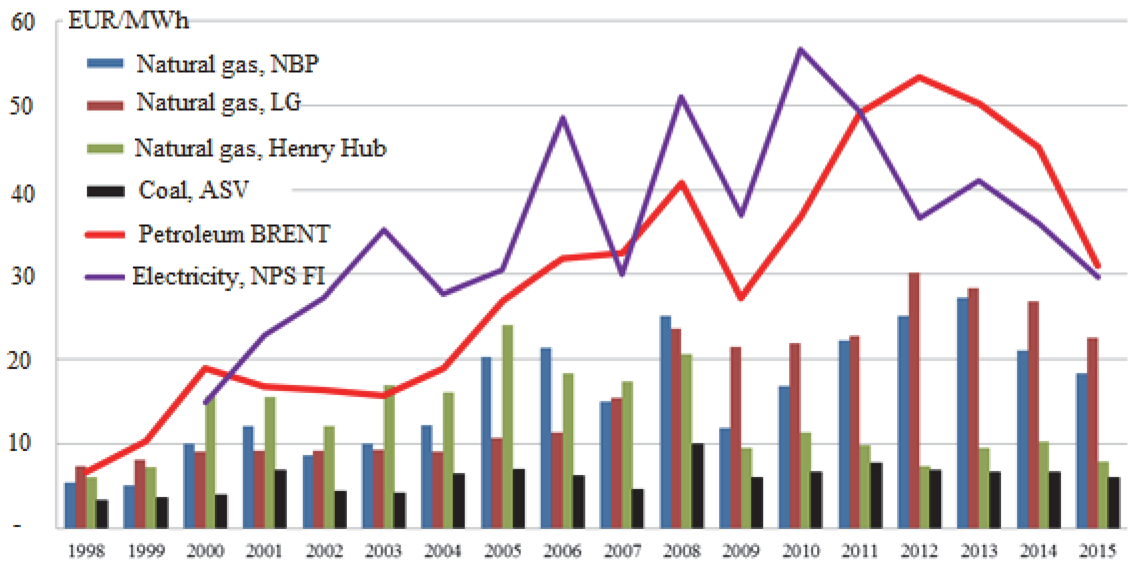


Fig. 10. Historical changes in the prices of energy resources and electricity (by the author; based on [5], [6]).

Initially, market mechanisms were introduced in a situation of redundant rated capacities. From the aspect of resource economy, this allows running the plants having the highest efficiency. Market mechanism ensures that demand is met at the lowest short-term variable cost. However, the market price fails to reflect production costs in the long term: as a result, investments in new capacities fuelled by fossil sources are not encouraged. The introduction of support to RES power plants (such as mandatory procurement) significantly shrinks the market share for competing power plants. Electricity supply optimisation models should be able to operate under such restrictions. These models should also take into consideration the sectors discussed above and their technical, technological, economic, financial, environmental, management, organisational etc. commitments.

2. ENERGY SYSTEM MODELS

Chapter Two: 42 pages, 11 figures and 8 tables.

The models of energy systems are necessary in order to address a wide range of issues related to optimal utilisation of resources, demand in resources, deliveries, prices, optimisation of deliveries (especially in a situation when resources are in short supply); models are handy for market analysis at the present moment and for the future, the interaction between the market players etc.

The first energy system models (including optimisation models) were created back in the 1970s, when, in the wake of oil crisis, analysts started considering the possibilities for a more efficient use of oil and ultimate energy. In the beginning, energy systems were described in a rather generalised manner, and mainly linear models were used. With the advance of computing technologies, more complex optimisation methods were put into use (non-linear programming methods and algorithms etc.). When dynamic models appeared, it became possible to perform discreet calculations year by year, instead of approaching the entire time series as one period. The application of dynamic programming for optimisation process allowed attaining optimal solutions and machine time savings (which is no longer a big issue nowadays).

As the modelling for achieving balance between the demand and supply includes all critical correlations in the energy system, the approach of balance between the energy resources and their consumption is among the structures commonly employed for the analysis of energy systems. The energy balance sheet should reflect all activities across the energy systems throughout the entire supply chain, taking into account the technological features of the operations. Such an approach enables including the present as well as any future technologies in the analysis and facilitates the analysis of the effect of alternative solutions on the economy, resources and environment. Several models have been created for broad-based general application. Many of the existing models have been expanded and complemented with new functionalities, e.g., the analysis of environmental issues, the interaction between energy and environment, risk analysis, etc.

The advances in computing methodology and resources, as well as the achievements of the complex multi-sectoral methods for studying ecology and natural resources combined with a progress of more specialised statistical methods have enabled scientists to employ agent-based modelling on a broader scale, especially in respect of decision makers and policy makers [7], [8]. Multi-agent modelling is a simulation approach that takes into account the individual features of the market, e.g., strategic behaviour, asymmetric information and other non-economic effects [9]. One of the main constraints for further developing and employing of multi-agent models is the huge demand for additional empirical data to be able to model the behaviour of a variety of agents [7].

The use of models allows solving specified mathematical problems through a specified target function and a set of parameters/limitations. These could be solved using a variety of methods of different degree of complexity depending on the possibility to solve the problem with more complex or less complex target functions and limitations (linear/non-linear, deterministic/stochastic etc. models) [10].

Due to a large variety of energy system models, they have been classified. Literature [11] refers to six features, according to which energy models are classified: 1) the “top-down” or “bottom-up” modelling approach; 2) time period; 3) sectoral coverage; 4) optimisation or simulation approach; 5) data aggregation level; 6) geographical coverage, trade.

The division between the so-called “top-down” and “bottom-up” models is the most important one. The traditional “top-down” approach is macroeconomic in its nature and relies on the price and market influence, whereas the “bottom-up” models are focused on the technological and economic parameters of the energy sector. The “top-down” models have a major advantage, namely, they take into account the feedback between the energy system and the socio-economic system and include the correlations with the social welfare level, employment, economic growth, etc. This endogenous evaluation of economic and social effects raises general awareness of the influence of energy policies on the national or regional economy. On the other hand, the top-down models lack technological details, and the information they provide is rather generalised. Due to this fact, they are not able to provide adequate guidance in respect of technological progress, constraints to energy efficiency or some customised policies with regard to specific technologies or sectors. This is particularly true over longer horizons, when one can anticipate sweeping changes in technologies or changes in saturation and structural changes of internal sectors.

The current trend in the modelling of energy systems is moving towards hybrid energy system models, combining at least one macroeconomic model with at least one set of "bottom-up" models for each ultimate energy sector and transformation sector. As mentioned in [12], [13], a high quality hybrid model system should be a combination of no less than three properties: the accuracy of technologies, the realism of microeconomics and the comprehensiveness of macroeconomics.

In power engineering, the primary task for production planning is to find such combination of generation equipment that is able to ensure the reliable and cost-efficient delivery of electricity. In the planning process, more often than not artificial limitations are added (e.g., the restriction to develop capacities of nuclear power plants). With such limitations or forced activation it is possible to model various development scenarios and even political set-ups. The main variables are the forecasts of demand, the availability (or limitations) of different types of energy sources, the description of technologies, costs of different types.

To facilitate the decision-making process, the expert systems and decision support instruments should be operated by employing scientifically justified modelling tools. The main topics in relation to the development of energy supply and planning of lower costs in generation are:

- expansion and security of generation systems,
- optimal use of the system,
- timing in respect of launching new equipment into operation and removing the old equipment,
- the effect of independent producers and purchased energy on the development of the generation system,
- the use of non-traditional sources and cogeneration for power generation.

Figure 11 provides a classical algorithm for evaluating the optimisation of capacity increase.

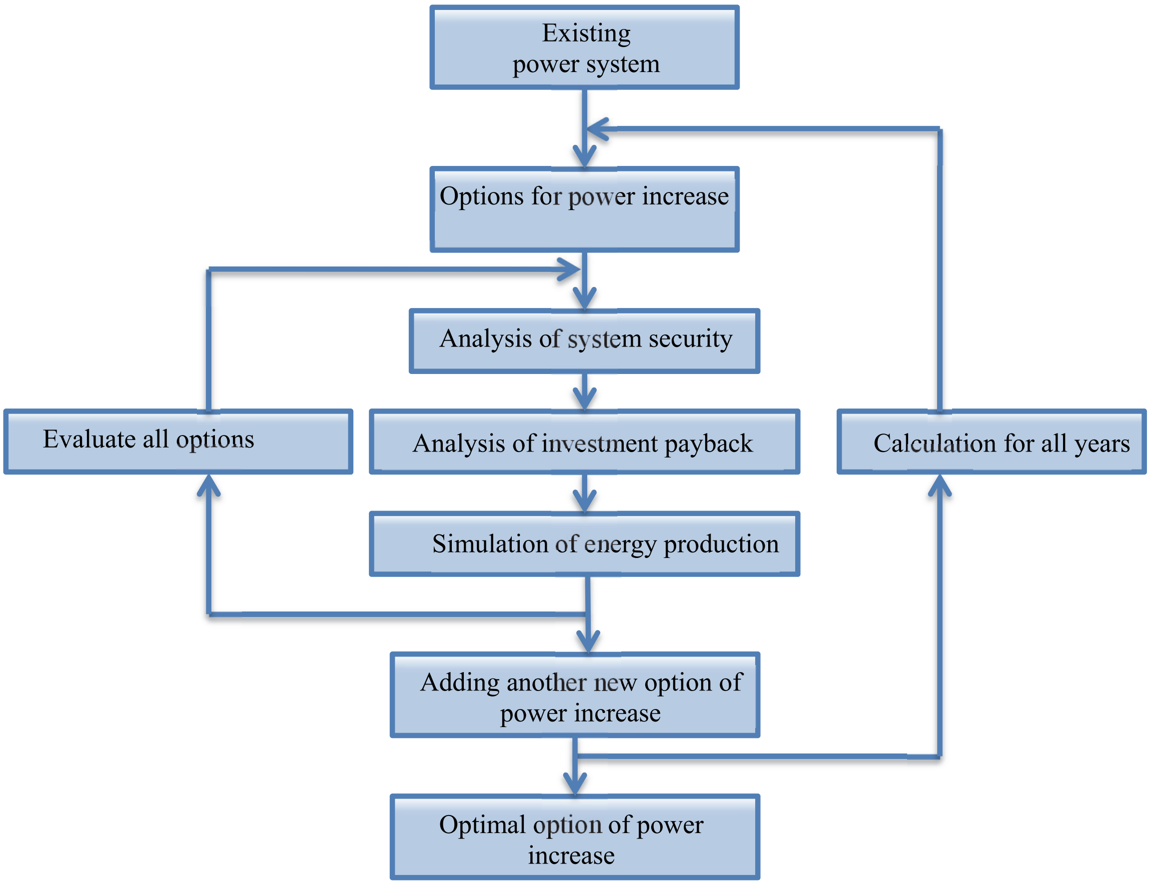


Fig. 11. Classical algorithm for evaluating the optimisation of capacity increase (by the author).

The need for forecasting the demand, planning of new generations, optimisation of the operations in the existing objects are the factors in energy supply that determine modelling across the entire system. Depending on the complexity and objective of the problem to be solved, different mathematical methods are applied.

The optimisation modelling is often based on a number of mathematical equations that represent the interaction between the system components, processes and factors. For most traditional methods, modelling parameters and coefficients are usually defined as deterministic (precise). However, in real-life many parameters and coefficients of energy supply systems as well as the coherence between the parameters may be uncertain, with several measurements and layers. Most recently, interval, stochastic, fuzzy sets as well as hybrids thereof have been the most frequently used approaches for modelling optimisation under uncertainties [14]. Stochastic models take into consideration the fact that it is impossible to accurately predict the future, because some elements (for example, non-scheduled downtime of a power-plant or deviations in the output of renewable energy sources from the projected volumes) are out of control and cannot be fully forecast due to their very nature. The stochastic modelling approach, as a rule, envisages two steps: first, optimisation is carried out in order to ensure strategies for any further possible situations in the system; and the next step is to adjust this strategy for the specified scenario (decisions/actions in each time period).

Literature [14] mentions several examples of developed optimisation models across a number of countries that have been used for solving different optimisation problems for energy systems. These models include: MILP (Mixed Integer Linear Programming) model, employed for determining the optimum combination of energy sources from the economic perspective; MODEST model, developed on the basis of linear programming and designated for minimising the investment and operational costs of energy demand and supply; BESOM (Brookhaven Energy System Optimization Model) for determining the optimum combination of energy resources, technologies and investment according to the system minimal cost principle; step-by-step optimisation model TESOM (Time-stepped Energy System Optimization Model), offered as a support instrument for modelling of energy management optimisation; MARKAL (Market Allocation Model), a technology-oriented model for the analysis of energy supply; MENSA (Multiple Energy System of Australia) model, developed for determining the optimum combination of demand-supply technologies, the reduction of costs being set forth as a condition; EFOM (Energy Flow Optimization Model), broadly employed across Europe for the purposes of energy supply planning; LEAP (Long-range Energy Alternatives Planning System) model; NEMS (National Energy Modelling System) and Energy 2020, developed for the evaluation of the economic and environment effects of energy generation; as well as other models.

Some very specific models have been developed for in-depth solution of some individual problems. For example, a dynamic simulation-optimisation model has been created to support the management of autonomous renewable energy system with hydrogen storage (RESHS) [15].

The author has performed the comparison of the models according to the modelling approach, i.e., the comparison of “bottom-up” models, the comparison of hybrid models and the comparison of energy demand forecasting models (see Table 2).

Table 2

Comparison of Models by Modelling Approach (by the author; based on [7])

Criterion	**Bottom-up, optimisation**	**Bottom-up, accounting**	**Top-down, econometric**	**Hybrid**
Geographic coverage	From local to global, mainly national	National, can be regional as well	National	National or global
Scope of operation	Energy system, environment, trade	Energy system and environment	Energy system and environment	Energy system, environment and energy trade
Distribution level	High	High	Various	High
Technological scope	Broad	Broad, usually pre-defined	Varying, usually limited	Broad, usually pre-defined
Data requirements	Extensive	Extensive, yet able to work also with limited data amount.	High	High to extensive
Qualification requirements	Very high	High	Very high	Very high
Time horizon	Medium to long range	Medium to long range	Short, medium or long range	Medium to long range

The employment of hybrid models expands the possibilities to integrate the problems that have to be solved on national and global / regional levels. They can be used in various sectors of national economy.

Up to now, four optimisation models for the development of power generation capacities have been used in Latvia. Their practical use, main characteristics and limitations have been summarised in Table 3.

Table 3

Energy Planning Models Used in Latvia (by the author)

	WASP	UPLAN	MESSAGE	MARKAL/TIMES
Model type	Evaluation of the system probability; linear programming techniques; dynamic optimisation method (for different sub-blocks)	Non-linear programming algorithm. The programme has two options for modelling generation – probability and chronology.	Bottom-up approach. Dynamic linear programming. The delivery of energy resources is demonstrated through transformation technologies, activities and connection network.	Bottom-up approach. Dynamic linear programming. Possibility to use reciprocal feedback between supply and demand.
Period under review	<30 years	long-range	<30 years	30+ years
Area of application	Development of power generation capacities	Development of power generation capacities	Energy supply Provision of primary energy sources Emission volumes Transport	Energy supply Provision of primary energy sources Emission volumes Transport
Possibility to establish own links and interactions	not possible	not possible	possible	possible
Possibility to investigate cogeneration	not possible	possible after modification of the programme	possible	possible
Complexity from the operator's aspect	simple	medium	complex	complex (especially with macros)

WASP enables planning of the most efficient development of power plants by applying the least cost method. However, the drawback of this model is that it has not been designed for the analysis of cogeneration plants; therefore, the operation of CHP plants is described in a highly simplified manner. With the help of this programme the power demand coverage has been modelled for Latvia. It has envisaged a possibility to build a new natural gas- and/or coal-fuelled power plant in Kurzeme region (Liepāja) and to perform full-range reconstruction of the existing Riga CHP, and further increases of electricity imports.

MESSAGE software has been used for modelling the energy sector and for analysing scenarios, and it has allowed for a complex modelling of extraction of primary energy sources, processing and transport process, import and export of primary energy sources, power and heat generation, transmission and distribution, final consumption of energy and energy resources.

The aim of the research has been to develop the potential development scenarios for the energy sectors of the Baltic States up to 2030. Representatives of the International Atomic Energy Agency, NATO, Estonia, Latvia and Lithuania have been engaged in the project.

The most typical elements of the energy sector infrastructure have been optimised in each country's model. As to Estonia, these have been the extraction and export of oil shale and shale oil, power generation primarily in oil shale fuelled power plants in Narva, district heating systems for Tallinn, Narva and other cities. As to Latvia, these have been the import and export of petroleum products, power generation in the HPP cascade on the Daugava River and combined heat and power plants in Riga, district heating systems in Riga and other cities. In respect of Lithuania, these have been the extraction of petroleum products, refining, import and export, power generation at the Ignalina nuclear power plant, natural gas/heavy fuel oil, condensing power plant and combined heat and power plants, import of nuclear fuel, hydro accumulation power plant, district heating systems in Vilnius, Kaunas, Klaipeda and other cities. Apart from that, import and export of natural gas and coal, peat extraction, output of wood, peat briquettes and biogas, fuel transportation and distribution, the conditions for energy transmission, final consumption of energy and fuel by industry, agriculture, transport, commercial sector and households have been taken into consideration for modelling. The modelling results have indicated that after the year 2015 more attention should be paid to CO_2 and especially to NOx emissions.

Various possible development scenarios have been compared with the help of mathematical model, including various forecasts and assumptions about fuel prices.

With the help of the "Uplan-E" programme, the least cost generation plan was calculated for the Baltic region. Experts of Eesti Energija, Lietuvos Energijas, DC Baltija and Latvenergo have participated in drawing up the plan. The Uplan-E programme performs the optimisation correctly only in respect of condensing power plants. In order to optimise combined heat and power plants dominating in Latvia, it has been necessary to introduce a number of dummy assumptions in the available Uplan-E version. These assumptions compromise the accuracy of calculations.

To avoid these drawbacks, the model has been modified. The concept of the modified cogeneration model is to find such combination of generation equipment that could provide adequately secure delivery of electricity and heat at a lower cost. The cogeneration model has been expected to compare the generation of heat and power in cogeneration plants (heat in boiler houses and electricity in power plants).

MARKAL-LV model has been used to calculate the types of primary sources to be consumed up to 2030, describe the transformation sector and perform cost analysis in the modelled scenarios.

The historically developed energy planning models have been designed as universal instruments that could be applied in any country with any type of energy generation equipment installed. However, when it is necessary to obtain relevant country-specific results, one has to face some limitations in the models and specific additional provisions and circumstances, and should take into account a number of additional factors, peculiarities, the need to adequately set the values of the exogenous indicators, etc.

Latvia's joining the NordPool Spot (NPS) power market had a significant effect on the Riga CHP operational modes. Prior to joining the NPS market, Riga CHP used to work depending on the demand in heat energy, whereas after joining the NPS power generation was the primary factor [16]. This is explicitly demonstrated by Figs. 12 and 13. Figure 12 shows the operation at Riga CHP prior to joining the NPS market, when power generation depended on the demand in heat energy and its generation. Conversely, Fig. 13 shows the operation at Riga CHP after joining the NPS market, when power output depended on the electricity price on the NordPool Spot market. This is why cogeneration power plants in February 2015 were running at lower capacities, as well as, due to very low electricity prices, they were operated in a cyclic mode, with frequent reduction or switching off the capacities [16].

The author concludes that in order to further enable operating at such modes new optimisation programmes are needed for production planning.

The several optimisation methods employed for long-term forecasting of power supply in Latvia are based on the analysis of large volumes of data and a detailed evaluation of different consumption and delivery structures in the case of various scenarios. Updating of complex models is time consuming. More often than not, the results obtained have not given the desired results. They could be used for relatively short periods of time, since the changes in impact factors and the economic situation have outrun the adjustments introduced to the evaluations. This leads to a necessity of a simultaneous employment of system dynamic methods, which, though offering a lesser degree of detail and accuracy, allow for a quicker evaluation of the optimisation of development scenarios, especially in the cases when there are time constraints for taking decisions on strategic projects that have a material effect on a number of sectors in national economy or energy supply services.

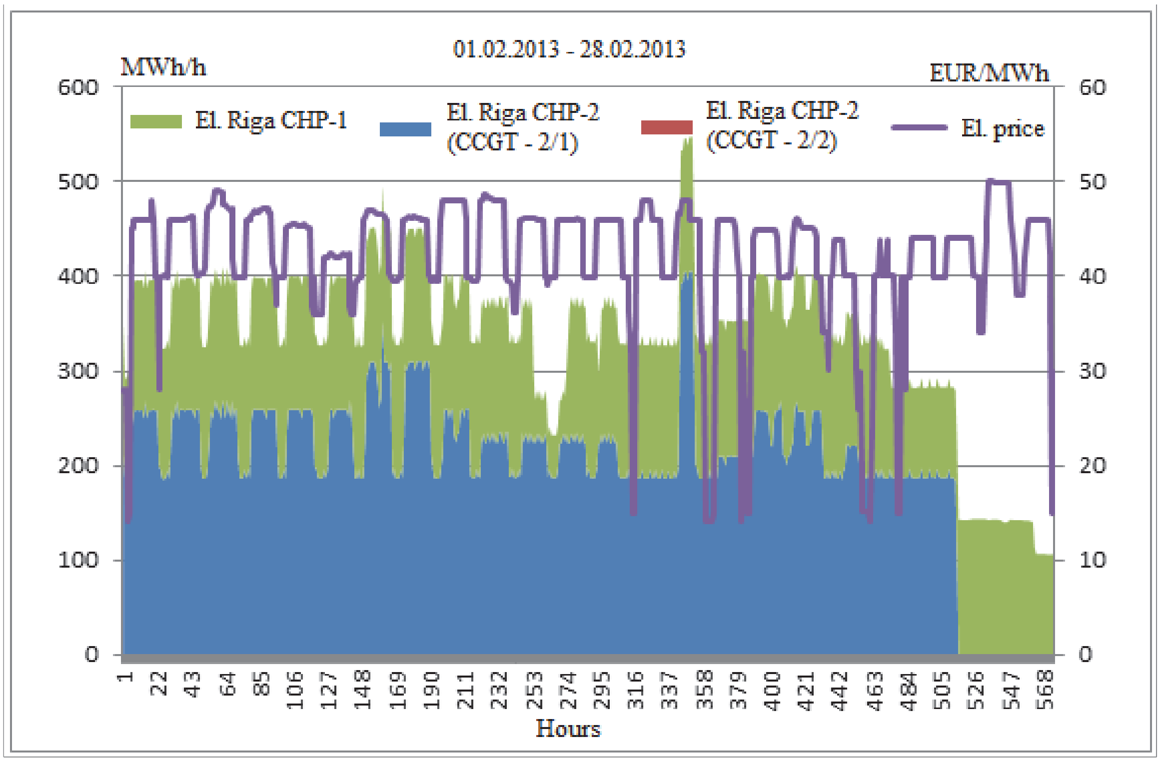


Fig. 12. Riga CHP operation in February 2013: CCGT 2-2 was not launched into operation (prior to joining NPS) (by the author according to production data of Riga CHP plants).

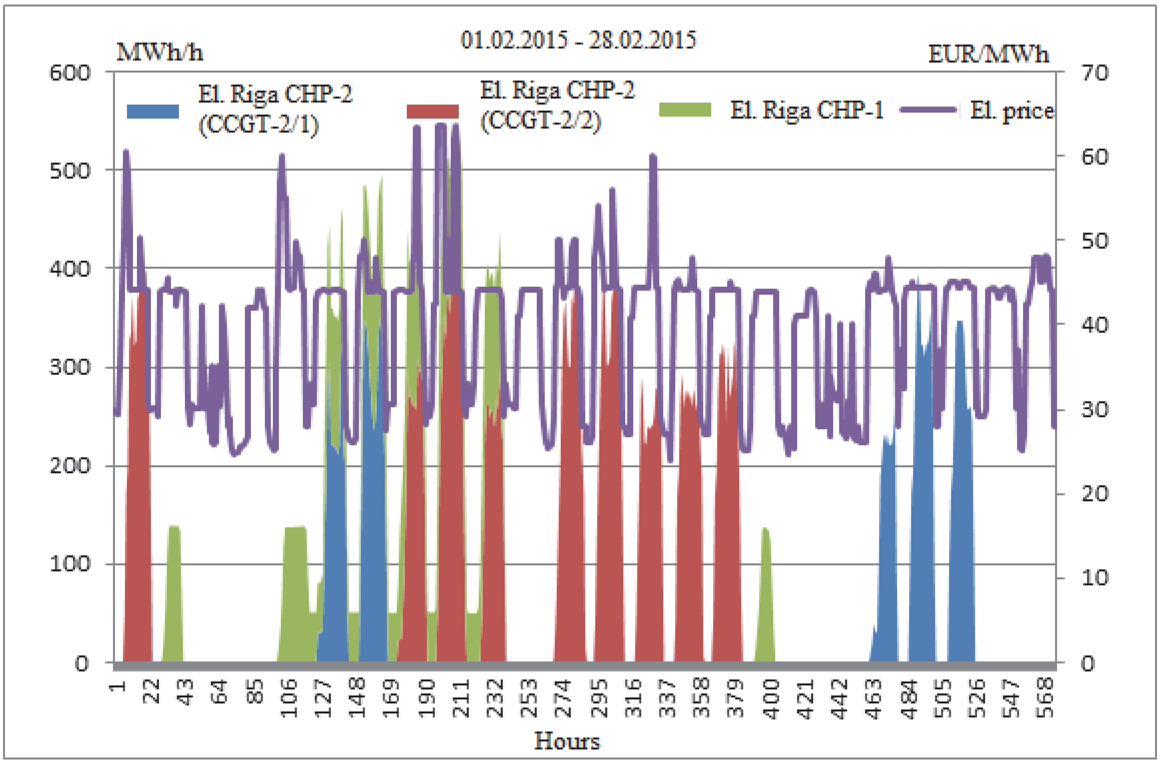


Fig. 13. Riga CHP operation in February 2013 (after joining NPS) (by the author according to production data of Riga CHP plants).

3. DEVELOPMENT MODEL FOR THE ENERGY SYSTEM IN LATVIA

Chapter Three: 26 pages, 17 figures and 1 table.

The author has created a model for the development of the energy system in Latvia, taking into account the specifics of energy supply in Latvia and the need to enable swift calculations. The model comprises the possibility to analyse the evaluation of the integration of RES on the operation of energy supply objects, the effect of resource prices, consumption dynamics, production capacities in energy resource generation, etc. The need to analyse and model the current changes in the situation, which are related to changes in the power market, has been taken into consideration. The developed model comprises optimisation, system dynamics, econometric and algorithmic modelling elements. This is why it is a hybrid model in its form. A complex systemic approach to the situation analysis and calculations has been applied to implement the model. The rationale behind opting for the above-mentioned hybrid model is as follows:

- The operational modes (scheduled by hour) of power plants are changing according to the changes in the conjuncture of market prices, and this should also be taken into account for long-range modelling.
- Broad-based measures are taken towards diversification of fuels (to increase the proportion of biomass) for district heating. The measures can be implemented in a relatively short period of time and may have a significant effect on the entire structure of energy supply.
- A necessity emerges to link the power market with modifications in the heat energy trading regulations.
- It is necessary to respond to any potential changes in the intensity of support (the mandatory procurement component).
- The mutual interaction of the heat generation block and the power generation block with the overall efficiency in energy supply.

The most appropriate method has been selected for each of the blocks in the model. District heating block, power generation block, power market block and energy efficiency indicator block have been created applying the system dynamics method, as it allows for quicker data processing and introduction of modifications. The econometric method has been applied for the power and heat consumption blocks, as it assures a higher degree of accuracy when the parameters of variables are smaller figures. The merging of both methods into a single hybrid-type model allows increasing both the speed of calculations and the credibility of the results obtained.

The overall demand and supply structure in the Latvian energy sector has been presented as a block chart in Fig. 14.

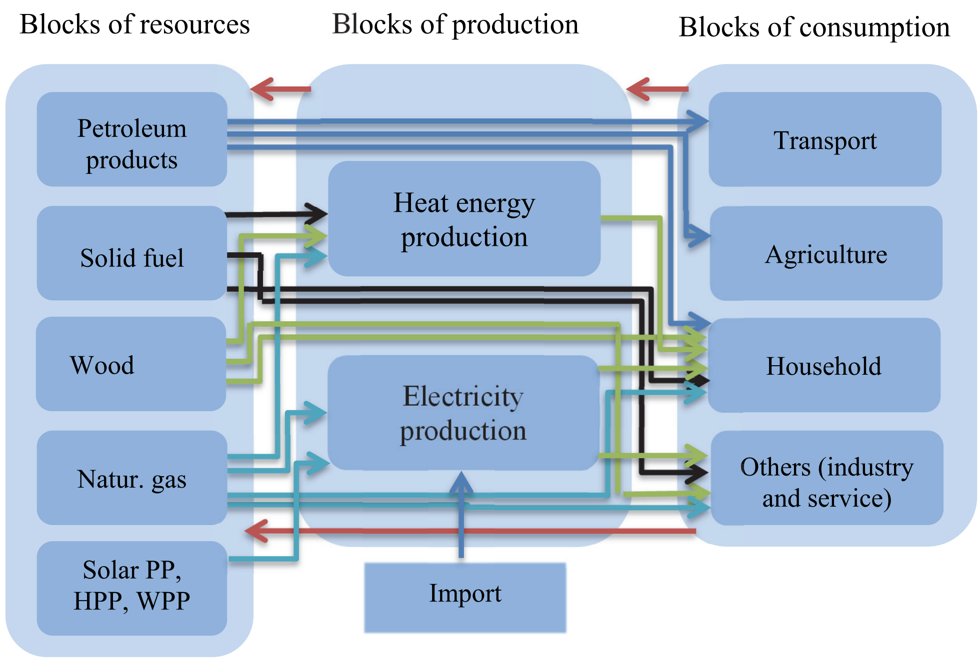


Fig. 14. Overall demand and supply structure in the Latvian energy sector (block chart by the author; based on [17]).

In greater detail, the generation block is broken down into sub-blocks for power generation at combined heat and power plants, power import sub-block, district heating, calculation of cogeneration costs and capacities, optimisation of the planning of cogeneration modes and condensing capacities, power market, RES policies, CO_2 quotas, primary energy source savings modelling and other sub-blocks.

The consumption block consists of transport, agriculture, household and other (industry and services sector) sub-blocks. The breakdown in the above-mentioned blocks and sub-blocks is based on the specifics of the energy sector in Latvia [17].

The power consumption block forecasts the consumption of energy depending on various development scenarios for the economic sector. The structure of the model is provided in Fig. 15.

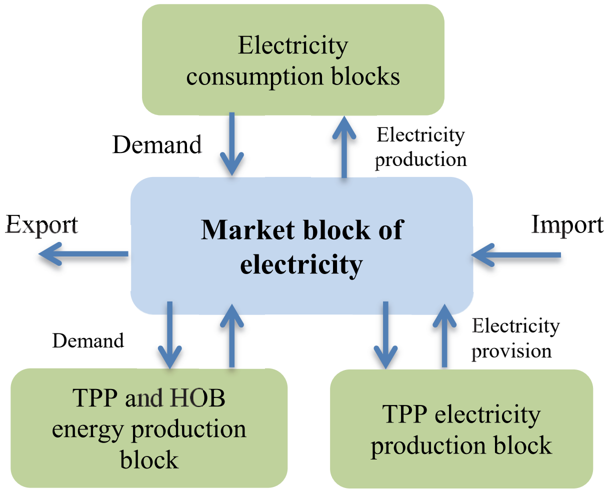


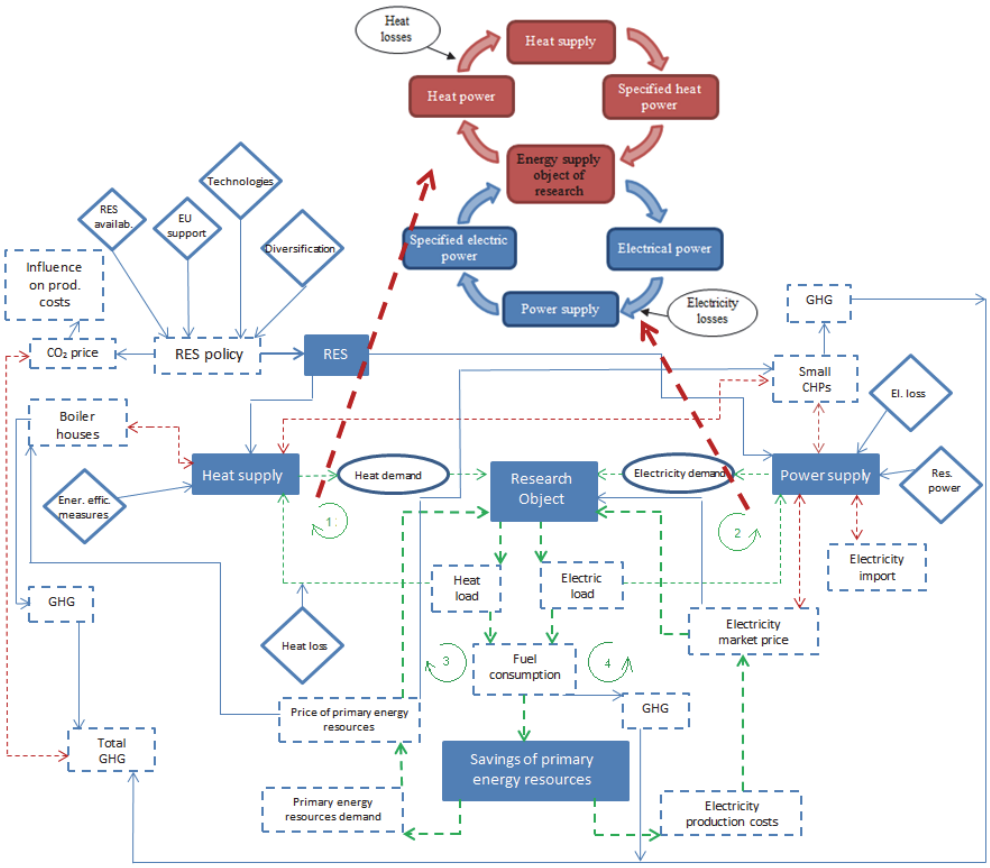
Fig. 15. Key blocks in the energy supply system dynamics model
(by the author; based on [18]).

Power market block combines power demand and supply and assesses the competitiveness of the energy sub-sectors on the international market. The group of generation blocks consists of the CHP and boiler house heat generation blocks and the CHP plant power generation block.

Figure 16 provides a more detailed flowchart of the Latvian energy sector model.

The block *Research object* has been divided into four parts: CHP-1 (cogeneration energy units), CHP-2 (cogeneration energy units), water boilers in the premises of CHP-1 and water boilers in the premises of CHP-2. They set up a selection matrix. This selection matrix envisages various operational modes for combined heat and power generation plants depending on the set heat and power load, as well as taking into account the effect of such sub-blocks as *Price of primary energy sources*, affecting also the sub-block *Gas-fuelled boiler houses* and *Small CHP*, and *Power market price*, which also influences the block *Energy supply* and establishes a feedback with it. The research object generates heat and power, which affect the blocks *Heat supply* and *Power supply*, respectively. As a result, two causality loops are established, which are combined into one.

The first loop demonstrates that any changes in district heating determine the heat load set for the research object, which, in its turn, determines the operational modes of the research object and the choice of equipment. Conversely, the heat energy amount generated by the research object affects the overall district heating system. The variable *Heat loss* influences the primary causality loop.



An element in the model structure denoting a principal block

An element in the model structure denoting a sub-block

An element in the model structure denoting a variable

A part of the model structure denoting a link between the elements in the model (a blue arrow pointing in one direction).

A part of the model structure denoting a feedback between the elements in the model (a red arrow pointing in both directions).

A part of the model structure reflecting the causality between the elements in the model (an arrow in any colour pointing in one direction).

A part of the model structure reflecting the direction of the causality loop (the figure denotes the number of the causality loop).

Fig. 16. A detailed flowchart of the Latvian energy sector model (by the author).

The second loop demonstrates that any changes in power supply determine the power load set for the research object, which, in its turn, determines the operational modes of the research object and the choice of equipment. Conversely, the power amount generated by the research object affects the overall power supply system.

The power consumption block is based on the forecasting of power consumption by the key sectors: agriculture, industry, construction, transport and other sectors as well as households. Final power consumption is calculated by adding up the consumption by sectors and households, which, after adding power losses, sums to total power consumption. Figure 17 provides the overall flowchart for the power consumption block.

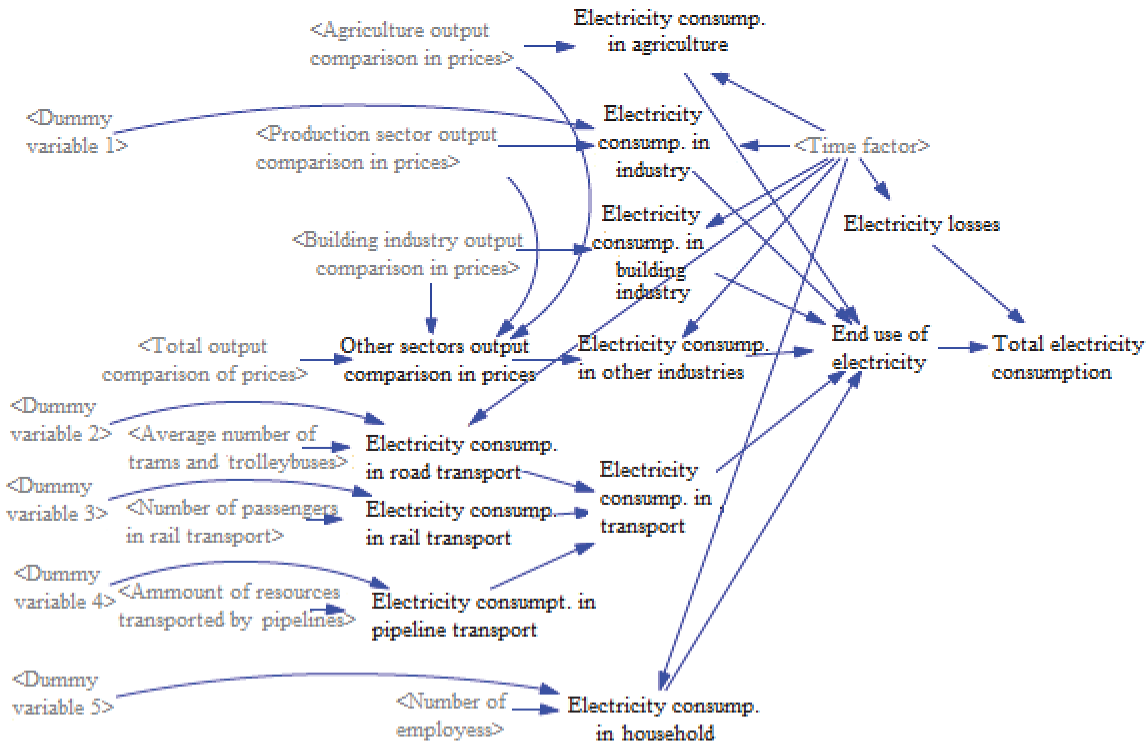


Fig. 17. Flowchart of power consumption sub-model (by the author and scientific advisor).

The power consumed by sectors is forecast based on their respective power consumption specifics. In respect of the sectors where the power consumption is related to the output volumes, power consumption is forecast based on the projections for the output volumes (e.g., for manufacturing). As to the sectors where power consumption depends on the number of consumers, power consumption is forecast according to the anticipated number of consumers (e.g., the number of trolleybuses and trams for power consumption in road transport). Power consumption in households is linked to the number of people employed in the economy.

Figure 18 provides the flowchart of the heat supply block. The sub-model *Heat supply* calculates the energy efficiency and heat capacities for CHP plants and boiler houses, which, in their turn, are determined by two flows – an increased energy efficiency for heat in CHP plants and boiler houses and changes in heating capacities. Conversely, the changes in heating capacities in CHP plants and boiler houses are determined by an increase in heating capacities, the degree of wear and tear of the equipment, the demand in heat energy, total consumption and other parameters. The sub-model enables calculating the heat generation costs in CHP plants and in boiler houses taking into account a large number of impact factors. This makes it possible, for example, to forecast the changes in the CHP plant and boiler house heat generation, heating capacities and demand in heat.

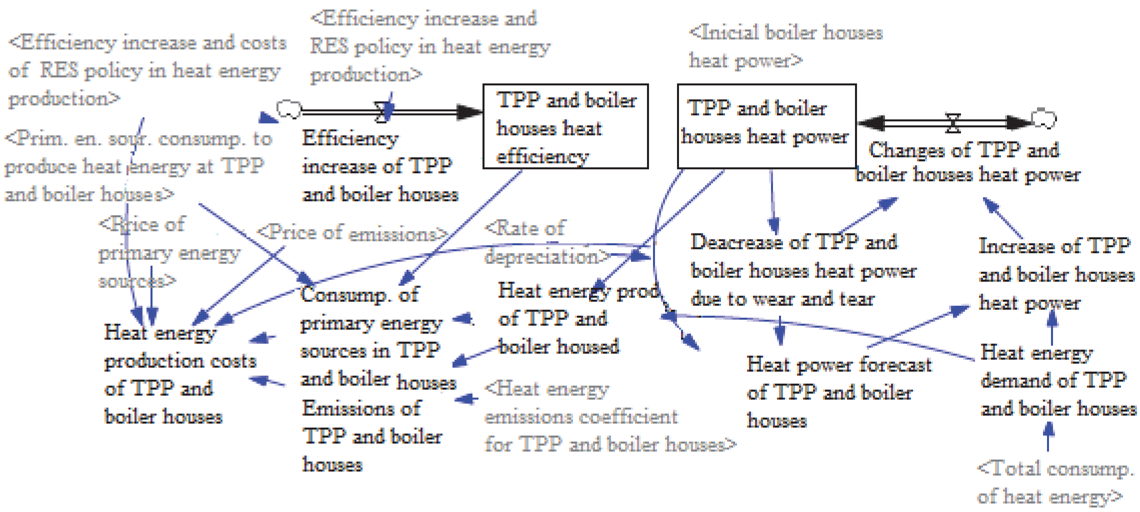


Fig. 18. Heat supply sub-model (by the author and scientific advisor).

Table 2 provides legend and descriptions for the elements in the sub-blocks.

Table 2

Elements of System Dynamics [18]

No.	Legend	Name
1.		Physical flows
2.		Non-tangible and information flows
3.	<C>	Convector or reservoir "C" from the linked sub-model
4.		Controller of physical flows
6.		External environment
7.	A	Storage "A"
8.	B	Converter "B"

The demanded heat energy is determined in the sub-model *Heat supply*. Several situations are reviewed, e.g., a situation when the RES policies provide for introduction of new renewable energy sources into the system or for diversification of the existing energy sources, which meet the demand in heat and power outside market competition.

Figure 19 provides the overall flowchart of the CHP plant power generation model block.

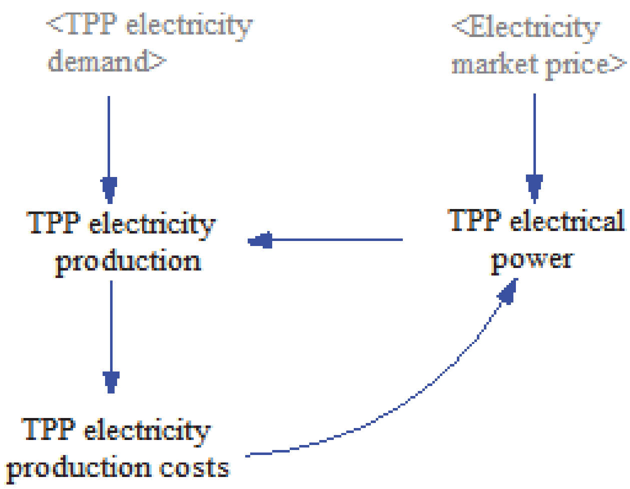


Fig. 19. Overall flowchart of the CHP plant power generation model block (by the author and scientific advisor).

In the model, electricity production volumes in CHP plants have been expressed depending on the demand in electricity and electricity price. In a situation of high demand, generation is capped by technical capabilities, i.e., by the production capacities. Production costs, being in interaction with market price of electricity, determine the possible development course for the production company, including power increases.

While developing the model, there has been a special focus on the calculations of reinvestment, because it is not always the case that reinvestment amount equals the profit. A smaller amount may be due to "profit taking" in the sector, whereas a higher amount may be related to the specifics of the sector, namely, huge capital investment in fixed assets. Simulation series have been performed using various profit reinvesting algorithms, thereby, with a practical exercise, it has been identified how the algorithm concerned imitates the development of the sector best.

Compared to the *Heat supply* block, the *Power supply* block has more sub-blocks and variables. The sub-blocks are *Small CHPs*, *Market share of small CHPs, Large CHPs*, *Power capacities import*, which establish a feedback with the *Power supply* block, and the variable *Stand-by capacity* and *Electricity loss*.

The created sub-model can be used, for example, for modelling the electricity volumes generated by small CHPs, the changes in power demand and in power capacities (see Fig. 20).

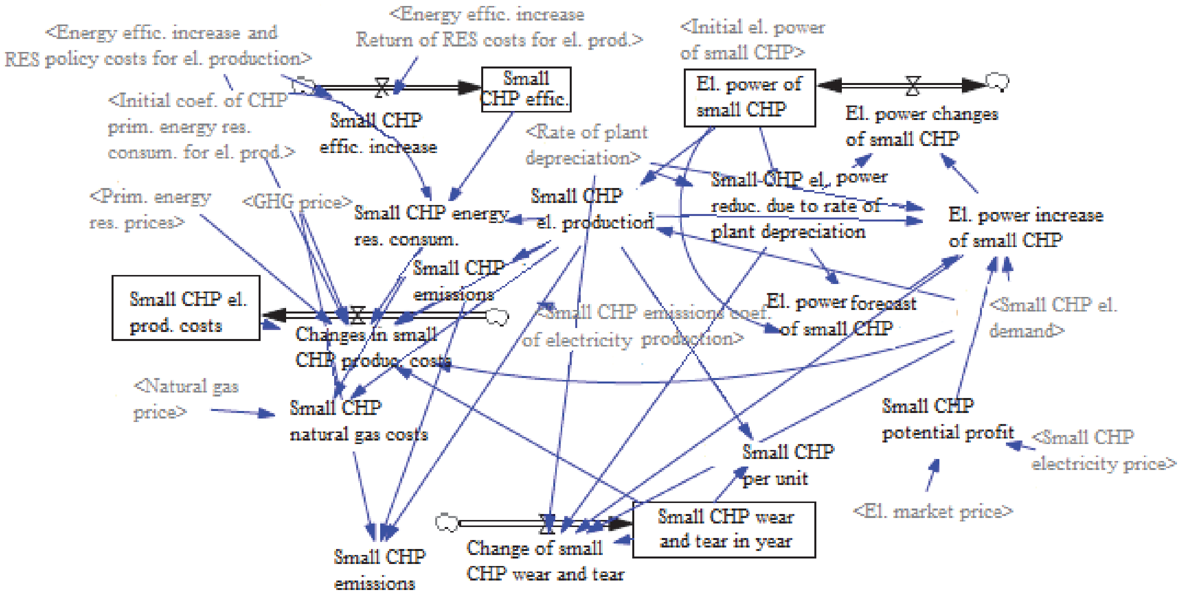


Fig. 20. *Small CHP* sub-model (by the author and scientific advisor).

The sub-model of large cogeneration plant models the operations in the Latvenergo CHP plants in a manner similar to that of small CHP model. The structure of this model is similar to the “*Small CHPs*” sub-model.

The share of CHPs in the power market depends on the base level, changes in the market shares and technical limitations. The changes in market share have been calculated as the difference between the present and the previous market share of CHPs.

As to Latvia, power generation in HPP has a major effect on the power market. When modelling the operation of HPPs, the author has been guided by an assumption that power generation in HPPs does not depend on the modelling results or the economic situation. In fact, it depends solely on the climatic conditions (influx of water). For the purposes of the model, power generation in HPPs is outside the market competition. This assumption is reasonable, since the cost price of power generated by HPPs is always lower than that generated by CHPs, or import price.

In general, all the models have been based on the real-life situation in Latvia.

The heat and power energy generated determines the amount of fuel consumed by the research object. The model algorithm walks from the block *Research object under* through the sub-blocks *Heat capacity*, *Power capacity* and *Fuel consumption* and passes on to the block *Savings in primary energy sources*. The sub-block *Fuel consumption* establishes a direct link with the sub-block *SEG* (greenhouse emissions).

Based on the structure of the model, the impact of the integration of RES in energy generation on the operation of the research object has been studied, which has been assumed as the element of the system. JSC Latvenergo combined heat and power generation plants have been selected as the research object, while the researched system is the heat and power supply systems in Latvia.

When creating long-range planning models, it is critical to know how continuous short-term optimisation of power plants on hourly basis is implemented in practice. Likewise, the author has analysed an algorithm for the planning of cogeneration modes and the possibility to employ the capacities in a condensing mode.

4. ANALYSIS OF THE MODELLING RESULTS

Chapter Four: 26 pages, 21 figures and 3 tables.

In this chapter the author has discussed the key modelling results that have been obtained by using individual models, their blocks and sub-blocks, applying econometric and system dynamics equations and optimisation and technical-economic calculations. The author of the Doctoral Thesis has calculated the parameters for the model by specifying the values of endogenous indicators for creating various development scenarios and performing the expert evaluation of the results. The modelling results include the analysis of power consumption and generation possibilities for a time span of 10 years, the analysis and forecasts with respect of energy resources, the evaluation of the market situation and the analysis of RES utilisation. The calculations using the model have been performed on block-by-block basis: consumption block, production block, market block, RES block, etc.

The modelling shows that, in general, a small yet stable increase in total power consumption is anticipated – by about 12 % over the period under review. The increase in power consumption is also forecast for sectors, with the exception of rail transport and pipeline transport. In the research, the author has compared the obtained forecasts with other studies. The reason for the discrepancies between different forecasts is the difference in sensitivity factors of the assumed parameters and of other exogenous parameters. The forecasts in respect of power consumption that have been published in Latvia are similar to the data obtained in the model: they also anticipate that power consumption is going to increase together with the growth of economy.

No significant changes have been planned in power outputs by CHP plants after 2021. No changes in demand for heat energy can be anticipated in the future. Consequently, the total heat output generated by CHP plants and boiler houses is expected to reach its maximum and stabilise.

The objective of the model is to identify a situation/situations when the Latvian energy sector companies will increase their competitive power. For this purpose, a number of simulation series have been run. The author has carried out the analysis of scenarios, comparing the base scenario with different depreciation rates that influence the competitiveness of plants. To detect the influence of depreciation rates on competitiveness, the modelling scenario has been reduced by two times compared to the base period and assumed to be 0.02 (or 2 % per annum; the average assumed useful life of fixed assets is 50 years). In this scenario, the demand in power and power generation at HPP remains unchanged. Electricity import volumes and output by CHP plants (GWh) have been compared in Fig. 21.

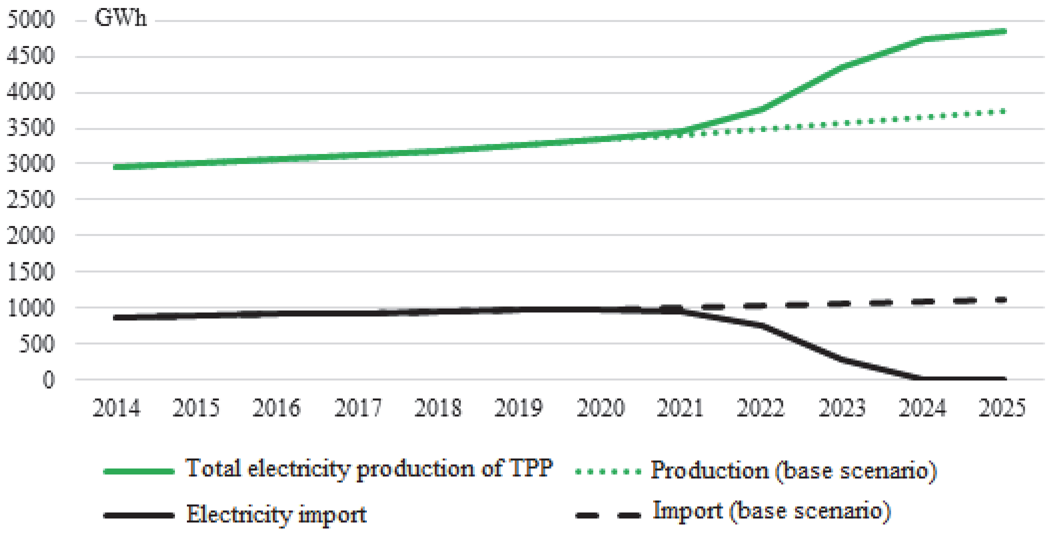


Fig. 21. The projected substitution of power import
at a depreciation rate of 2 % per annum (by the author).

Along with fixed costs, the competitiveness of electric energy is significantly affected by variable costs. Natural gas costs form an essential part of variable costs. In the base scenario, the base price of natural gas is assumed to be 268 EUR/t.m³ (without VAT, with excise tax, actual data for August 2015). As the price of natural gas is in close correlation with oil prices, significant fluctuations are possible.

A number of calculations have been performed to identify the circumstances under which the competitiveness of the sector would increase, and the effect of the price of natural gas on the development of the sector has been detected. The simulation results are provided in Fig. 22.

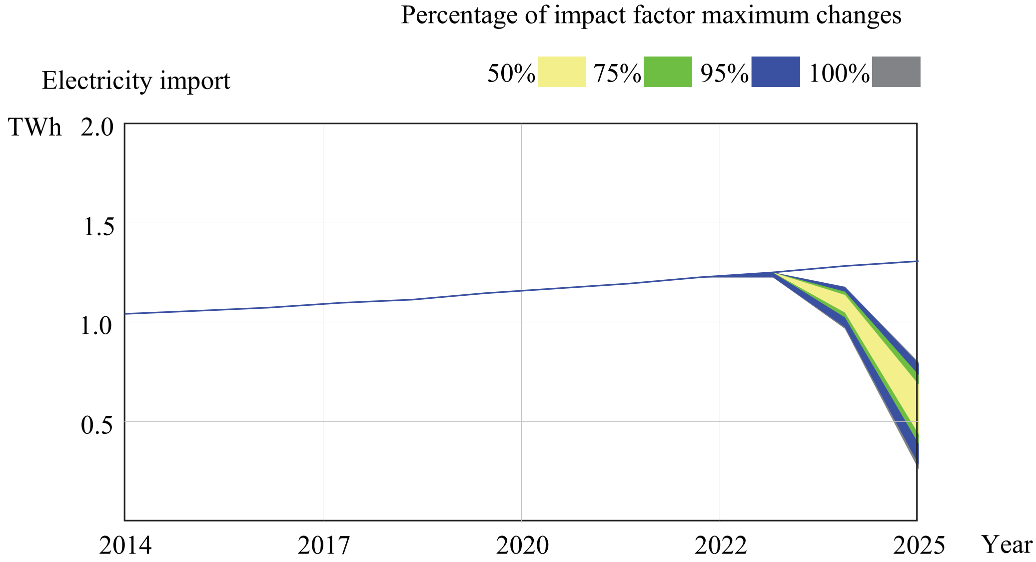


Fig. 22. The effect of decrease in natural gas prices on electricity import, TWh (by the author and scientific advisor).

Figure 22 demonstrates the import of electricity under a condition that the base price of natural gas decreases by 30–40 % (i.e., to 160–190 EUR/t.m³) (the scenario data are compared with the base scenario, which is the straight line in the chart). The scenario reflects the effect of net market prices, i.e., assuming that the depreciation rate remains on the base level.

The results suggest that in the model, when taking into account average electricity prices (ignoring hourly fluctuations), an instant reduction of the natural gas (and other primary source) prices significantly improves the competitiveness of the sector and encourages a substitution of electricity imports with domestic production in a more distant period, after the year 2022. The data in the scenario discussed above coincide with the base scenario up to the year 2022. The reason is that a decrease in average prices of resources will not be sufficient to result in an immediate potential fall in prices down to the market level of the electricity generated by CHP plants. When performing a complex analysis using a system dynamics model, taking into consideration also the short-term (on hourly basis) optimisation possibilities of production capacities, the changes in competitiveness become possible already in the short term.

Earlier simulation results reflect the effect of individual factors on the competitiveness of the sector. For the purposes of carrying out a complex evaluation of the competitiveness of the sector, it is assumed that the depreciation rate is reduced to 2 % per annum, and at the same time the base price of natural gas falls by 30–40 %, and the market price for electricity goes up by 4 % each year. The results are provided in Fig. 23.

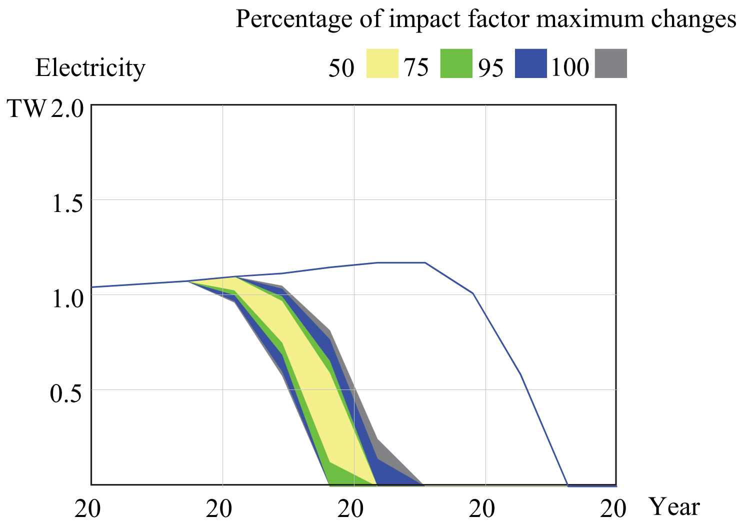


Fig. 23. A complex effect of factors on electricity import
(by the author and scientific advisor).

The analysis of the results featured in Fig. 23 indicates, that, given the above conditions, the sector could become competitive very soon if the situation is favourable or especially favourable. The impact of all three factors could notably reduce import by 2019.

The combined impact reflects and intensifies the impact of each individual factor. A reduction in depreciation rate and a decrease in natural gas prices leads to lower cost prices, which, coupled with an accelerated price increase, notably improve the competitive power of the sector.

The author has participated in the calculations where WASP and MESSAGE models have been applied, as well as has analysed the results obtained using UPLANE-E and MARKAL models, by evaluating the parameters, setting the values of endogenous indicators, formulating the conditions for development options, performing expert evaluation of the results, etc. Various possible development scenarios have been compared with the help of mathematical models, including various forecasts and assumptions about fuel prices. The results obtained with the hybrid model created as part of the Doctoral Thesis are similar with the forecasts obtained earlier, e.g., with MESSAGE model, where similar conditions have been used. It should be noted that in 2016 the natural gas prices returned to their historical levels of the time when the study with the help of the above-mentioned model was carried out (2005).

CONCLUSIONS

1. The liberalisation of power market, mechanisms in support of renewable energy sources and the development of capacities market are the factors behind the increasing uncertainties in respect of price fluctuations for energy resources and electricity. These uncertainty elements dictate a need for an in-depth complex economic evaluation of the production capacity development scenarios, which will enable to improve the optimisation of the long-term balance sheet of energy resources.
2. Given the significant changes in the fuel resources and power markets, the consideration of factors for short-term planning of energy system models has a material influence on the long-term planning results. The integration of its elements into the long-term optimisation models is a critical prerequisite.
3. It is necessary to enhance the structures of the energy sector optimisation models that have been employed up to now and to adjust the energy price assumptions determined in the development scenarios.
4. Transport and heat supply (including decentralised) sectors have a remarkable potential for reaching the targets set forth in respect of energy efficiency and RES. Electricity supply has a relatively low share in the total energy resource balance sheet, and its contribution is unable to effectively influence the achievement of overall targets in respect of adequate costs.
5. A system dynamics model has been developed for a comprehensive evaluation of the situation, using appropriate software. While developing the model, all the most important and critical elements of the model have been singled out, along with the most critical coherence of the research object. The model comprises the key elements (blocks, sub-blocks, specific variables, parameters) and the key links (direct, indirect, causal, reflexive etc.) as well as other elements capable of influencing the result. The structure of the model is flexible and allows quickly supplementing with new elements, exogenous data and limitations.
6. In general, the developed model can be used for the evaluation of the overall efficiency of the energy supply system and the potential benefits to end users. When necessary, separate blocks of the model and data may be used for the evaluation of effect on individual energy supply objects.

7. With the help of the developed model, it has been assessed that a moderate increase in total power consumption can be anticipated in Latvia over the next 10-year period (~12 %). No significant demand in heat energy is anticipated. The import of electricity is expected to fall. An increase of the energy output generated by the research object is possible.
8. The use of the existing cogeneration potential and the diversification of fuel for district heating systems related thereto may have a significant influence on the efficiency and security indicators of the energy supply system both on the national and regional level.
9. The criteria obtained as a result of the approbation of the created model with the data from the Riga City district heating and production are also applicable for other cities/districts with a high proportion of district heating for the purpose of fulfilling the energy supply optimisation tasks and evaluating its efficiency on the national or regional level, taking into consideration the availability of resources and infrastructure in the area concerned.
10. The developed model and the conclusions derived will enable a quicker evaluation of the quantitative indicators of the impact factors used for economic justification in long-term planning and management processes.
11. A complex analysis of the situation is required for the development and application of system dynamics model in the energy sector, along with engagement of appropriate specialists, experts and scientists; likewise, a broad vision should be taken on overall trends that are not limited to energy market only, but span also the related sectors, for example, the transport sector.
12. The results of the Doctoral Thesis can applied for the development of programmes/concept in the energy sector for the future periods in the actual planning of the development of energy systems.

RECOMMENDATIONS

Based on the conclusions above, the author has formulated recommendations that can be implemented in practice.

1. In addition to the currently used updated models, the author recommends employing a system dynamics model for the situation evaluation processes on the regional scale (in the Baltic States), thereby improving strategic decision taking in respect of development projects, taking into account the rapidly changing situation in the markets and the advancement of technologies. It can be used by research institutions, by the Ministry of Economics and in the business sector by power supply entrepreneurs.
2. Short-term factors need to be integrated when modelling long-term development scenarios (such as hourly optimisation of power and heat capacities), which will notably improve the accuracy of the results.
3. As to the fuel diversification project development, the critical factors of the existing fuel delivery infrastructure need to be considered for optimum use of the cogeneration potential, which, all in all, may result in lower specific expenses of delivery of all products (natural has, heat, electricity).
4. It would be reasonable to conduct a study on how potential changes in the base capacities in Latvia (combined cycle energy units in Riga) may influence the security of power supply (a study by the Latvian transmission system operator) and the macroeconomic indicators (a study by the Ministry of Economics). As to a more remote future, prerequisites for establishing a capacity replacement mechanism (CRM) market should be worked out. A system dynamics model may be used for the evaluation of macroeconomic indicators.
5. In respect of large-scale projects, a complex evaluation should be performed on economic consequences on the Latvian economy in large, taking into consideration all the interlinked aspects in order to avoid excessive investment in capacities. The implementation of complex solutions and any improvements in national energy supply should be facilitated by enhanced regulatory enactments. The implementation of new production capacity products should not lessen the total primary energy savings.

7. To promote the use of RES, a priority should be given to the sectors (district heating and transport) with the highest proportion or primary energy source consumption in the overall energy balance sheet. The use of RES in district heating and transport may contribute to higher total investment efficiency and achievement of the RES targets for the country.
8. As to strategic planning documents for national development, it is reasonable to adjust them by complementing with calculated investment amounts required for achieving the goals set forth for individual sectors. In respect of using local resources for energy production in Latvia, the indicators that determine the scope feasible from the economic perspective need to be adjusted. Analysis of alternative use of these resources should be performed by reprocessing resources or exporting as a product with higher value added.

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