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Rīga Stradiņš University

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Development of Electricity Demand Response Mechanism for Renewable Integration and Consumer Engagement in Latvia

Summary of the Doctoral Thesis for obtaining a doctoral degree "Doctor of Science (*Ph.D.*)"

Sector – Economics and Business
Sub-Sector – Regional Economics

Riga, 2022

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Table of Contents

Abbreviations used in the Thesis 4

Introduction 5
The aim of the Thesis 11
Objectives of the Thesis 11
Hypotheses of the Thesis 12
Novelty of the Thesis 13

1 Electricity Demand Side Management in the Context of the Renewable Energy Integration: Theoretical Framework 19
1.1 Genesis of the Demand Response concept 19
1.2 Electricity Demand Response optimizations models for implementation of regional aggregator 20

2 Economic and Institutional Environment of the Demand Response in the electricity market 24
2.1 Electricity market liberalization process 24
2.2 Regional and economic framework of the electricity sector in the Nord Pool 27

3 Trends of Indicators in Electricity Sector and Factors Influencing Wholesale Electricity Price in Latvia 34
3.1 Methodology for Relationship Analysis of Physical Parameters and Price Real Time Variables Applicable to Demand Response Mechanism in the Latvian Electricity Sector 34
3.2 Characteristics and trends of indicators of export, import, and electricity consumption in Latvia. Wind power consumption characteristics and trends 44

4 The Model for Regulating Electricity Consumption in Latvia on the Basis of the Regional Aggregator of Demand Response 59
4.1 The role of the energy prosumer in the electricity market 60
4.2 The development of model of a two-stage optimization methodology of regulating of electricity consumption using Demand Response 63

Conclusions and Recommedations 81

Bibliography 88

Abbreviations used in the Thesis

AC	Active consumer
CEP	Clean Energy Package
CO2	Carbon dioxide
CEEP	Clean Energy for all Europeans Package
DA	Day-ahead electricity prices
DAM	Day-ahead Market
DERs	Distributed energy sources
DM	Demand Management
DR	Demand Response
DSOs	Distribution system operators
ENTSO-E	European Network of Transmission System Operators for Electricity
IBDR	Incentive-Based Demand Response
ISO	Independent System Operator
ICTs	Information and communication technologies
IPBDR	Incentive Payment-Based Demand Response
KP	Integer optimization “Knapsack Problem”
PBDR	Price-Based Demand Response
P2P	Peer-to-Peer
TSO	Transmission System Operator
VRE	Variable renewable energy

Introduction

When arguing for the relevance of a doctoral dissertation, it would be correct to start by thinking about the nature of substantial changes in society. Sustainable Development and Sustainable Development Goals[1] has clearly become one of these changes suggested by the United Nations Currently the nations are dealing with an evolutionary process, the causes of which go back at least to the times of the first industrial revolution. It is believed that, because of it, the population has increased rapidly, and production has been developing. Human beings have been exploiting wealth from nature and the volume of wastes and pollutants thrown into the environment has gradually increased. Preserving the global life support systems has become more difficult due to the rapid and continuing human-caused environmental changes.[2] Furthermore, the current geopolitical tensions, based on Russian invasion to Ukraine, the European Commission proposed a document "REPowerEU: Joint European action for more affordable, secure and sustainable energy".[3] According to the President of the EC: "The quicker we switch to renewables and hydrogen, combined with more energy efficiency, the quickest we will be truly independent and master our energy system"[4]

By the EU the term Sustainable Development was mentioned in the 2001 EU Sustainable Development Strategy, in the first EU policy document detailing ways for the EU to use resources efficiently, and calling for better coordination between competing economic, environmental, and social

1 Sustainable Development. United Nations. https://sdgs.un.org/goals. [Accessed: 12.08.2020]

2 Shi, L., Han, L., Yang, F., Gao, L. 2019. The Evolution of Sustainable Development Theory: Types, Goals, and Research Prospects. *Sustainability*. 11(24):7158. https://doi.org/10.3390/su11247158. [Accessed: 12.08.2020]

3 REPowerEU: Joint European action for more affordable, secure and sustainable energy. European Commission. https://ec.europa.eu/commission/presscorner/detail/en/ip_22_1511. [Accessed: 08.03.2022]

4 *Ibid*.

sustainability policies.[5] However, the initial attempt to define environmental sustainability considered the First Environmental Programme in 1973. Thus, in the course of the past five decades, since the adoption of one, EU environmental policy and legislation have expanded dramatically, and gradually become one of the main EU areas of intervention.

At the same time, Stimson et al[6] offers the following definition: "Regional Economic Development is the utilization of economic processes and available resources that result in the sustainable development of the region and the desired economic development results for the region and that meet the values and expectations of entrepreneurs, residents and immigrants." Further emphasizing that regional economic development is:

1) the use of economic processes and available resources that result in the sustainable development of the region and the results of economic development desired for the region;
2) the process in which regional (local) government or community organizations are involved in order to stimulate or maintain business activity and / or employment;
3) a combination of qualitative and quantitative aspects of the region's economy;
4) structural features, such as the capacity to maximize the remaining benefits in the region and the ability to generate new economic activity.

The topicality and relevance of the Thesis is due to the emergence of new components both in the relationship between society and new technologies, and the emergence of new substantial systems in the electricity sector. As

5 Council of the European Union (2001). Presidency Conclusions Göteborg European Council, 15 and 16 June 2001. [Accessed: 12.08.2020]

6 Stimson, R., Stough, R., Roberts, B. H. 2002. Regional Economic Development: Analysis, and Planning Strategy, Springer, Berlin.

a result, insufficient understanding of the complexity and multifacetedness of the problem, as well as of the multiplicity of actors involved in the situation. The main principle of electricity market clearing is maximization of the social welfare.[7] The social welfare is the sum of the consumer surplus, the supplier surplus and the congestion rent. For decades, debating the safety of the electricity sector has emphasized the importance of supply and demand balance. At the same time, studying mainly the supply potential, reasonably assumed that the demand for electricity is inelastic. However, in order to address the three major challenges of European energy policy: sustainability, security of supply and competitiveness while guaranteeing energy equity,[8] the present understanding of electricity system supply and demand need to be actualized. Following the liberalization of electricity markets, discussions have shifted the focus of security on measures from the supply side. Besides increasing generation capacity, demand should also be exploited.[9] Emerging deployment of information and communication technologies (ICTs), power electronics, for example smart meters, and distributed energy resources[10] endanger the security of electricity sector, thus need for transition. In addition, an activation of the role of the consumer in the transition should be addressed.

7 NEMO Committee, EUPHEMIA Public Description. Single Price Coupling Algorithm, 2019. [Online]. Available: http://www.nemocommittee. [Accessed: 12.09.2020] eu/assets/files/190410_Euphemia%20Public%20 Description%20version%2

8 Mengolini, A. M. 2017. Prosumer behaviour in emerging electricity systems. PhD thesis, DOI:10.6092/polito/porto/2675327 [Accessed: 12.09.2020]

9 Koliou E., Eid, Ch., Chaves-Ávila, J. P., Hakvoort, R. A. 2014. Demand response in liberalized electricity markets: Analysis of aggregated load participation in the German balancing mechanism, Energy, Volume 71, 245–254, ISSN 0360-5442 https://doi.org/10.1016/j.energy.2014.04.067. [Accessed: 12.09.2020]

10 Distributed energy sources (DERs) - e.g., gasfired distributed generation, solar PV, small wind farms, electric vehicles, energy storage, and demand response

In open electricity markets, the use of demand response comes with a risk of conflict of interest between different parties. Nevertheless, at least three different groups of actors should be recognized. First, as mentioned above, nowadays electricity consumers already have reasonably more power to influence their energy costs through informed selection of electricity retailer and tariff plan, energy efficiency measures and even participation in various demand response programmes, albeit, with unreasonable difficulties. Second, operators of demand response mechanisms / aggregators can increase the overall electricity market efficiency by striving to optimize their own techniques. And, finally, policy-makers have significant impact on the operation of the electricity market and they can influence how it affects electricity end-consumers. The research work presented in this Thesis directly concerns two of the groups of actors mentioned – demand response mechanisms / aggregators and policy-makers. For the former, methods and algorithms to optimize their participation in an electricity spot market have been proposed. For the latter, decision support is realized in the form of assessment and recommendations in regard to the influence realization of new business models – aggregator entrepreneurship on the electricity market and, subsequently, the options to support it. A common feature of these topics is the aim – the maximization of the social welfare, albeit from different perspectives. Despite the fact that the movement of prosumers in Latvia is at an early stage of development, active electricity consumers / prosumers' awareness also was addressed.

In the modern world, everything is connected – as one industry changes, so do others, and the chain continues to infinity. The energy field also does not stand still. Not only technology and new role of consumer, but also new business models in the energy sector are developing.[11] Regardless, the process of these

[11] Stecenko, I., Silinevicha, V., Viskuba, K. 2020. Political, Economic, Social and Technological Perspectives of Aggregator of Demand Response for Renewable

changes, the Baltic energy systems have only partially achieved their development goals: emissions are still overall high, and the Baltic energy system as a whole has become acutely deficient. In 2020, local power plants generated only 55 % of the consumed electricity.[12] To solve the problem of generation shortage, significant capacities of renewable energy power plants will be required in the near future. This challenge is compounded by the fact that an increase in electricity consumption in transport, households and industry is expected. In this regard, the author undertakes a serious task to investigate the problem of demand response for renewable integration and consumer engagement. As a problem, it has been solved yet neither in theory nor in practice in Latvia, which emphasizes the importance of the chosen theme. The difficulty of solving the problem lies not only in the lack of experience as such in Latvia, but also in the fact that it is connected with the maximization of the social welfare. The price of electricity affects nearly all facets of a nation's economy, from gross domestic product, all the way down to an individual household's standard of living. Energy is an essential element in the production of nearly all goods and services, therefore energy prices have a ripple effect to the general level of prices for the country as a whole. Able to quickly balance demand and supply, demand response management also can decrease wholesale electricity prices, which then leads to lower retail prices as well. The author, using regional economics, economic and mathematical tools and methodologies, as the main sciences of research, suggests the solution of the problem of demand response for renewable integration and consumer engagement and application of econometric methods allows expanding the essence of regional economics as

Integration, Acta STING, vol. 4, Brno, 16–32, e-ISSN 1805-6873. [Accessed: 22.09.2020]

12 AS Augstsprieguma tīkls. *Elektroenerģijas tirgus apskats.* http://www.ast.lv/lv/electricity-market-review?year=2020&month=13

a part of applied economics. In addition, this aspect emphasizes the interdisciplinary connection with the other economic disciplines.

The problem and peculiarities of Demand Response Mechanism development in Latvia has not been widely considered in publications of Latvian scientists from this point of view, which confirms the relevance of the given research.

The degree of development of the research theme

The comprehensive studies of peculiarities of energy sector are well developed in Latvia. Their results are used for the elaboration of the Latvia's National Energy and Climate plan (NECP) 2021–2030[13] (one of the main energy planning documents in Latvia). Its long-term objective is climate-neutral economy by improving energy security and the well-being of society in a sustainable, competitive, cost-effective, secure, and market-based manner. The following experts and scholars greatly contributed to the development of these documents: A. Blumberga, G. Bažbauers, D. Blumberga, D. Jaunzems, D. Slišāne, V. Priedniece and others. Vast number of scientists contributed to investigation and academic research in investigating and assessing economic potential for Demand Response (DR), the role of aggregators in the energy transition under the latest European regulatory framework, possibilities of Latvian households' potential participation in the energy market as prosumers. Among them are following scientists: A. Sauhats, M. Balodis, R. Varfolomejeva, N. Sokolovs, H. Coban, K. Baltputnis, Z. Broka, M. Rubins, I. Pilvere, O. Linkevics, R. Petrichenko, L. Sadoviča, G. Junghāns, A. Krumins,

[13] National Energy and Climate Plan of Latvia 2021–2030. For Submitting to the European Commission for Evaluation Latvian Ministry of Economy. Riga, 2018. Available online: https://ec.europa.eu/energy/sites/ener/files/documents/ec_courtesy_translation_lv_necp.pdf [Accessed: 14.03.2020]

A. Tamane, E. Dzelzitis, D. Lauka, A. Barisa, P. Shipkovs, K. Lebedeva, L. Migla, G. Kashkarova and others.

R. Moura, M. C. Brito address concepts of consumer aggregation, but does not include any recent European regulatory framework, such as the Clean Energy for all Europeans Package (CEEP), however they present some business model case studies of DR for transport industry. Okur et al., Lu et al., Stede et al., Burger et al. in their comprehensive investigations offer extensive classification on concurrent literature on aggregator strategies, however, the assessed strategies are not directly linked to the different possible aggregator models, missing an aggregator taxonomy for business models.

The aim of the Thesis

The aim of the Thesis is to develop the conceptual framework of the electricity Demand Response for renewable integration and consumer engagement, based on the Demand Response aggregator that is by itself an information and technological company in electricity sector of Latvia.

Objectives of the Thesis

1. Based on the analysis and synthesis of scientific literature compare definitions and approaches related to the electricity Demand Side Management and to provide a theoretical framework for defining the Demand Response for market of electricity as well as to study the impact of the economic and institutional environment of the Demand Response in the electricity market and integration of renewable sources.
2. To develop a model for implementation of the concept of regional Demand Response aggregator, that will allow to solve the problem of reducing electricity consumption and the choice of active

consumers to be switched off for the current hour if the amount of electricity is not enough, even considering a decrease in its consumption.

3. To analyse the institutional and economical aspects of demand response for market of electricity, issues and current situation with integration of renewable sources processes in the energy market.
4. To identify and examine the trends of physical indicators of the energy industry, renewable energy and system prices of electricity, approximate formulae dependencies and the coefficients of determination.
5. To develop a methodology for a comprehensive analysis of correlation and regression dependencies of an electricity sector physical and system price indicators, based on the adaptation of the corresponding classical mathematical models.
6. To analyse the consumer behaviour, based on the Demand Response, carrying out quantitative research of prosumers in Latvia.
7. To develop and suggest a new advanced model of the bi-level optimization technique of the balance of supply and demand, where on the first stage it is proposed to solve the problem of reducing electricity consumption and, at the second stage – to solve the optimization problem of determination of temporarily disconnected user groups in response to electricity market prices, to devise and, based on case studies, validate a method for the optimized model.

Hypotheses of the Thesis

The development of electricity Demand Response Mechanism strategies for renewable integration and consumer engagement in Latvia can be based on the application of regional demand response aggregator – an information and technological company, in electricity sector of Latvia.

Research object

The Demand Response Mechanism in the energy sector.

Research subject

Demand Response services in Latvia, that impact the implementation of a technology of Demand Response aggregator.

Novelty of the Thesis

The most important scientific results obtained by the author are as follows:

1. Definitions and approaches related to the electricity demand side management have been improved and a theoretical framework for defining the Demand Response for market of electricity have been developed.
2. The impact of the economic and institutional environment factors of the Demand Response in the electricity market and integration of renewable sources has been categorized.
3. The trends in macroeconomic and physical indicators of the energy industry, renewable energy and a system price of electricity, approximate formulae of dependencies and the coefficients of determination have been identified.
4. A new methodology for a comprehensive analysis of correlation and regression dependencies of an electricity sector physical and system price indicators, based on the adaptation of the corresponding classical mathematical models, has been developed, which adds to the literature on state support impact on the electricity market.

5. A new model of the bi-level optimization technique of the balance of supply and demand, developed and substantiated where on the first stage it is proposed to solve the problem of reducing electricity consumption and, at the second stage – to solve the optimization problem of what groups of active consumers loads should be shifted off, if the amount of electricity is not enough and, therefore, in response to electricity market prices.
6. Based on the new model, the "Regional Aggregator", which is an information and technological company, in electricity sector of Latvia is developed.

The Practical value of the Thesis

The scientific results obtained by the author are valuable for practical application in development of long-term national strategies and plans for energy industry, with the emphasis on renewable energy sources deployment and active involvement of electricity end-users. The methods developed by the author can help entrepreneurs to effectively implement their business projects within the frameworks of energy sector in the Latvia and other EU member states.

Methods of the research – the research methodology was based on the systemic and dialectical analyses. At different stages of the research and depending on the nature of the tasks, different research methods were applied.

The Thesis research is based on:

- monographic-descriptive method: content analysis of the literature on the chosen research topic, the comparative analysis and synthesis of scientific literature, research results and reports, analysis of legal acts of the EU and of the Republic of Latvia related to the relevant problems presented in scientific publications and other academic sources, materials of scientific conferences and seminars, Internet resources (applied in Chapters 1 and 2);

- retrospective analysis of the development of the Electricity Demand Side Management in the Context of the Renewable Energy Integration;
- qualitative research methods, including gathering of information, processing and analysis of qualitative data, interviews of experts, case-study analysis, the author's observations;
- quantitative research methods (the survey of potential consumers and results of surveys and interviews carried out by the author, using the tool developed by the author, comparative analysis of empirical data by using central trends or location and variation indices, grouping and analysis of ratios (applied in Chapter 3);
- the statistical method: methods of statistical and econometric analysis employed for assessing the dynamic of absolute and relative indicators, identifying their relationships, formulation of equations and identifying the trends in indicators for given period of observation, published statistical data of the Central Statistical Bureau applied in Chapter 3);
- the modelling research method: the method of theory of operations investigation for the formulation and solution of the problem of combinatorial optimization of the balance of supply and demand of electricity (applied in Chapter 4);

The implementation of each phase resulted in intermediate results of the study (data collections, data tables and figures, summaries of information, analysis, evaluations, etc.), that formed the basis to launch and develop the next phase of research. That is – each subsequent phase of the study implementation was based on the interim results of the previous phase of the study.

Limitations of the Research

The Thesis focuses on the electricity day-ahead market in the Nord Pool region. The physical parameters used in this Thesis are specific for the region. Thus, some adjustments will be needed if one wants to apply the results from this Thesis to different markets and areas. Demand and supply of electricity, and consequently system electricity prices in Latvia are determined by various factors, such as fuel structure, cross-border interconnections, markets interconnection, renewable energy, concentration of market suppliers, weather conditions, etc. Nevertheless, this Thesis focuses only on some of them. The technical aspects are discussed in this Thesis to some extent. They are undoubtedly important aspects for this study as an electricity market will develop only if it is technically feasible. However, this Thesis will not propose detailed technical solutions for future scenarios of integration of Demand Response mechanism since this Thesis will focus more on how Demand Response mechanism could be implemented as Demand Response Regional Aggregator. The author analyses the electricity day-ahead market data for the period 2014–2019, part of data for the 2020. Economic data for the 2020 and 2021 have not been analysed owing to their limited availability and the impact of COVID-19 pandemic.

Time and Regional Framework of the Research

Calculation of trends of indicators, approximating formulae dependencies and the coefficients of determination for the relevant diagrams and charts are based on big data collected from the Latvian transmission system operator, Central Statistical Bureau of Latvia, European Network of Transmission System Operators for Electricity ('ENTSO-E'), and Nord Pool the power exchange. The data used in the empirical study is collected from hourly data from the period 1 January 2014 to 31 December 2019, and partly data for year 2020.

Theses for Defence

The following main theses are presented for defence:

1. The development of scientific research in the field of demand management for electricity consumption is influenced by both external factors in relation to the electric power industry, such as economic crises, the spread of information technologies, and internal factors, such as the development of energy markets, the development of technologies for distributed and renewable energy sources, the emergence of new technological trends, an activation of electricity consumers and prosumers.
2. The provision of a demand response – aggregator services should be based on the author's research methodology for a comprehensive analysis of correlation and regression dependencies of an electricity sector physical and price indicators, based on the adaptation of the corresponding classical mathematical models.
3. The development of the company "Regional Aggregator" should be based on the author's devised and applied bi-level optimization technique of the balance of supply and demand.

The evaluation of the research results

Theoretical and practical provisions of the Thesis have found the reflection in the publication of eight scientific articles and reports at the eleven international scientific and practical conferences and seminars.

Structure of Thesis

The Thesis structure is determined by the aim, objectives, and logic of research. The Thesis includes abstract, introduction, four chapters, conclusions, recommendations, and references.

The introduction determines the relevance of the topic of research of the Thesis. The hypothesis, the aim and objectives of the research are determined, as well as the research subject and object, scientific novelty and practical significance, as well as the review of the literature, examined sources and used scientific methods is given.

In the first chapter, the author analyses the theoretical, methodological foundations of the peculiarities in Demand Response for electricity sector.

In the second chapter an economic and institutional environment have been studies, including electricity market liberalization in the EU countries. Attention was given to electricity price factors. Regional framework of the Demand Response has been assessed.

In the third chapter, the author represents the reasoned analysis of the trends of macroeconomics and physical indicators of the energy industry, renewable energy and system prices of electricity, approximate formulae dependencies and the coefficients of determination; there has been devised a methodology for a comprehensive analysis of correlation and regression dependencies of an electricity sector physical and system price indicators, based on the adaptation of the corresponding classical mathematical models, it adds to the literature on state support impact on the electricity market.

In the fourth chapter, the author has put forward, developed and substantiated a new model of the bi-level optimization technique of the balance of supply and demand, were on the first stage it is proposed to solve the problem of reducing electricity consumption and, at the second stage – to solve the optimization problem of what groups of active consumers loads should be shifted off, if the amount of electricity is not enough and, therefore, in response to electricity market prices.

Finally, the conclusions and recommendations are formulated.

1 Electricity Demand Side Management in the Context of the Renewable Energy Integration: Theoretical Framework

Chapter 1 consists of 2 sections, 24 pages, 4 figures, and 4 tables

1.1 Genesis of the Demand Response concept

This part of the Thesis, in order to achieve the goal, set in the work, presents the different definitions of DR and its end users – prosumer / active customer / renewable self-consumer, discusses the concept of DR Aggregator, and analyses its role in the EU energy market, reveals the peculiarities of the renewable energy prosumer. First, the author investigates the EU legislation on the subject of terminology and different definitions, then continues with the academic literature on energy.

From the author's point of view, in disclosing the cause-and-effect relationships of the development of world research in the field of demand management, it is advisable to single out 6 main stages, at each of which urgent scientific problems of its time are solved and at the same time the prerequisites for the emergence of objective tasks of the following period are formed:

Stage 1 – Identification of the problem of demand volatility, systematization of knowledge about the mechanisms in the field of demand volatility management (1971–1980);

Stage 2 – the beginning of the implementation of electricity demand management in the form of programmes (1980–1994);

Stage 3 – development and implementation of electricity demand management programmes in various countries of the world (1994-2004);

Stage 4 – integration of demand management models into the system of electricity markets (2004-2009);

Stage 5 – integration of energy demand management technologies with the Smart Grid concept (2009–2014);

Stage 6 – the introduction of distributed energy technologies, renewable energy, electric vehicles and the Internet of Things (2014 – present).

The analysis and systematization of the stages of the genesis of scientific research in the field of demand management for electricity consumption allow us to conclude that the development of scientific research is influenced by both external factors in relation to the electric power industry, such as economic crises, the spread of information technologies, and internal factors, such as the development of energy markets, the development of technologies for distributed and renewable energy sources, the emergence of new technological trends.

1.2 Electricity Demand Response optimizations models for implementation of regional aggregator

When a consumer decides on its own to use less electricity when it is more expensive (e.g. in the peak hours) and use it more when it is cheaper (e.g. at night) it turns into the demand response, i.e., final consumers (the demand-side) responds to the market incentives. There are two pre-conditions:

- consumer must have a dynamic electricity price agreement with its' electricity supplier;
- consumer must have a smart electricity meter installed.

A dynamic electricity price agreement with the electricity supplier means that the consumer pays for the electricity the real-time power exchange market tariff. There will be a risk of high electricity price fluctuations, but it can also become very advantageous for the consumer in a longer low-price period.

Considering beforementioned, in this study the author proposes to investigate DR Aggregator objectives and economic benefits to define criteria for the optimization problem.

Optimization problems can be categorized according to several criteria. Depending on nature (degree in the polynomial form of the function) of the objective functions and constraints involved, linear and nonlinear optimization exists. If at least one of the objective functions and / or constraints is nonlinear, the problem is said to be nonlinear optimization. A mixed integer programming problem denotes whether some of the variables are integers. Additionally, based on the nature of the variables (deterministic or the stochastic) involved, optimization problems can be classified into deterministic and stochastic

Table 1.1

The Proposed Optimization Classification Compared with Methods Reviewed in Literature (made by author)

Optimisation Objective	**Optimisation Method**	**Active Consumers (AC) Groups**	**Demand Response Pricing**
Maximising the energy consumption based on the choice of AC groups	Combinatorial optimisation (linear integer programming)	Choice of AC groups	Real time pricing (a day-ahead or an hour-ahead)

A crucial factor that must not be forgotten when developing mathematical optimization models, however, is their ease of implementation and peculiarities caused by application to a particular system. In other words, to have a practical purpose the mathematical model has to be implemented in an actual software tool that can be deployed on an Aggregator operator's workstation and would allow the software to utilize it.

Thus, at the first stage, based on predicted data on the shortage of electricity for the next day, it is proposed to solve the problem of reducing its consumption. At the second stage, the choice of active consumers to be switched off for the current hour is optimized if the amount of electricity is not enough, even taking into account a decrease in its consumption. The developed methodology (See Chapter 3) should be based on the corresponding mathematical models at each of their stages, for which the corresponding optimization problems should be formulated at each stage.

Conclusions

1. The author has analysed the definitions and classifications of the electricity consumption response (DR) The author has developed a chronology of the development of electricity Demand Response – the genesis of scientific research. The analysis and systematization of its stages allows to conclude that the development of scientific research is influenced by both external factors related to electricity, such as economic crises, the spread of information technologies, and internal factors, such as the development of energy markets, the development of distributed and renewable energy technologies, the emergence of new technological trends.
2. Due to the nature of renewable, it is not possible to control or request power when it is needed. The main objectives of Demand Response techniques are reduction of peak load and the ability to control consumption according to generation. Usually, end-users have very little practical knowledge about their flexibility and are unaware of their usage patterns and behaviour. Hence, participants in DR programmes show a lower response than the expected levels.
3. The analysis of various tools for managing the demand for electricity consumption, as well as functioning demand management programmes in the countries of the world, allows us to state a significant differentiation and specificity of such tools and programmes in the country context. A retrospective analysis of the scientific development of electricity consumption response by developing a classification of electricity Demand Response

programmes in different countries. It is important to note that the Demand Response programmes shown in Table 1.1 are not interchangeable and all of these mechanisms can be used in a complex.

4. The author of the Thesis proposes combinatorial optimization for implementation of the concept of regional Demand Response Aggregator, that will allow to solve the problem of reducing electricity consumption and, at the second stage, the choice of active consumers to be switched off for the current hour is optimized if the amount of electricity is not enough, even considering a decrease in its consumption.

2 Economic and Institutional Environment of the Demand Response in the electricity market

This part of the Thesis, in order to achieve the goal, set in the work, presents the review and analysis of economical and institutional environment for DR Aggregator implementation, discusses the impact of renewable energy sources to the system price of electricity. First, the author reveals the peculiarities of price of electricity on Nord Pool exchange then, will continue the subject of economic and financial indicators for activation DR Aggregator in the electricity system.

2.1 Electricity market liberalization process

In November 2018[14], The European Commission published a strategic long-term vision for a prosperous, modern, competitive and neutral economy for 2050. The strategy reflects on how Europe can move forward towards climate neutrality by developing new technological solutions and coordinating important areas such as industry, finance and research. It will be based on the new energy policy system created in accordance with the „Clean Energy for All Europeans" package which gives the European consumers rights to become active participants in the energy transition stage and sets two new goals for the EU for 2030[15]: at least a 32 % renewable energy target and at least a 32,5 % energy efficiency target – with a possible upwards re-calculation. For the electricity market, it sets a 15 % interconnection target by 2030. Miguel Arias Cañete, the

[14] European Committee of the Regions, Commission for the Environment, Climate Changes and Energy. Models of Local Energy Ownership and the Role of Local Energy Communities in Energy Transition in Europe, 2018. [Online]. Available at: https:// op.europa.eu/en/publication-detail/-/publication/667d5014-c2ce-11e8-9424-01aa75ed71a1/language-en/format-PDF/source-77208198 [cit. 16.02.2020]

[15] European Commission. 2030 Energy Strategy. [Online]. Available at: https://ec.europa. eu/energy/en/topics/energy-strategy-and-energy-union/2030-energy-strategy [Accessed 24.10.2019]

EU Commissioner for Climate Action and Energy, states that the EU is on the right track to achieve the RES target, indicating that Europe is the world's first major economy that is planning on becoming climate-neutral by 2050 and reaching an 80 % RES target. These statements will promote the competitiveness, overall growth and employment of the European industry, decrease electricity costs, help prevent energy loss and improve quality[16].

Renewable energy resources will mostly dominate when forecasting Europe's offer. It is expected that by 2050 wind energy will amount to approximately 30 % of the total production capacity. Regarding fossil power, it is planned to build mostly natural gas power plants in Europe. By 2050, nuclear energy and coal power station capacity will decrease to 10 % of the total installed capacity. Overall, the fossil production capacity will be reduced from 50 % to 30 %[17]. Deregulation of electricity market so that there are several institutions running various components of the grid has the potential to improve efficiency, reliability and stability of the grid. Moreover, customers can have their electricity costs reduced and additionally can get value-added services because of competition among utilities. Typically, deregulation of electricity market means having several players in generation and retail supply while keeping transmission and distribution components legal monopolies.[18] This provides an opportunity

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[16] European Commission. 2030 Energy Strategy. [Online]. Available at: https://ec.europa. eu/energy/en/topics/energy-strategy-and-energy-union/2030-energy-strategy [Accessed 24.10.2019]

[17] European Commission. Europe leads the global clean energy transition; latest Eurostat data confirms. Published 12 February 2019. [Online]. Available at: https://ec.europa. eu/info/news/europe-leads-global-clean-energy-transition-latest-eurostat-dataconfirms-2019-feb-12_en [accessed 19.01.2020]

[18] Nooriya A.M., Albadi, M.H., 2020. Demand response in electricity generation planning, The Electricity Journal, Volume 33, Issue 7, 106799, ISSN 1040-6190, https://doi.org/10.1016/j.tej.2020.106799. (https://www.sciencedirect.com/science/article/pii/S1040619020300919) [Accessed 14.10.2021]

for customers to choose their preferred cost / service quality package from multiple competing utilities.

More effective use of Europe's energy potential requires the involvement of all energy market players[19]. The core of any business model is a consumer. A consumer is the point of reference that defines the vector of business development. Today, the energy industry is undergoing a transformation where the consumer is no longer just a point; it turns into a vector itself.

The Latvian electricity market has been liberalized since 2015, and households as well as legal users can freely choose their trader by agreeing on the electricity price. Since 2013, electricity trading has also been carried out within the Nord Pool exchange. Currently, 38 companies operate on the Latvian electricity market.

Evidently, the more liberalized the market, the more it responds to fluctuations in demand and supply. In an effort to maximize the liberalization of the European energy market, European market decision makers intended to use it as a tool that would provide an ever-increasing, growing and diversified range of offers, which would put downward pressure on prices.

According to the Decree of the Cabinet of Ministers developed on 02/04/2020, in order to increase the stability and security of the energy system, it is necessary to develop a legal basis for the operation of aggregators until 2022, to define the rights and obligations of the aggregator, payments for its services and relations between the aggregator and other participants in the system and the market. This will increase the balancing capacity and flexibility of the system.

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[19] European Committee of the Regions, Commission for the Environment, Climate Changes and Energy. Models of Local Energy Ownership and the Role of Local Energy Communities in Energy Transition in Europe, 2018. [Online]. Available at: https:// op.europa.eu/en/publication-detail/-/publication/667d5014-c2ce-11e8-9424-01aa75ed71a1/language-en/format-PDF/source-77208198 [Accessed 16.02.2020]

High final electricity prices impose a significant cost burden on households and generating companies, thus also affecting the country's competitiveness.

2.2 Regional and economic framework of the electricity sector in the Nord Pool

This part of the Thesis, in order to achieve the goal, set in the work, presents the review and analysis of economic environment for DR Aggregator implementation, discusses the impact of renewable energy sources to the system price of electricity. First, the author reveals the peculiarities of price of electricity on Nord Pool exchange, then continues on the subject of economic and financial indicators for activation DR Aggregator in the electricity system.

Wholesale of electricity on the Nord Pool exchange

Electricity wholesale in Latvia takes place on the Nord Pool electricity exchange, where the Latvian trading area was opened on 3 June 2013 for the next day's electricity market (Elspot) and on 10 December 2013 for the current day's market (Elba). As practically all electricity-trading transactions in the Latvian area are performed in the next day market[20], only the Elspot market is considered in the following analysis.

In terms of energy sold, Nord Pool is the largest power exchange in Europe, currently operating in the Nordic countries (Norway, Denmark, Sweden, Finland), the Baltic countries (Estonia, Latvia, Lithuania), as well as Germany and the United Kingdom. Nord Pool is owned by the Nordic transmission system operators Statnett SF, Svenska kraftnät, Fingrid Oyj, Energinet.dk and the Baltic transmission system operators Elering, Litgrid and Augstsprieguma tikls

[20] 99.8% of the amount of electricity purchased in Latvia and 98.1% of the amount of electricity sold by Latvian producers in 2019.

(AST)[21]. The large number of participants ensures high market liquidity and, consequently, the lowest possible costs for purchasing electricity on the stock exchange.[22]

The electricity market price, also known as the Nord Pool system price, is determined according to the intersection of the supply and demand curves, which is the equilibrium point of the market. Demand and supply must therefore constantly be balanced for system stability. The electricity demand is also inelastic over short period of times, resulting in high volatility and non-stationary prices.[23] For the next day's market, these curves are created the day before, summarizing for each hour separately the electricity sales and purchase offers submitted by the exchange participants according to the announced price and volume. By ranking all the offers in ascending order by price, an economic profitability curve is obtained. It should be noted that Nord Pool has restrictions on electricity price offers: it may not be lower than -500 € / MWh and higher than 3000 € / MWh. It is worth mentioning that there could exist a significant number of variables affecting the market equilibrium, and at the same time some of them lack information.

The resulting price for the Nord Pool system also serves as a reference point for electricity futures and forwards contract trading, but to get real the next day's market hourly price in each Nord Pool shopping area required also comply with the restricted transmission line throughput between them.

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[21] Nord Pool. About Us. [Online] [Cited: May 13, 2020.] https://www.nordpoolgroup.com/about-us.

[22] Baltputnis, K. 2020. Decision-Making Support Methods, Algorithms and Tools for Electricity Market Participants. Doctoral Thesis. Riga: RTU Press, 117.

[23] Cerjan, M., Krželj, I., Vidak, M., and Delimar, M. 2013. A literature review with statistical analysis of EPF methods. In Eurocon 2013. 756–763. https://doi.org/10.1109/EUROCON.2013.6625068 [Accessed 12.10.2019]

VRE influences to wholesale energy prices

In order to understand the essence of the problem the factors influencing electricity exchange price in EU Latvia been analysed.

Comparing the correlations with the wholesale price of electricity in the Nord Pool Latvian trade area with various potentially influencing factors, it can be seen that the largest positive correlation is with the volume of consumption and development in Latvia and Lithuania, as well as with electricity generation from certain types of sources: mainly natural gas and oil shale thermal power plants in the Baltic States, Kroņi HPP and HPP[24]. In other words, as the total volume of consumption and generation increases, the price in the market increases. In turn, as the market price increases, certain types of power plants are started up. The price in Latvia has a high positive correlation with the price in the Lithuanian region[25]. This follows from the analysis of Nord Pool data from 2016 to 2020.

In order to assess in more detail on the conditions under which a particularly high next day market price is formed in the Latvian trading area, hourly prices from 2016 to 2019 have been analysed (see Chapter 2). Hours with atypically high prices have been distinguished.

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24 Viskuba, K. and Silinevicha, V. 2021. Renewable Energy Sources in the Baltic States and New Business Approach of the Sector, *Vilnius University Open Series*, 120–127. doi: 10.15388/VGISC.2021.16. [Accessed 12.10.2019]

25 Sauhatas, A. and Baltputnis, K. 2017. *Price of Electricity and Its Influencing Factors* Riga Technical University. Academic Search Complete. [Online]. Available at: https://www.em.gov.lv/files/attachments/Elektroenergijas_cenu_petijuma_noslegum a_zinojums_2017-05-31.pdf... ID 25645. [Accessed 17.09.2019]

Analysis of the main economic indicators of the industry

The author shows basic indicators of the sector in Latvia for the past few years, basing the information on statistical data analyses. In the previous researches and publications[26] the author has already explored the main indicators of Latvian energy sector, but, in the author's view, it is valuable to observe data updates, because this is the way how we can see the most recent changes, respond to the changes and make more precise future prognosis. The average contribution of the energy industry to the national GDP is not particularly changed and is 2.11 % during the 2013–2019 period. Latvia is one of those countries that are strongly relying to imported energy resources from other countries, because Latvia is not able to fully meet the necessary electricity consumption.

The production and consumption of energy resources is a major factor in the global economy. The energy sector is stimulated by global energy supply and demand. Latvia belongs to those countries that are heavily dependent on imported energy resources because they are unable to fully meet the required electricity consumption. The volumes of electricity import, export and consumption in Latvia for the period 2014–2019 were defined.

The data of Latvian total electricity demand, net electricity production, import and export for the period 2014–2019 is shown on Figure 2.1.

[26] Viskuba, K., Silinevicha, V. 2020. Wind Farm Project Results and Innovative Business Models. Humanities and Social Sciences: Latvia. Volume 28, Issue 1, ISSN 1022-4483. 5–29

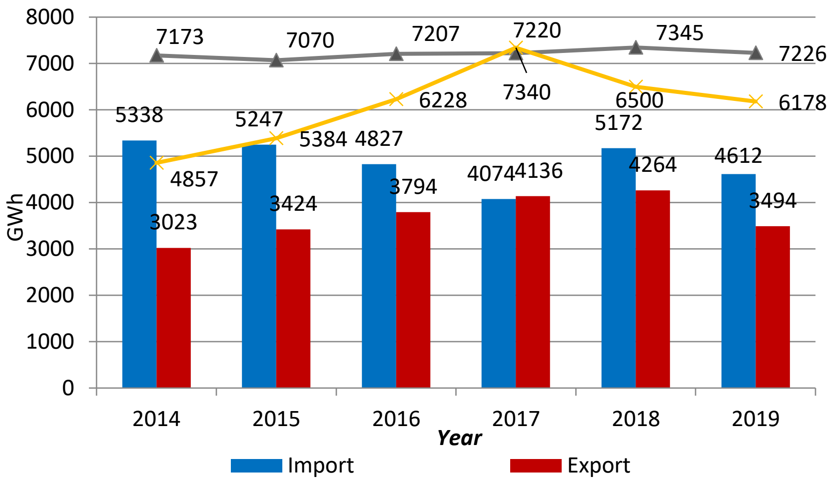

Figure 2.1 **Latvia's Electricity Import, Export, Consumption and Net Electricity Production 2014–2019 years, GWh**

Source: created by the author, using [27] data

The situation with wind power plants capacity is different and not only in total Baltic volumes, but in volumes of each country. In 2001 installed capacity of wind power plants was only 2 MW, but following next two years it substantially increased to 24 MW. The next leap when installed capacity increased rapidly to 62 MW in total was in 2012. It can be explained with the start of exploitation period of several wind farms, for instance, 20.07 MW of installed capacity by producer Ltd. "*Winergy*". Latvia's total installed capacity of wind turbines in 2019 was about 68 MW. In contrast, in Estonia the installed capacity in 2019 was 310 MW, which is 4,5 times higher than Latvia's. However, Lithuania is absolute leader between Baltic counties with 548 MW installed.

[27] Central Statistical Bureau of Latvia. Elektroenerģijas imports, eksports. [Accessed on 15.12.2020.] Available: https://www.csb.gov.lv/lv/statistika/statistikas-temas/vide-nergetika/energetika/tabulas/en010m/elektroenergijas-razosana-imports-eksports; Nord Pool. Historical Market Data. Consumption. [Accessed on 15.12.2020.] https://www.nordpoolgroup.com/historical-market-data/

According to the "National Energy and Climate Plan for 2021–2030"[28], which was prepared by The Ministry of Economics of the Republic of Latvia, Latvia plans to increase the share of RES in electricity generation by increasing the installed capacity of wind generators and solar photovoltaics, taking into account the capacity of Latvia's electricity transmission network, which currently allows to increase the amount of electricity transferred to the network by 800MW.

The Baltic countries have not used all the potential, which in combination with the EU target of carbon neutral by 2050, investments, support schemes and auctions, smart strategy and implementation can lead us to sharply increasing RES, especially of wind and solar capacities. According to Latvia's National Energy and Climate Plan 2021–2030, the Latvian electricity transmission system is capable of accepting up to 800 MW of additional capacity from new RE plants, which is about a third of all electrical capacities currently installed in Latvia.

Conclusions

1. The chapter represents the assessment conducted by the author of various legal documents and regulations suggested by international organizations such as UN, EU as well as the Cabinet of Ministries of the Republic of Latvia. The more liberalized the market, the more it responds to fluctuations in demand and supply. In an effort to maximize the liberalization of the European energy market, European market decision makers intended to use it as a tool that would provide an ever-increasing, growing and diversified range of offers, which would put downward pressure on prices.

[28] Ministru kabineta 2020. gada 4. februāra rīkojums Nr. 46 Par Latvijas Nacionālo enerģētikas un klimata plānu 2021.–2030. gadam. https://likumi.lv/ta/id/312423

2. To this end, the Baltic countries have not used all the potential, which in combination with the EU target of carbon neutral by 2050, investments, support schemes and auctions, smart strategy and implementation can lead us to sharply increasing RES, especially of wind and solar capacities. According to Latvia's National Energy and Climate Plan 2021–2030, the Latvian electricity transmission system is capable of accepting up to 800 MW of additional capacity from new RE plants, which is about a third of all electrical capacities currently installed in Latvia.
3. As mentioned before, the correlation of the wholesale price of electricity in the Nord Pool Latvian trade area with the generated wind energy is considered weak. However, for hours with the highest price situation could be considerably different.

To estimate the impact of consumption changes on the day-ahead electricity price, the author in Chapter III analyses the relationships between fundamental factors and electricity prices in Latvia, the availability of renewable resources such as hydro and wind should have statistically significant influence on day-ahead prices in Latvia because short-term marginal costs of hydro and wind stations are negligible.

3 Trends of Indicators in Electricity Sector and Factors Influencing Wholesale Electricity Price in Latvia

Chapter 3 consists of 2 sections, 33 pages, 8 figures, and 23 tables

3.1 Methodology for Relationship Analysis of Physical Parameters and Price Real Time Variables Applicable to Demand Response Mechanism in the Latvian Electricity Sector

The goal of this analysis is whether there is a connection of the electricity price and the wind power generation, and physical indicators of energy sector of Latvia, and if there is such connection, whether this fact influence on the demand perspective and on the relevance of the examined topic.

For carrying out this analysis, the quantitative analysis of the results of research has been chosen by the author.

In this chapter, the author proposes a methodology for the complex analysis of correlation and regression dependences of the relationship between the electricity price and the wind power generation in an electricity market of Latvia, based on the adaptation of the corresponding classical mathematical models. The methodology is based on the adaptation of correlation and regression classical models' analysis in relation to the analysis of industry statistical indicators of electricity production and imports in the period 2014–2019 (See Chapter 1), average hourly electricity consumption and the price of one MWh of wind power in 2019, and similar indicators for hours of peak consumption from 8:00 to 12:00. Because the electricity price is determined by demand and supply and therefore endogenously specified within the market, hourly expected wind generation have been used as a variable to proxy electricity prices. The statistical indicators are supplemented with details of electricity consumption and wind power generation unit price on average per day and at peak hours (from 8:00 to 12:00 CET / GTM+2) monthly in 2019. The author has also substantiated the use of the sinusoidal dependence of wind energy indicators on the month of the year, as a basic model, for the correlation study. It is shown that if the maximum and minimum outliers of the studied data do not have the same average deviations from the general average level, then it is necessary to introduce additional accompanying variables that identify these outliers, which leads to the corresponding modified model. There are established the regression dependences of monthly wind power data. There also presented the calculated data on the validation of the obtained models. Calculations were made using the algorithmic language MATCHAD. The developed models are recommended as an analytical tool for the real time indicators for understanding and estimation of demand response mechanism business model of electricity aggregator.

One of the main tasks of the chapter is to develop a methodology for a comprehensive analysis of correlation and regression dependencies of an electricity sector physical and price indicators, based on the adaptation of the corresponding classical mathematical models. Author believe that the proposed adapted models can be used in the understanding of the peculiarities of the DR mechanism and development process of the Latvian regional aggregator.

The underlying regression model – Classical analyzing model

In general, regression allows us to approximate a mathematical relationship between two or more variables if their values are known in a number of points. For analysis purposes, the processed statistical data is usually presented in the form of Table 3.1, where *V1* and *V2* are interrelated indicators related to the same object of research and calculated in increasing time intervals (i). For the electricity sector, *V1* means physical indicators expressed in MWh and *V2* are price indicators in EUR / MWh.

Table 3.1

General presentation of statistical data for a complex analysis of natural and price indicators of the electricity sector

Vector of indicator / serial number	**1**	**2**	**i**	***n***
$V1$	$V1_1$	$V1_2$	$V1_i$	$V1_n$
$V2$	$V2_1$	$V2_2$	$V2_i$	$V2_n$

Source: created by the author based on[29] data

In the following formulas the available statistical data are presented in the form of the corresponding matrices *Tj*. Average value, dispersion and standard deviation for the data represented by the vector *V* (*V* takes the value *V1* or *V2*) of matrix *Tj* are calculated using the usual equations[30]:

$$E(V) = \frac{1}{n}\sum_{i=1}^{n} V_i \tag{3.1}$$

$$D(V) = \frac{1}{n-1}\sum_{i=1}^{n}\left(V_i - E(V)\right)^2 \tag{3.2}$$

$$\sigma(V) = \sqrt{D(V)} \tag{3.3}$$

The covariance of two variables, presented in the Table 3.1, is calculated by the equation[31]:

$$cov(V1, V2) = \frac{1}{n}\sum_{i=1}^{n} V1_i V2_i - E(V1)E(V2) \tag{3.4}$$

29 Seber, G. A. F. 1977. Linear regression analysis. John Wiley and Sons, New York – London – Sydney – Toronto,

30 Afifi, A. A., Azen, S. P. 1979. Statistical Analysis. A Computer Oriented Approach. Academic Press, New York – San Francisco – London,

31 Adams, A., Bloomfield, D., Booth, Ph., England, P. 1993. Investment Mathematics and Statistics. Graham @ Trotman, London – Dordrecht – London,

The correlation coefficient is defined as follows:

$$corr(V1,V2) = \frac{cov(V1,V2)}{\sigma(V1)\sigma(V2)} \quad (3.5)$$

The general polynomial regression model[32] assumes the dependence of the random variable Yi from the values of the factors (related variables, regressors) $x_{i,1}, x_{i,2}, \ldots, x_{i,k}$ in the *i*-th observation:

$$Y_i = \beta_0 + \beta_1 x_{i,1} + \cdots + \beta_k x_{i,k} + Z_i, i = 1, \ldots, n \quad (3.6)$$

$\beta_0, \beta_1, \ldots, \beta_k$ – regression coefficients

Z_i – random component with a zero average value and final standard deviation

n –number of observations

The regression task is to estimate the coefficients $\beta_0, \beta_1, \ldots, \beta_k$ based on n observations. In the *i*-th observation, the values of the related variables $x_{i,1}$, $x_{i,2}, \ldots, x_{i,k}$ and the value of the random variable Y_i are fixed.

The estimate of the regression coefficients $\beta_0, \beta_1, \ldots, \beta_k$ is presented in vector-matrix form. In regard to this, the following vectors and matrices are considered:

$Y = (Y_1, \ldots, Y_n)^T$ – a column vector of dependent variables (T means matrix transposition);

$X = (x_{i,j})$ – matrix of related variables of size $n \times (k+1)$, whose lines correspond to the observations, but columns to the regression coefficient;

$\beta = (\beta_0, \ldots, \beta_k)^T$ – column vector.

[32] Seber, G. A. F. 1977. Linear regression analysis. John Wiley and Sons, New York – London – Sydney – Toronto, Ch.3

The classical estimate of the regression coefficients is calculated by the equation[33] :

$$\hat{\beta} = (X^T X)^{-1} X^T Y \quad (3.7)$$

where $(X^T X)^{-1}$ means the matrix inverse to $X^T X$.

In this case, the estimate of the random variable Y_i is:

$$\hat{Y}_i = \ddot{\beta}_0 + \widehat{\beta_1} x_{\mathrm{i},1} + \cdots + \hat{\beta}_k x_{i,k}, i = 1, \ldots, n \quad (3.8)$$

Adaptation of Classical Mathematical Models for the Analysis of Correlation and Regression Dependences of Natural and Price Indicators of the Electricity Sector

To start with, there have been mathematical models developed for the analysis of the electricity sector natural and price indicators in relation to the processing of statistical data presented by tables with specific natural and price indicators of:

- electricity production and imports in the time period 2014–2019;
- average hourly electricity consumption and the price of one MWh of wind power in 2019, and
- similar indicators for hours of peak consumption from 8:00 to 12:00.

Motivation of choosing variables is as follows. As mentioned in chapter 1, implementation of DR programmes can result in shift peak demand, enhance system reliability, can reduce transmission bottleneck and highly priced energy bills by shifting or re-adjusting consumption patterns. It can also reduce the effects of intermittent RE generation since the capacity of introduced RE

33 Seber, G. A. F. 1977. Linear regression analysis. John Wiley and Sons, New York – London – Sydney – Toronto.

sources will be optimally minimal, and the consumer can also be encouraged to embark on self RE generation and sell self-produced excess energy to the grid. Calculation are based on big data collected from the Latvian transmission system operator, Central Statistical Bureau of Latvia, and Nord Pool the power exchange. The data used in the empirical study is collected from hourly data from the period 1 January 2014 to 31 December 2019. (See Anex1). All the calculations in this and subsequent sections were carried out by using the *Mathcad* programming language.

The calculated average per diem and peak hours indicators of wind energy are equal to 157 and 147.6 MWh, 45.3 and 55.5 EUR / MWh accordingly Tables 3.3 and 3.4. Indicators differ insignificantly in volume (6 %) and significantly, in price (18 %), moreover, during peak hours, the average consumption of wind power is less, but the average hourly price is higher.

As the next step, author has developed a regression model that describes the dependence of the indicators from month number *i*. The number of observations is the number of months, i.e. n = 12.

The related variables should be chosen so that the smoothing of the presented data is acceptable. The smoothing criterion is the sum of the squares of the deviations:

$$R = \sum_{i=1}^{12} \left(Y_i - \hat{Y}_i\right)^2 \qquad (3.9)$$

Initially, it was supposed to use a general polynomial regression model (Eq.2.8)[34]:

$$Y_i = \beta_0 + \beta_1 i^2 + \beta_1 i + \cdots + \beta_k i^k + Z_i, i = 1, \ldots, 12$$

34 Afifi, A. A., Azen, S. P. 1979. Statistical Analysis. A Computer Oriented Approach. Academic Press, New York – San Francisco – London.

However, the results were completely unsatisfactory. This is explained in the monograph[35]: "It is well known that the matrix $X^T X$ is quite poorly conditioned". Moving further the author points out: "One of the ways to reduce the influence of bad conditionality of the matrix $X^T X$ is to use Chebyshev polynomials …". This possibility was tested, but the result was again unsatisfactory. The author has adopted for further research the sinusoidal dependence of the indicator on the month number:

$$Y_i = \beta_0 + \beta_1 \sin\left(\frac{\mathrm{i-c}}{6}\pi\right) + \mathrm{Z_i}, \mathrm{i} = 1, \dots, 12 \quad (3.10)$$

where c – known integer with possible values from 0 to 11.

In this case, there is a single related variable $x_{i,1} = \sin\left(\frac{i-c}{6}\pi\right)$. Statistics are given by the vector $Y = (Y_1, Y_2, \dots, Y_{12})$ and the smoothing criterion is written as:

$$R = \sum_{i=1}^{12}\left(Y_i - \hat{Y}_i\right)^2 = \sum_{j=1}^{12}\left(\hat{\beta}_0 + \widehat{\beta_1} \sin\left(\frac{j-c}{6}\pi\right) - Y_i\right)^2 \quad (3.11)$$

It allows you to get simple estimation equations:

$$\beta_0 = \frac{1}{12}\sum_{i=1}^{12} Y_j \quad (3.12)$$

$$\beta_1 = \left(\sum_{i=1}^{12} \sin\left(\frac{i-c}{6}\pi\right)(Y_i - \beta_0)\right) * \frac{1}{\sum_{i=1}^{12}\left(\sin\left(\frac{i-c}{6}\pi\right)\right)^2}$$

35 Adams, A., Bloomfield, D., Booth, Ph., England, P. 1993. Investment Mathematics and Statistics. Graham @ Trotman, London – Dordrecht – London. 209.

The latter formula follows from the fact that the derivative to β_1 from R gives the following relation:

$$\beta_0 \sum_{i=1}^{12} \sin\left(\frac{i-c}{6}\pi\right) + \beta_1 \sum_{i=1}^{12} \left(\sin\left(\frac{i-c}{6}\pi\right)\right)^2 - \sum_{i=1}^{12} Y_i \sin\left(\frac{i-c}{6}\pi\right) = 0$$

It remains only to emphasize that the constant c is chosen so that the criterion R is minimal. Application of the obtained estimates shows that individual outliers violate smoothing. The estimates can be improved by introducing an additional related variable of +1 for the cases with the highest values and -1 for the cases with the lowest values[36]. According to Tables 3.3 and 3.4 the highest values of average hourly wind power generation and average hourly peak wind power generation are in February, March and December, but the lowest values are in June and August. If using Boolean variables

$$x_{i,2} = \begin{bmatrix} -1, \text{if } i = 6 \text{ or } 8, \\ 1, \text{if } i = 2, 3 \text{ or } 12, \\ 0, \text{otherwise}, \end{bmatrix} \quad (3.13)$$

where i – number of month, then the modified regression model can be written as follows:

$$Y_i = \beta_0 + \beta_1 \sin\left(\frac{i-c}{6}\pi\right) + \beta_2 x_{i,2} + Z_i, i = 1, \ldots, 12 \quad (3.14)$$

Model (2.14) assumes that the maximum and minimum outliers have the same average deviations from the total average. If this is not the case, then additional related variables should be introduced to identify the maximum and minimum outliers:

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[36] Adams, A., Bloomfield, D., Booth, Ph., England, P. 1993. Investment Mathematics and Statistics. Graham @ Trotman, London – Dordrecht – London.

$$x_{i,2} = \begin{cases} -1, \text{if } i = 6 \text{ or } 8, \\ 0, \text{otherwise}, \end{cases} \tag{3.15}$$

$$x_{i,3} = \begin{cases} 1, \text{if } i = 2, 3 \text{ or } 12, \\ 0, \text{otherwise}. \end{cases} \tag{3.16}$$

The regression model will now look like this:

$$Y_i = \beta_0 + \beta_1 \sin\left(\frac{i-c}{6}\pi\right) + \beta_2 x_{i,2} + \beta_3 x_{i,3} + Z_i, i = 1, \dots, 12 \tag{3.17}$$

Next, the author has considered a regression model that approximates both tables, at once. To do this, the author introduces an additional related variable identifying the table under consideration, and the estimation will be carried out on all data from both Tables 3.3 and 3.4. Let us illustrate this using the example of the last model (3.17). A related variable $x_{i,4}$ will be added here:

$$x_{i,4} = \begin{cases} 1, \text{if the observation refers to table } 1, \\ 0, \text{otherwise} \end{cases} \tag{3.18}$$

As a result, we get the model:

$$Y_i = \beta_0 + \beta_1 \sin\left(\frac{i-c}{6}\pi\right) + \beta_2 x_{i,2} + \beta_3 x_{i,3} + \beta_4 x_{i,4} + Z_i, i = 1, \dots, 12 \tag{3.19}$$

As the tables shows, the developed model of the regression quite precisely describes our data. R-square is much closer to the unit that means that the model is qualitative. In addition, the lack of residual autocorrelation indicates us to the quality of the forecast.

Comparison of the two models (Eq. 3.14) and (Eq. 3.17) for the purpose of their practical use leads to the following recommendations. If we proceed from the formal criterion, the sum of squares of deviations (Eq.3.9), then the preference should be given to the model (Eq. 3.17). However, expert analysis shows that the results provided by the model (Eq. 3.14) are more logically justified. In this regard, model (Eq. 3.14) is recommended for practical use.

Conclusions

1. The author has substantiated the use of the sinusoidal dependence of wind energy indicators on the month of the year, as a basic model, for the correlation study. It is shown that if the maximum and minimum outliers of the studied data do not have the same average deviations from the general average level, then it is necessary to introduce additional accompanying variables that identify these outliers, which leads to the corresponding modified model. There are established the regression dependences of monthly wind power data. There also presented the calculated data on the validation of the obtained models.
2. In developing process of a methodology for statistical analysis of wind energy yearly and monthly (2019) data, it was established that for practical use should be applied analysis methods that give not only good quality criteria, but also the values of the considered indicators corresponding to the logical meaning. Polynomial regression has proven to be an ineffective tool for electricity demand forecasting. One of its main strengths is the negligible computational time it takes to perform forecasts without losing much in terms of accuracy. Furthermore, the forecasting model can be improved by certain modifications, the most promising of which has turned out to be subtraction of the model residuals averaged over hour-of-day.
3. Multiple (polynomial) regression has proven to be an ineffective tool for the analysis of monthly statistical data gave unsatisfactory results, therefore, it is recommended to use the model of sinusoidal dependence of the corresponding indicators on the month number.

4. While other modifications (*x* component and time series filtration) did not produce a consistently beneficial effect over the whole dataset, there were days when their inclusion aided in improving the accuracy. Thus, a model, which automatically selects the features the forecasting program, should consider before each daily forecast is advisable. Additionally, it should consider automatic selection of the training set size, since the optimum look-back horizon tends to vary during the peak wind power.
5. The developed models are recommended to be used as analytical tools for the electricity aggregator development in Latvia.
6. Such results can be a valuable input for analysis on necessity for compensation between aggregators and balance responsible parties or basis for further analysis for policy makers when considering necessity for state support to accelerate introduction of the service.

3.2 Characteristics and trends of indicators of export, import, and electricity consumption in Latvia. Wind power consumption characteristics and trends

As mentioned before, energy markets with high penetration rates of renewables are more likely to face price fluctuations or volatility, which is in part due to the stochastic nature of renewables. The Latvian electricity market is an excellent example of such a market, with over 40 % of Latvia's electricity generation based on hydropower, which disputes the spot electricity price forecast for the Latvian electricity market.

In this part of Thesis the author identifies trends in physical and value indicators of total exports, imports, total exchange turnover and electricity consumption in Latvia, and with a more detailed study of the characteristics and trends of indicators of electricity consumption from renewable resources for the period 2014, 2015–2019. Additionally, the indicators of the use of wind electricity were addressed both in general for the observed period and monthly for 2019. Overall, the results of the study confirm the feasibility of Latvia's plans to increase both the total consumption of electricity and its share from renewable sources. At the same time, the coronavirus pandemic has already begun to lead to negative consequences of electricity consumption in the EU countries, which have so far affected Latvia to a lesser extent. Nevertheless, these consequences will inevitably lead to an adjustment of Latvia's electricity plans towards an increase in the share of production and consumption of electricity from renewable sources, including wind energy, despite its upward price trend. The author with employment of the tools Excel Trendline obtains the trends of indicators, approximating formulae dependencies and the coefficients of determination for the relevant diagrams and charts.

Motivation for research

Trends, indicators and prospects for the development of the Latvian energy sector in combination with climate change for the next decade are reflected in the National Plan of Latvia for 2021–2030.

The author set herself the task of analyzing the dynamics and trends of the indicators under consideration for the period 2015–2019 – a period ending, on the one hand, with the adoption by the European Union of strategic decisions to combat harmful emissions into the atmosphere and the global transition to the production of electricity using renewable sources, and, on the other hand, the outbreak of the coronavirus pandemic.

The expansion of electricity production from renewable sources will grow only due to the wind power industry, since the hydro power generation capabilities of the Daugava HPP cascade are limited by its design characteristics. The results obtained will serve as a basis for the subsequent identification of trends for the analysed indicators and for the development of appropriate practical recommendations.

Calculation of trends of indicators, approximating formulae dependencies and the coefficients of determination for the relevant diagrams and charts are based on big data collected from the Latvian transmission system operator, Central Statistical Bureau of Latvia, and Nord Pool, the power exchange. The data used in the empirical study is collected from hourly data from the period 1 January 2014 to 31 December 2019. (See Annex1)

The analysis of a small number of selected indicators in the work is carried out using graphs and displaying on them the equations of the trends of these indicators, and the coefficients of determination R^2, obtained by the author using the Trendline Excel toolkit. With a large number of analysed indicators, their display on the graphs is cumbersome; therefore, tables in which the trend equations and the coefficients R^2 and R are given – the correlation coefficients between the estimated and observed values of Y and X, accompany the graphs. Trends reflects the dynamics of growth (decrease) of statistical indicators and can be used to forecast them for a short-term period (usually for one period – a month, a year). Regression dependences[37], which makes it possible to qualitatively assess the direction of the trend, were selected by the author from linear equations that, according to observations of Xi Yi, have the following general form:

$$Y = bX + a \tag{3.20}$$

where the coefficients a and b – are the least squares estimates

Linear regression relationships were used only to assess the qualitative direction of trends. Other types of trends provided by the *Trendline Excel* toolkit are partially used in the work in order to obtain greater reliability of their

[37] Rawlings, J. O., Pantula, S. G., Dickey, D. A. 2018. Applied Regression Analysis. A research tool. 2nd ed. Springer-Verlag NY. 21, 87, 107–110. ISBN 0-387-98454-2

direction. Recall that for a linear regression model with one parameter *X*, the coefficient R^2 is equal to the square of the correlation coefficient between the estimated and observed values of *Y* and *X*. In estimating regression models, the value of the coefficient of determination R^2 is interpreted as the model correspondence to the presented data[38].

The dynamics of statistical physical electricity indicators in Latvia in MWh for the period 2014 – 2019 is presented in Table 3.2 and shown in Figure 3.1. The following designations of average hourly volumes (MWh) have been introduced: production (*Q*1), consumption (*Q2)*, import (*Q3*), export (*Q4*), total exchange turnover (*Q5)* (import + export: *Q5 = Q2 + Q3*) and the excess of import over export (*Q6) (Q6 = Q3 – Q4*).

Table 3.2

Electricity generation, import, export and consumption in Latvia, 2014–2019

Indicator MWh (Year)	2014	2015	2016	2017	2018	2019
Total net electricity production (*Q*1)	4857	5384	6228	4401	6500	6108
Deliveries to the internal market, Consumption (*Q*2)	7172	7201	7263	7278	7408	7226
Import (*Q*3)	5338	5247	4827	4074	5172	4612
Export (*Q*4)	3119	3424	3794	4136	4264	3494
Import + Export, total (*Q*5)	8457	8671	8621	8210	9436	8106
Import-Export (Q6)	2219	1823	1033	(62)	908	1118

Source: created by the author based on Central Statistical Bureau of Latvia[39].

38 Abdey J. 2018, *Data Analysis for Management Programme*, Module 6 Unit 1, London School of Economics and Political Science, UK, 8–16.

39 Central Statistical Bureau of Latvia. [Online]. Available at: www.csb.gov.lv/en [Accessed 07.08.2020]

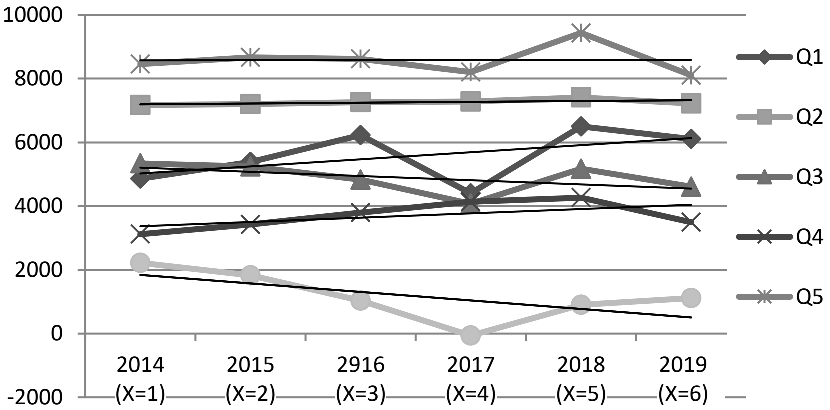

Figure 3.1 **Dynamic of electricity generation, import, export and consumption in Latvia, 2014–2019**

Source: created by the author based on data from Central Statistical Bureau of Latvia.

The data in Table 3.2 and Figure 3.1 show that Latvia's electricity imports increase with a drop in the electricity generated at the Daugava HPP cascade due to a drop in the water levels in the reservoir. Accordingly, the export of electricity significantly increases with an increase in the generated electricity at the cascade of the Daugava HPPs with an increase in the inflow of water into the reservoir. During the observed period, only in 2017, the volume of exports *Q4* = 4136 MWh slightly exceeded the volume of imports *Q3* = 4074 MWh of electricity.

Table 3.3 shows the minimum, average and maximum values of the average hourly indicators *Qi*, the corresponding trend equations *Qti*, as well as the values of the coefficients R^2 and *R*. From Table 3.2 and Figure 3.1 it follows that the annual electricity consumption in Latvia is practically unchanged and averages 7258 MWh, reaching a maximum value of 7408 MWh in 2017 and decreasing to 7226 in 2019.

Table 3.3

Minimum, average and maximum values of average hourly indicators *Qi* and their *Qti* trend equations

Indicators	*Qi*min	*Qi*max	*Qi*mid	Equation *Qi*	R^2	*R*
***Q*1**	4401	6500	5580	*Qt*1 = 222.17X +4802.1.1	0.2471	0.5
***Q*2**	7172	7408	7258	*Qt*2 = 25.886X + 7167.4	0.339	0.58
***Q*3**	4074	5338	4878	*Qt*3 = -131.66X + 5339.1	0.2629	0.51
***Q*4**	3119	4264	3705	*Qt*4 = 0.135.34X + 3231.5	0.3294	0.57
***Q*5**	8106	9436	8584	*Qt*5 = 3.6857X + 8570.6	0.0002	0.014
***Q*6**	(62)	2219	1173	*Qt*6 = -267X + 2107.7	0.398	0.63

Source: created by the author.

Note that the closeness of the relationship (according to Scale Cheddoka) between statistical data on these indicators and linear trend equations, expressed by the coefficients R^2, ranges from weak (*Qt1*, *Qt3*) to moderate (*Qt2*, *Qt4*, *Qt6*). These equations can be used for short-term "approximation" of the corresponding indicators for the next year, but not for accurate estimation, since regression models with coefficients R^2, <1 are of low practical value. Electricity production (*Qt1*), consumption (*Qt2*) and export (*Qt4*) trends are upward. The trends in imports (*Qt3*) and the excess of imports over exports (*Qt6*) of electricity are of a downward character, which indicates the dynamics of a slow but decreasing dependence of Latvia on imports of electricity. The trend of the exchange turnover of electricity (*Qt5*) has a neutral character with practically zero coefficient R^2, and the corresponding equation cannot be used for a short-term "approximate" forecast of this indicator.

Let address the dynamics of changes in the total share of electricity produced by HPP and WPP from the total volume of electricity produced for the period 2014–2019 in Latvia. Table 3.4 presents data on the share (%) of electricity generated (without own consumption and losses) in Latvia from renewable sources, which are HPP and WES, obtained by the author by calculation using statistical data from JSC "Augstsprieguma tīkls"[40], Latvian electricity market overview. The total share of HPP and WPP by year is shown in Figure 3.2.

Table 3.4

Shares of electricity generated in Latvia at HPP and WPP, 2014–2019

Indicator (%)	2014	2015	2016	2017	2018	2019
HPP (%)	34	30	50	58	37	34
WPP (%)	2.4	2.3	0.7	0.7	1.9	2.5
HPP + WPP (%)	36.4	32.3	50.7	58.7	38.9	36.5

Source: created by the author based on JSC "Augstsprieguma tīkls". Latvian electricity market overview.

Figure 3.4 shows the dynamics of changes in the total share of electricity produced by HPP and WPP from the total volume of electricity produced for the period under review in Latvia. The linear trend of this indicator (lower line in Figure 3.2), as well as the logarithmic trend, over the observed period has a neutral character with a barely noticeable increase, but with very low determination coefficients – R^2 = 0.022 and 0.0791, respectively.

[40] Electricity Market Review by JSC Augstsprieguma tīkls [Online]. Available: http://ast.lv/lv/electricity-market-review [Accessed 05.08.2020]

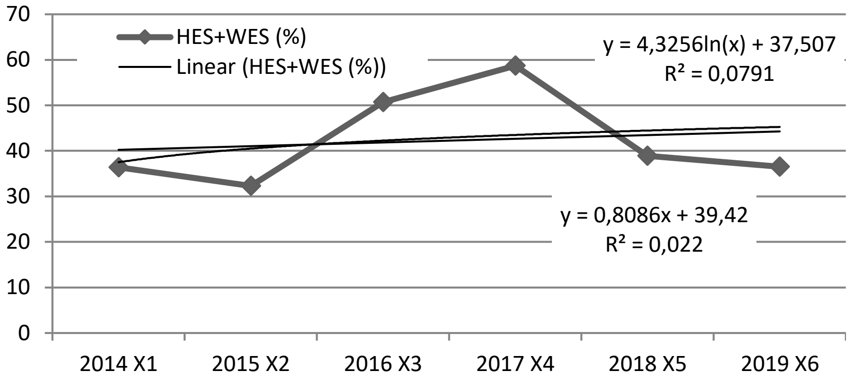

Figure 3.2 **Dynamics of the share of HPP and WPP in the total share of electricity generated in Latvia**

Source: created by the author based on JSC "Augstsprieguma tīkls". Latvian electricity market overview.

From Table 3.4 and Figure 3.2 it follows: first, the share of electricity production from RES over these years averaged 42.25 % with a maximum value of 58.7 % in 2017 and a drop in 2018 and 2019; second, both the total share and its components are unpredictable; therefore, this trend can be identified more qualitatively from the statistical data of 2020 and 2021. We recall that in accordance with National Energy and Climate Plan of Latvia 2021–2030, the share of renewable energy sources in final energy consumption should grow (in %) in 2020, 2022, 2025, 2027 and 2030, respectively, to 40.95, 41.25, 42.5 43.75 and 45, respectively.

In order to minimize risks, maximize profits and make plans, it is important for participants of electricity market to forecast future prices. In this part data of Latvia's price zone in Nord Pool power market is analysed. The data set consists of historical hourly electricity prices (Euro / MWh) from January 1, 2014 to December 31, 2019. In Figure 3.3 shows the dynamics of changes in the average cost (C) of one MWh of consumed electricity in Latvia (European Network of Transmission System Operators for Electricity 2020).

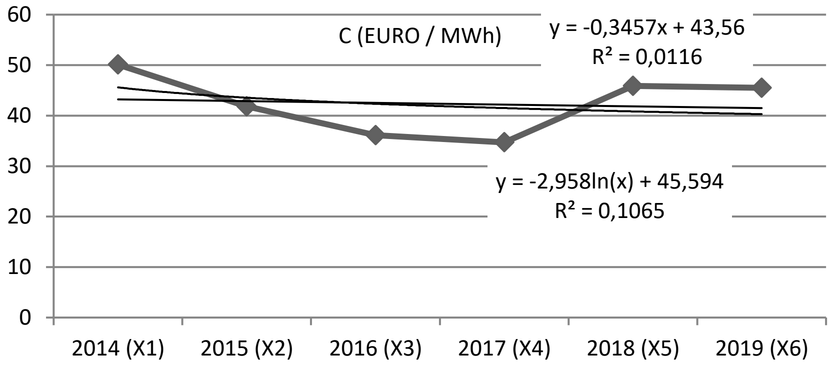

Figure 3.3 **Dynamics of the cost of one MWh for electricity consumers in Latvia, 2014–2019**

Source: created by the author based on (European Network of Transmission System Operators for Electricity 2020[41].

For the period 2014–2015, the price indicators of the minimum (C_{min}), maximum (C_{max}), average (C_{mdl}) values are, respectively, 34.7 (2017), 50.1 (2014) and 42.35 EURO / MWh. Linear regression with a very low coefficient of determination R^2 = 0.0116 shows a neutral trend in this indicator with a barely noticeable downward trend. Logarithmic regression with a higher coefficient R^2 = 0.1065 gives more confidence in the downtrend of the indicator in question. In 2018, the average price on the electricity exchange in the Latvian trade zone was 46.28 EURO / MWh, while the average daily price ranged from 11.99 to 89.45 EURO / MWh.

[41] European Network of Transmission System Operators for Electricity. URL: https://www.entsoe.eu [Accessed 05.08.2020]

Wind power consumption characteristics and trends

The situation with wind power plants capacity is different and not only in total Baltic volumes, but in volumes of each country.

Figures 3.5 and 3.6 show, respectively, the dynamics of statistical indicators for the planned consumption of wind energy Q_{wes} (MWh) for the day ahead and its cost C_{wes} (EURO / MWh) on the NordPool exchange for Latvia [42]. The observation covers the period from 2015 to 08/20/2020.

The trend of the Q_{wes} indicator (Figure 3.4) with the coefficient $R^2 = 0.7$, also shown in Figure 3.4, has a clearly pronounced upward character with a high strength of connection with statistical data and indicates a steady annual increase in wind power consumption in Latvia.

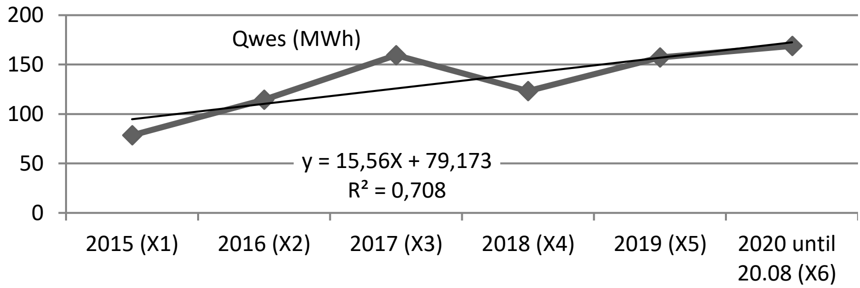

Figure 3.4 **Dynamics of planned wind power consumption for the day ahead in Latvia, 2015–2020**

Source: created by the author based on (Nord Pool. Market Data 2020).

The upward trend of the C_{wes} indicator, shown in Figure 6 by the equation with a high value of $R^2 = 0.7$, in turn indicates a significant increase in the cost of one MWh of wind power consumed in Latvia. Over the past 5 years, this cost has doubled on average. Comparing the data for the comparable period 2015–

[42] Nord Pool. Market Data. URL: https://www.nordpoolgroup.com/ [Accessed 22.11.2020]

2019, presented in Figures 3.4 and 3.5, we get: firstly, the corresponding trends are in different directions; secondly, the average cost of consumed wind electricity (123.5 EURO / MWh) is three times higher than the average cost of electricity 40.8 (EURO / MWh) consumed from all PPs. Such ratios are not yet in favour of wind power, and during its development, it is necessary to correlate economic with environmental justifications.

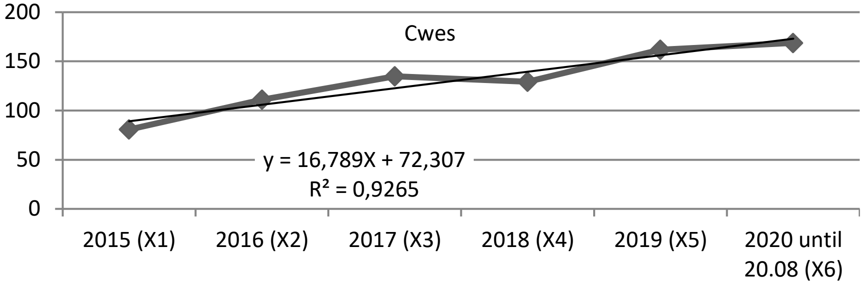

Figure 3.5 **Dynamics of the cost on the Nord Pool exchange of wind energy planned for consumption for the day ahead in Latvia, 2015–2020**

Source: created by the author based on (Nord Pool. Market Data 2020).

Let us further investigate in more detail the indicators of consumed wind energy in 2019 during peak hours from 8.00 to 12.00, calculated by the author, based on statistical data.

Table 3.5 shows the author's calculated indicators of the amount of wind electricity planned for consumption the day ahead and its cost on the NordPool exchange in the corresponding month (MWh, EURO / MWh):

- $\hat{W}$, $\hat{C}$ – hourly average;
- $\hat{W}_p$, $\hat{C}_{Wp}$ – average values during peak hours from 8.00 to 12.00.

Table 3.5

Estimated indicators of wind power consumption in Latvia, 2019

Month	$\hat{W}$	$\hat{C}$	$\hat{W}_p$	$\hat{C}_{Wp}$
January	171	57	174	64

Month	$\hat{W}$	$\hat{C}$	$\hat{W}_p$	$\hat{C}_{Wp}$
February	219	47	211	50
March	222	40	230	43
April	141	44	118	52
May	135	44	123	57
June	89	45	76	66
July	122	49	96	61
August	58	39	47	60
September	161	49	149	67
October	159	47	153	56
November	183	45	181	48
December	224	39	213	42

Source: created by the author based on (Nord Pool. Market Data 2020).

Graphs displaying the dynamics of monthly changes in $\hat{W}$, $\hat{W}p$ (MWh), and $\hat{C}$, $\hat{C}_{Wp}$ (EURO / MWh) are shown in Figure 3.6 and 3.7.

The graphs of the $\hat{W}$ and $\hat{W}_p$ indicators (Figure 3.6) practically repeat each other, with close monthly values and close averaged values of 157 and 148 (MWh), which indicates that the peak periods practically do not affect the change in the trend of consumed wind energy. At the same time, the months of the year significantly affect the trend of these indicators, which take the lowest values in the warm months from April to September and the highest in the rest of the months.

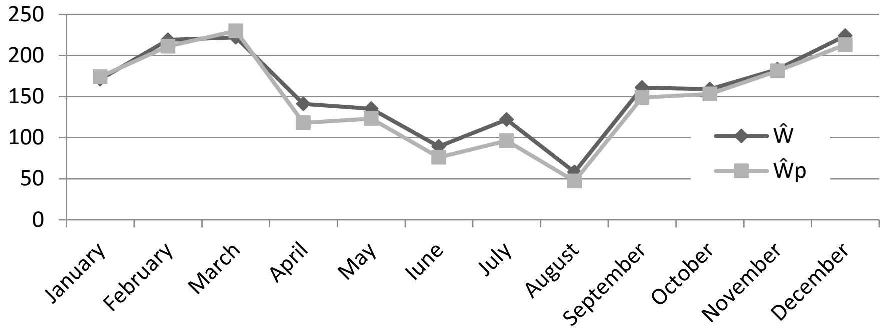

Figure 3.6 **Dynamics of average hourly values of indicators**
Ŵ and $\hat{W}_p$ (MWh), 2019

Source: created by the author based on (Nord Pool. Market Data 2020).

The graphs of the $\hat{W}$ and $\hat{W}_p$ indicators (Figure 2.7) practically repeat each other, with close monthly values and close averaged values of 157 and 148 (MWh), which indicates that the peak periods practically do not affect the change in the trend of consumed wind energy. At the same time, the months of the year significantly affect the trend of these indicators, which take the lowest values in the warm months from April to September and the highest in the rest of the months.

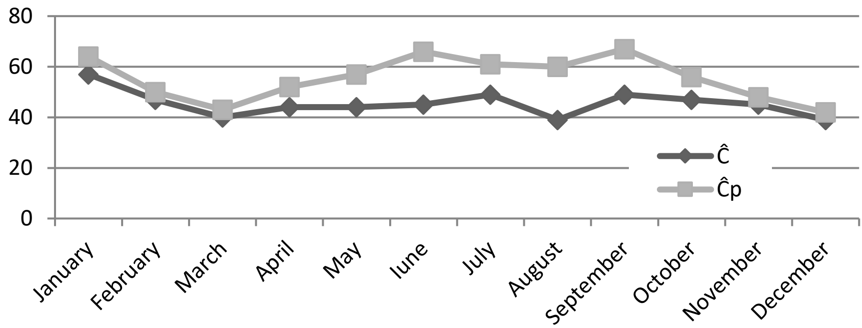

Figure 3.7 **Dynamics of average hourly values of indicators**
Ĉ and $\hat{C}_{Wp}$, 2019

Source: created by the author based on (Nord Pool. Market Data 2020).

The graphs of the $\hat{C}$ and $\hat{C}_{\mathrm{Wp}}$ indicators (Figure 3.7) are also similar in character. In general, the indicator values during peak hours ($\hat{C}_{\mathrm{Wp}}$) are higher than the average hourly monthly values. Their averaged values 45 and 55 (EURO / MWh) differ by only 18 %.

Conclusions

1. Trends in the production, consumption and export of electricity in Latvia are weak, but upward. The trends in imports and the excess of imports over exports of electricity are of a downward nature, which indicates the dynamics of a slow but decreasing dependence of Latvia on imports of electricity. Cannot be used for a short-term "approximate" forecast of this indicator.
2. The trend of planned wind power consumption for the day ahead in Latvia has a clearly pronounced upward character with a high strength of connection with statistical data (coefficient $R^2 = 0.7$) and indicates a steady annual increase in wind power consumption in Latvia, which corresponds to the goals of increasing the share of RES in final energy consumption should grow and reach its share up to 45 % by 2030. At the same time, the upward trend in the cost of one MWh (wind power consumed in Latvia with a high value of $R^2 = 0.7$) does not correlate with the trend in its consumption. This circumstance, as well as the consequences of the coronavirus pandemic, may require adjusting plans to increase electricity consumption from RES, which will require a more detailed assessment of the volume of wind power imports and, possibly, the implementation of measures to increase the capacity for the production of this energy in Latvia.

3. In developing process of a methodology for statistical analysis of wind energy yearly and monthly (2019) data, it was established that for practical use should be applied analysis methods that give not only good quality criteria, but also the values of the considered indicators corresponding to the logical meaning. Multiple (polynomial) regression has proven to be an ineffective tool for electricity demand forecasting. One of its main strengths is the negligible computational time it takes to perform forecasts without losing much in terms of accuracy. Furthermore, the forecasting model can be improved by certain modifications, the most promising of which has turned out to be subtraction of the model residuals averaged over hour-of-day.
4. Multiple (polynomial) regression has proven to be an ineffective tool for the analysis of monthly statistical data gave unsatisfactory results, therefore, it is recommended to use the model of sinusoidal dependence of the corresponding indicators on the month number.
5. While other modifications (*x* component and time series filtration) did not produce a consistently beneficial effect over the whole dataset, there were days when their inclusion aided in improving the accuracy. Thus, a model, which automatically selects the features the forecasting program, should consider before each daily forecast is advisable. Additionally, it should consider automatic selection of the training set size, since the optimum look-back horizon tends to vary during the peak wind power.
6. The developed models are recommended to be used as analytical tools for the electricity aggregator development in Latvia.

4 The Model for Regulating Electricity Consumption in Latvia on the Basis of the Regional Aggregator of Demand Response

Chapter 4 consists of 3 sections, 33 pages, 7 figures, and 19 tables

The analysis carried out in the 1st and 2nd chapters implicate the need of creation of model, of regulating of electricity consumption using Demand Response and customer engagement. Demand response (DR) is considered as a major method that can be taken in order to reduce consumer electrical energy usage when contingencies occur to disturb the balance of supply and demand. DR is introduced as a tariff or programme to motivate the end-users in response to changes in the electricity price or to incentive payments which are designed to induce lower electricity consumption when system reliability is jeopardized or during high prices of the wholesale market.[43]

Therefore, ***the goal of this chapter will be: the development of model of a two-stage optimization methodology of regulating of electricity consumption using Demand Response.***

For the implementation of this goal it is necessary:

- to analyse the customers behavioural potential for participation in demand response aggregator, carrying out quantitative research of prosumers in Latvia;
- to suggest the two-stage optimization of the balance of supply and demand, were on the first stage it is proposed to solve the problem of reducing electricity consumption and, at the second stage – to

[43] Rashidizadeh-Kermani, H., Vahedipour-Dahraie, M., Shafie-khah, M., Catalão, J. P. S. 2019. Stochastic programming model for scheduling demand response aggregators considering uncertain market prices and demands, International Journal of Electrical Power & Energy Systems, Volume 113, 528–538, ISSN 0142-0615, https://doi.org/10.1016/j.ijepes.2019.05.072. [Accessed 07.08.2020]

solve the optimization problem of what groups of active consumers loads should be shifted off, if the amount of electricity is not enough and, therefore, in response to electricity market prices.

Thus, the author suggests starting with investigation of the place and role of electricity consumer in the electricity market.

4.1 The role of the energy prosumer in the electricity market

Currently, the energy industry in the EU countries, as well as around the world, is undergoing a transformation in which consumers use, store or sell their own electricity or participate in Demand Management (DM) and energy efficiency schemes, thus transforming themselves into active consumers. At the same time, the number of active consumers of electricity (industrial, commercial, agricultural and household consumers) under DM conditions should become quite massive.[44]

The movement of prosumers in Latvia is at an early stage of development. However, there are various initiatives, including small enterprises, municipal, and individual citizens that incorporate the features of energy prosumers or renewable energy source (RES) projects. Various RES are used for electricity generation in the residential sector, such as solar and wind energy[45]. Up to June 2020, the Ministry of Economics (ME) had issued 282 permits to increase electricity generation capacity or introduce new generation facilities that

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[44] Jan Stede, Karin Arnold, Christa Dufter, Georg Holtz, Serafin von Roon, Jörn C. Richstein. 2020. The role of aggregators in facilitating industrial demand response: Evidence from Germany, Energy Policy, Volume 147, 111893, ISSN 0301-4215, https://doi.org/10.1016/j.enpol.2020.111893. [Accessed 29.08.2021]

[45] Lebedeva, K.; Krumins, A.; Tamane, A.; Dzelzitis, E. 2021. Analysis of Latvian Households' Potential Participation in the Energy Market as Prosumers. Clean Technol., 3, 437–449. https://doi.org/10.3390/ cleantechnol3020025[Accessed 5 January 2021]

do not meet the requirements for microgenerator connections[46]. According to the information of the ME on issued permits, 46 % of them use solar energy and 30 % use wind energy to generate electricity; the rest also use RES hydropower or biomass cogeneration plants. Thirty-seven percent of electricity is produced for their own consumption, and only 4 % of the permits have been for households and other legal entities[47].

Prosumer's awareness in Latvia

In order to investigate truthfulness of theoretical part of project, it is reasonable to conduct quantitative research among prosumers for better comprehension of definition of prosumers, the sense of electricity, type of energy used and produced by prosumers, heating types and other factors.

The goal of this analysis is to explore level of an awareness of Latvian consumers of electricity about prosumerism, willingness of people who are well aware of the concept to engage in the process and to recognize the main electricity consumption factors that may lead to it.

The survey was open to everyone interested in participating, however, the sample was not representative of the Latvian population because the aim was mainly to learn about the level of an awareness of Latvian consumers of electricity about prosumerism, and thus, about potential for engagement in demand response in Latvia. Representative data would enable more detailed analyses about the willingness and motives of different types of consumers to take part in demand response. Further, the differences in the preferred

[46] Bogdanovičs, R., Borodinecs, A., Zajacs, A., Šteinerte, K. 2018. Review of Heat Pumps Application Potential in Cold Climate. Adv. Intell. Syst. Comput. 543–554. [Accessed 5 January 2021]

[47] Latvian Ministry of Economics: Permits for the Introduction of New Electricity Generation Facilities. Available online: https://www.em. gov.lv/lv/ nozares_politika/atjaunojama_energija_un_kogeneracija/atlaujas_jaunu_elektro-energijas_razosanas_iekartu_ieviesanai/ (Accessed 4 December 2020).

information channel on electricity consumption and prices could be analysed. Finally, because of the survey method, it is possible that the respondents were more interested in energy issues than average residential consumers. The survey is thus susceptible to the same self-selection bias identified in other surveys and pilots about demand response or energy issues in general.

The study of the preferences of consumers (See Chapter 1.1 Genesis of DR) has been limited to the preferred set-up time for the scheduling of appliance operations or air or water temperatures, so there are no any approaches in the literature that assist the end-user to aggregate the total preferences regarding all effective parameters in energy consumption. In the methodology part, it is intended to apply quantitative method, which is valuable to gather respondents' opinion through numeric data. In differ from qualitative method, quantitative allows to amass replies and make correlation between independent and dependent variables by coded information. Initially step is to prepare questionnaire (see Annex 2) which is considered one of research tool for quantitative method. After construction of the tool, questionnaire was forwarded to random respondents through social media channel. As the final stage, it was collected replies from 108 respondents. After taking interview from prosumers, their answers were codded and inserted into Excel file that has been dragged by numeric way then to SPSS program. For obtaining the coefficient of reliability was used the Cronbach's alpha test (with the value, the module of which is between 0 and 1, which is carried out, using the SPSS programmes).

The coefficient of reliability is an important criterion for the evaluation of test results. It is a measure of accuracy with which is carried out the testing of some feature. In calculation was used the SPSS program, the Cronbach's Alpha with the value, the module of which is between 0 and 1.

The standardized Cronbach's alpha coefficient α_{st} is calculated by formula:

$$\alpha_{st} = \frac{N \cdot \bar{r}}{1 + (N - 1) \cdot \bar{r}} \qquad (4.1.)$$

where N is the number of the researched components, but determines the average coefficient of the correlation between the components.

4.2 The development of model of a two-stage optimization methodology of regulating of electricity consumption using Demand Response

Motivation for research

The rapid development of renewable energy and its integration into the energy system, the growing requirements of modern industry with a high level of digitalization to the quality of energy supply, as well as the widespread introduction of energy-saving technologies dictate the need for a radical renewal of the energy grid economy through the large-scale development of smart grids. Smart Grid is seen as a fully integrated, self-regulating and self-healing power system with a network topology and including all generating sources, trunk and distribution networks and all types of consumers of electrical energy, controlled by a single network of information and control devices and systems in real time.

In optimized consumption, higher peaks clip, and lower valleys fill by rescheduling electric appliances and energy usage over a time horizon in response to a DR signal.[48]

[48] Latvian Ministry of Economics: Permits for the Introduction of New Electricity Generation Facilities. Available online: https://www.em. gov.lv/lv/ nozares_politika/atjaunojama_energija_un_kogeneracija/atlaujas_jaunu_elektro-energijas_razosanas_iekartu_ieviesanai/ (Accessed 4 December 2020).

Objectives in Optimization

Optimization of DR mechanisms obtains the best possible variables to maximize or minimize an objective function value, provided that the variables are bounded by a set of constraints[49].

Optimization problems can be categorized according to several criteria. Depending on nature (degree in the polynomial form of the function) of the objective functions and constraints involved, linear and nonlinear optimization exists. If at least one of the objective functions and / or constraints is nonlinear, the problem is said to be nonlinear optimization. A mixed integer programming problem denotes whether some of the variables are integers. Additionally, based on the nature of the variables (deterministic or the stochastic) involved, optimization problems can be classified into deterministic and stochastic programming problems; the latter case describes optimization models that deal with RES, due to the stochastic nature of these sources.[50]

As have been mentioned in the first chapter, all EU countries both buy and sell electricity on the Nord Pool exchange. Many of them, including Latvia, import more electricity than they sell. Therefore, the optimization of the balance of supply and demand is an important task, for the solution of which a two-stage optimization methodology is proposed.

Thus, at the first stage, based on predicted data on the shortage of electricity for the next day, it is proposed to solve the problem of reducing its consumption. At the second stage, the choice of active consumers to be switched off for the current hour is optimized if the amount of electricity is not enough,

49 Vardakas, J. S., Zorba, N. and Verikoukis, Ch. V. 2014. A Survey on Demand Response Programs in Smart Grids: Pricing Methods and Optimization Algorithms, *IEEE Commun. Surv. Tutorials*, vol. 17, no. c, 1–1.

50 Ribó-Pérez, D.; Larrosa-López, L.; Pecondón-Tricas, D.; Alcázar-Ortega, M. 2021. A Critical Review of Demand Response Products as Resource for Ancillary Services: International Experience and Policy Recommendations. Energies, 14, 846. https://doi.org/10.3390/en14040846

even taking into account a decrease in its consumption. The developed methodology is based on the corresponding mathematical models at each of their stages, for which the corresponding optimization problems were formulated at each stage. Examples of solving problems by exact and approximate methods are given. The developed models are recommended to the regional aggregator of DR for use in the corresponding online software for balancing the demand and supply for electricity.

Another solution in the event of a shortage of electricity is to temporarily disconnect all or part of the active customers (AC) in accordance with the contractual terms with the electricity suppliers. In world practice, the main solution for involving consumers of the retail electricity market in DM was the creation of specialized organizations – demand management aggregators (ADM), whose commercial activity is to provide demand response services. It is important in IT ADM to use the appropriate analytical tools, on the basis of which it would be possible to carry out optimization calculations to determine both the amount of purchased electricity and temporarily disconnected AC. Thus, we get two optimization problems:

1) optimisation of the volume of reducing the consumption of electricity in case of its shortage;
2) determination (scheduling) of temporarily disconnected user groups in the event of a shortage of electricity.

To solve the problem, it is necessary to develop appropriate mathematical models and methods for their application, which are applied on the basis of forecast information on the amount of electricity shortage and its cost upon purchase.

The present research is devoted to the development of appropriate DR models and their validation, which, with this approach, can be considered pioneering in the area under consideration.

Stages of solving the problems of optimal regulation of the balance of supply and demand of consumed energy

The average daily generation and consumption of electricity, depending on many factors, in Latvia, as in many other EU countries, is generally not balanced, therefore Latvia carries out both imports and exports of electricity, buying and selling it on the Nord Pool electricity exchange. The sale and purchase of electricity is carried out by bid – one-time applications per day to the exchange for tomorrow before the start of trading, which determines the amount in megawatt-hours (MWh) that is missing for energy consumption. The price of one MWh of traded electricity is determined by the Nord Pool power exchange. It is proposed to solve the optimization problems of operational-hour energy consumption in case of its potential shortage in two stages (Fig. 4.2). At the first stage, based on the data on the forecast of energy shortages, the amount of additional purchased electricity for tomorrow is optimized. Forecast data are always probabilistic, therefore it is quite plausible to assume that even with the additional purchase of energy, completed yesterday, it may not be enough at certain hours of the current day and additional purchase on this day is no longer possible. Therefore, it is necessary to solve the problem of the second stage – optimization of the number, type and regional location of the hourly AC shutdown. Note that the first task is solved for the entire region (country), based on energy consumption per day, and the second task – for each current hour of energy shortage.

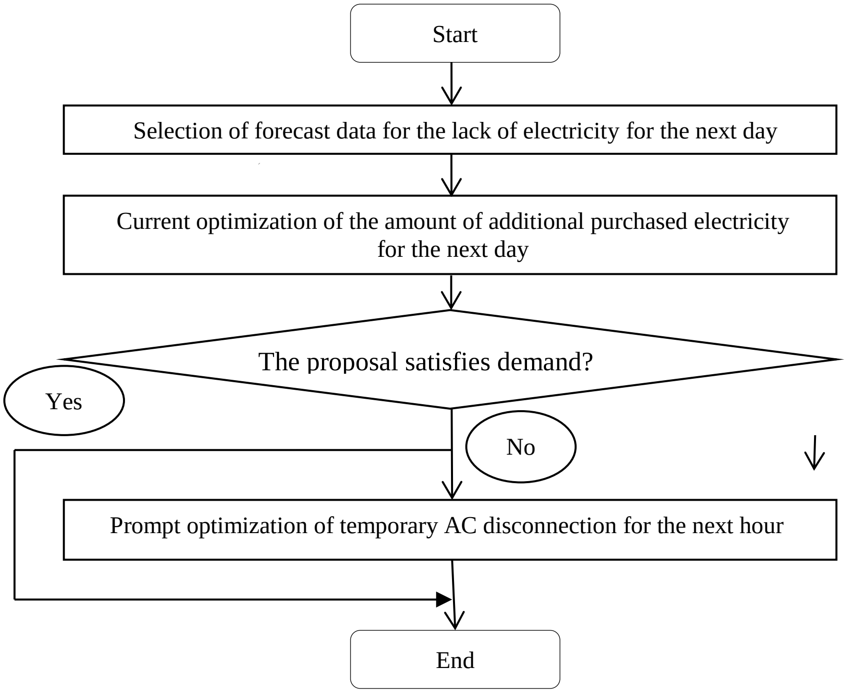

Figure. 4.1 **The algorithm structure of the two-stage procedure for optimal regulation of the balance of supply and demand for consumed electricity for the next day**

Source: created by the author.

a. The problem of the current optimization of the amount of additional purchased electricity for the day ahead with the forecast of its shortage

According to statistics (see Chapter 1), the excess of imports over exports of electricity in Latvia, i.e. its shortage averaged 1118 MWh in 2019 and about 3.06 MWh per day, which is about 18 % of the annual consumption of 6108 MWh. In general, the import was 4612 MWh and about 12.6 MWh per day. Current purchase prices *(c)* for 1 MWh ranged from 1 to 487 (EURO / MWH) and averaged $\hat{c}$ = 155.6 EURO / MWh. At the same time, the selling price of electricity (z) for various types of consumers in Latvia (households, agriculture, industrial enterprises, etc.) is always constant throughout the day and averages $\hat{z}$ EURO / MWh. Thus, the purchase of the missing electricity on the exchange is in all cases beneficial if $\hat{z} \geq c$ and the total purchase price *C (i) i* MWh (i = 1, 2, ..., n) linearly depends on *c*, i.e. *C (i = ic),* where c is the predicted value of the price of 1 MWh on the exchange for the next day. If *C (i)* depends nonlinearly on *c*, the value of *C (i)* with an increase in *i* may turn out to be too large. Therefore, in such cases, it is proposed to optimize the volume *(i)* of electricity purchased at the exchange, taking as a criterion the inequality:

$$Q = max \sum_{i=1}^{n} [i\hat{z} - C(i,c)] \leq 0 \quad (4.2)$$

i – predicted amount of MWh power shortages for the next day
$\hat{z}$ – the average price of 1 MWh of electricity supplied to consumers in Latvia (on the domestic market, the price of electricity does not change during the day)
$i\hat{z}$ – the cost of selling additional electricity purchased to Latvian consumers *i* MWh on the exchange;
c – predicted price of 1 MWh next day on the exchange
C(*i*,*c*) – nonlinear function of the cost of additionally purchased electricity *i* MWh at the price c on the Nord Pool power exchange in the Latvian trade zone

Thus, it is advisable to purchase only those *i* MWh of electricity for which the inequality max $Q \leq 0$ is satisfied. In any case, the decision on additional purchase remains with the Aggregator, which makes a decision not only on the basis of economics, but also other considerations.

Case study

The formulated optimization problem (Eq.4.2) is quite simple. Let us give its solution using an example based on the following considerations:

1. According to statistics (see Chapter 2), the excess of imports over exports of electricity in Latvia, i.e. its shortage averaged 1118 MWh in 2019 and about 3.06 MWh per day. Therefore, the approximate value of the index *n* is no more than 10 MWh.
2. The price $\hat{z}$ is assumed constant and equal to 150 EURO / MWH, based on the price of 0.15 EURO per 1 kilowatt hour.
3. The price of one MWh s on the exchange may vary widely. In particular, according to (Annex I Table 1 2015–2019 Wind / price statistic hour) for the period from 01.01 to 20.08 2019, this price varied from 1 to 484 EURO / MWh. For example, the dependence $C(i,c) = c^{i/2}$ is chosen with an initial c = 5 EURO / MWh.

The calculated data of the example and the result obtained are shown in Table 4.1.

Table 4.1

The problem of the current optimization of the amount of additional purchased electricity for the day ahead with the forecast of its shortage (Eq.4.2)

I	$i\hat{z}$	***C(i,c)***	***Q***
1	150	3.2	146.8
2	300	10	290
3	450	31.6	418.4
4	600	100	500
5	750	316.2	433.8
6	900	1000	(-)100

Source: created by the author.

The graphs of the dependences *iẑ* and *C (i, c)* are shown in Figure 4.2

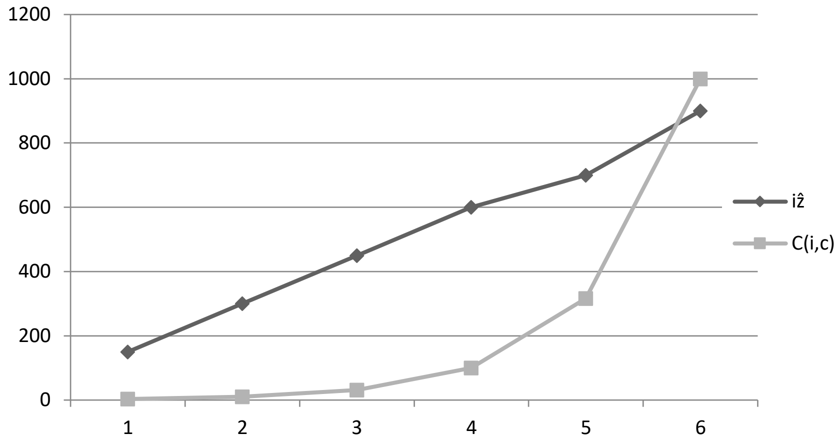

Figure 4.2 **The problem of the current optimization of the amount of additional purchased electricity for the day ahead with the forecast of its shortage**

Source: created by the author.

The calculation example shows that with the given initial data, the purchase of 6 MWh on the exchange is not profitable, since the Q criterion takes on a negative value (Q = -100). A reliable assessment of the functional dependence C (i, c) is important in the practical application of this problem. With a linear dependence C (i, c), the formulation of the problem in the form (1) does not make sense, since for any n the inequalities Q > 0 or Q < 0 will be satisfied, depending on the relation ẑ and c.

b. The task of operational optimization of disconnected AC groups for the next hour in case of a power shortage

In case, if consumer would like to maintain a certain consumption habits during peak hours and not change consumption behaviour, then they are ready to pay for it. However, if active consumers decide to not exceed budget / get profit, then they should alter energy consumption and turn off some appliances / equipment and shift the consumption to off-peak hours.

Combinatorial Optimization Methodology: Knapsack Problem

The knapsack problem (KP) is a very simple non-trivial integer programming model with binary variables and is a classic form of a maximization problem which has been studied for centuries. Although this method has only one single constraint and positive coefficient, this simple programmes considered difficult problem. This problem has borrowed its name by considering a mountaineer who has decided to pack his knapsack (rucksack) to climb a mountain. The capacity of his knapsack is limited, so he needs to select items carefully according to their values and weight.[51]

An important task with the current shortage of electricity is the choice of a mathematical model for its distribution between consumers of various groups and regions where such groups are represented, and the determination of the amount of disconnected electricity in each of the groups. Of course, such models constitute a trade secret of the Aggregator regulating the balance of demand and consumption of electricity, and, as a rule, are not published. One of the approaches to formulating such a problem can be reduced to the problem of integer optimization "Knapsack Problem", the purpose of which is to select a subset of items with the maximum total cost from a given set of items with the properties "cost" and "weight", while observing the constraint on the total weight[52]. There are different variations of this task for different objects. In

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[51] Sianaki, O. A. 2015. Intelligent Decision Support System for Energy Management in Demand Response Programs and Residential and Industrial Sectors of the Smart Grid.[Accessed 05.07.21]

[52] Martello, S., Toth, P. 1990. Knapsack problems: algorithms and computer implementations. John Wiley & Sons Ltd., C. 29, 50. 296 c. ISBN 0-471-92420-2 Accessed 05.07.21]

particular, in the works[53], [54] modifications of this problem are used in application to the tourism industry.

In general, to maximize the total profit, the binary KP can be formulated as linear integer programming as follows: find a set of Booleans $X=\{x_j\}$, such that

$$\boldsymbol{F = max \sum_{j=1}^{m} w_j z_j} \qquad (4.3)$$

$$\boldsymbol{\sum_{j=1}^{m} w_j x_j \leq W} \qquad (4.4)$$

j – a group of active customers with the same tariff plan (households, industry, agriculture, transport, business, etc.) in the corresponding territorial unit (city, district, rural municipality, etc.)

$x_j = 1$, if the consumer group j does not turn off for electricity consumption at the current hour (the group is "placed in the knapsack") and $x_j = 0$ – otherwise (disconnects from electricity consumption at the current hour (the group "does not fit in the knapsack")

w_j – the amount MWh of electricity consumed at the corresponding hour for a group of consumers j

z_j – electricity market price (€ / MWh) for the respective consumer group;

m – the maximum number of consumer groups with different tariff plans (different tariffs per unit of electricity)

W – the amount MWh of electricity distributed in the current hour for all consumer groups

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53 Rebezova M. 2013. A Modification of the Knapsack Problem Taking into Account the Effect of the Interaction Between the Items. Automatic Control and Computer Sciences, Vol. 47, № 2, Allerton Press, Inc. 107–112. ISSN 0146-4116. [Accessed 05.07.21]

54 Mahareva, K. 2019. Concept of creation and analysis of competitiveness regional NDC-aggregator company. Vestnik Cankt-Peterburgskogo Universiteta Grazdanskoj Aviacii. (in Russian language). № 1 (22). [Accessed 05.07.21]

The electricity market where the model is used is assumed to be organized according to the day-ahead trading rules as they are implemented in the Elspot market of the Nord Pool (NP) power exchange, which is one of the largest electrical power exchanges in Europe. The set task makes sense if the current demand for electricity exceeds its supply. The solution to the problem is to iterate over the options and find the option with the maximum value among those whose total electricity consumption does not exceed its supply.

The simplest exact method is the exhaustive search method[55]. However, this method is the most computationally intensive. The complexity of the problem being solved (the number of options to be sorted out) will be $O(2^m)$ (O – coefficient characterizing the number of computational operations to compute one option). This method is used for values of m that allow obtaining a solution in the foreseeable processor time. For example, if there are $m = 20$ consumer groups (the dimension of the problem will be $O(2^{20}) = 1048576$ and the frequency of the laptop is 3x109, the problem is solved in just a few seconds. However, for significantly large values of *m*, computer calculations can take tens of minutes and hours, during which waiting for the final result is tedious and unacceptable for a researcher. Exact methods also include better enumeration methods – the branch and bound method, and the dynamic programming method.

In order to save computational time, heuristic algorithms are used that give suboptimal results, i.e. close to optimal, but do not guarantee optimal results. Approximate algorithms include, in particular, "greedy", genetic, and other similar algorithms. Solving the problem with a "greedy" algorithm involves sorting items according to their specific value (that is, the ratio of the value of an item to its weight) and placing items with the highest specific value in the

[55] Martello, S., Toth, P. 1990. Knapsack problems: algorithms and computer implementations. John Wiley & Sons Ltd. C. 29,50. 296 c. ISBN 0-471-92420-2

backpack by going through the sorted options [56]. The difficulty of sorting items is O(*m*log(*m*)).

Genetic Algorithm [57] handles many of the best solutions to date. Many of these decisions are called generation. After a series of generational changes in which the fittest individuals are crossed and the remaining individuals are ignored, the algorithm is supposed to improve the original solutions.

Currently, many software packages and online calculators have been developed, which provide the solution of the problem "About the Knapsack" with accurate and heuristic methods. Therefore, it is not advisable to develop your own software. It is enough only to qualitatively and quantitatively determine the initial data that determine the complexity of solving the problem, and, in accordance with the estimated complexity, choose the necessary tools.

<u>The validation of optimisation mathematical model</u> of disconnected AC groups for the next hour in case of a power shortage is done by author. To check the model operability, the model validation is carried out on an abstract numerical example, in which: W – the amount MWh of electricity distributed in the current hour for all consumer groups; j – a group of active customers with the same tariff plan (households, industry, agriculture, transport, business, etc.) in the corresponding territorial unit (city, district, rural municipality, etc.);

Let us consider the exact and heuristic methods for solving the required problem using examples of the exhaustive search method and the "greedy" method for $W = 10$ (MWh) and other initial data presented in Table 4.2.

To solve the problem, taking into account all conditions, to verify and validate the result, the Mathcad software is employed, implementing the search of all possible solutions of the problem in Equation (4.3), with the restrictions

[56] Martello, S., Toth, P. 1990. Knapsack problems: algorithms and computer implementations. John Wiley & Sons Ltd. C. 29,50. 296 c. ISBN 0-471-92420-2]

[57] Davis, I. (ed.) Handbook of Genetic Algorithms. New York: Van Nostrand Reinhold, 1991.

and conditions (4.4), gives the maximum profit F at a different value of the price *z*.

Table 4.2

An example of initial data for solving a problem in the formulation (Eq. 3.3, 3.4)

j	w_j (MWh)	z_j (EURO)	F
1	5	120	480
2	4	130	520
3	3	250	750
4	1	300	300

Source: created by the author.

From the data Table 4.2 it follows that the demand for electricity consumption in the current hour exceeds consumption ($\sum_{j=1}^{m} w_j$ = 13, > 10). Consequently, it is necessary to solve the optimization problem of choosing the AC group (s), which must be temporally disconnected from electricity consumption.

Table 4.3 displays all possible combinations of the values of the variables *xj*, the corresponding sets of groups and the values of the criterion F for solving the problem by the exhaustive search method. Sets of non-disconnectable AC groups can be either each group separately (which is clearly not optimal), or other combinations of 2 or 3 groups, in which the total demand for electricity ($\sum_{j=1}^{m} w_j \leq 10$. If a group consists of only one consumer or a combination of groups consumes > 10 MWh of electricity, then the calculated data for it in table 4.3 not shown (–).

Table 4.3

An example of solving the problem in the formulation (4.3, 4.4)

x_1	x_2	x_3	x_4	**Set of x_j**	$\sum_{j=1}^{m} w_j$	F
0	0	0	0	{0}	–	–
0	0	0	1	{4}	–	–
0	0	1	0	{3}	–	–
0	0	1	1	{3, 4}	4	1050
0	1	0	0	{2}	–	–
0	1	0	1	{2, 4}	5	820
0	1	1	0	{2, 3}	7	1270
0	1	1	1	{2, 3, 4}	8	1570
1	0	0	0	{1}	–	–
1	0	0	1	{1, 4}	6	780
1	0	1	0	{1, 3}	6	1230
1	0	1	1	{1, 3, 4}	9	1530
1	1	0	0	{1, 2}	9	1000
1	1	0	1	{1, 2, 4}	10	1300
1	1	1	0	{1, 2, 3}	–	–
1	1	1	1	{1, 2, 3, 4}	–	–

Source: created by the author.

Zero in the matrices mean that there are no corresponding options for this group of customers. From the calculated data it follows that the maximum value of the criterion profit F = 1570 in case of meeting the electricity demand for the current hour will be for groups {2, 3, 4} and the group will be switched off {1}. The specific value of consumer groups (from Table 4.3) is presented in Table 4.4 for the subsequent solution of the problem in the formulation (4.3, 4.4) by the "greedy" method.

Table 4.4

Specific consumer value data for the example under consideration

J	**1**	**2**	**3**	**4**
z_j / w_j	24	32.5	83.3	300

Source: created by the author.

Of the permissible combinations of groups for which it is possible to meet the demand for electricity, we single out the combinations {1, 2, 4}, {1, 3, 4}, {2, 3, 4}, the total specific value of which is presented in Table 4.5.

Table 4.5

Specific consumer value data for the example under consideration

Sets of groups	**{1, 2, 4}**	**{1, 3, 4}**	**{2, 3, 4}**
z_j / w_j	356.5	407.3	415.8

Source: created by the author.

Here, too, the group for switch off will be group {1}, since the maximum unit value (415.8) will be in case the demand for the combination groups {2, 3, 4} is satisfied. In the given example, the solution of the problem by the exact method (exhaustive search) and the approximate method ("greedy" method) coincides. This coincidence is quite possible for a small number of AC groups. In practice, the number of AC groups can be measured in tens and hundreds, since, for example, different households with different tariff plans for electricity consumption can be divided into dozens of different groups, etc. Therefore, a regional aggregator should have application packages or online calculators for solving the problem in the formulation (4.3, 4.4) by both exact and approximate methods, the easiest to use are the brute force search method and the greedy method, taking into account the complexity of the problem.

Conclusions

1. Latvia suffers from a shortage of electricity for about 18 % of annual consumption, therefore, the problem of regulating the balance of demand and supply of consumers for its consumption is the most important task of the Aggregator, for the solution of which the author proposes a two-stage optimization procedure as the amount of electricity purchased for the next day on the Nord Pool power exchange in the Latvian trade zone and the choice of groups to be switched off by the AC in case of shortage during the current hours of its consumption. For each stage, the formulation of the problem is developed and methods for their solution with deterministic initial data are considered. Further development of the developed methodology in the future is supposed to be carried out with random initial data.
2. In the given example, the solution of the problem by the exact method (exhaustive search) and the approximate method ("greedy" method) coincides. This coincidence is quite possible for a small number of AC groups. In practice, the number of AC groups can be measured in tens and hundreds, since, for example, different households with different tariff plans for electricity consumption can be divided into dozens of different groups, etc. Therefore, a regional aggregator should have application packages or online calculators for solving the problem in the formulation (2, 3) by both exact and approximate methods, the easiest to use are the brute force search method and the greedy method, taking into account the complexity of the problem.

3. The level of awareness prosumerism of the respondents who participated in the survey is relatively high. Although, the author suggests that those who are not familiar with the term prosumerism simply did not continue to fill out the questionnaire.

It is important to note that the behaviour of electricity consumers testifies to the great potential of Latvian consumers to participate in the electricity generation and sale market. This means the potential to participate in the aggregation of electricity demand.

Based on the analysis the main **recommendations for the development of Regional electricity Aggregator in Latvia** are as follow:

1. A regional electricity aggregator should have application packages or online calculators for solving the problem by both exact and approximate methods, the easiest to use are the brute force search method and the greedy method, taking into account the complexity of the problem
2. Expanding the proposed knapsack method to an online stochastic knapsack: in Chapter 3 proposed optimization methodology, because there the data input to the system is done within the offline state. But the online and stochastic method can provide an approximation of future energy consumption trends for the Regional Aggregator.
3. The author of the Thesis proposes the implementation in Latvia of an expanded intelligent decision support system (IDSS) in order to create a unique energy consumption profile for family members: comparing an electrical system with a telecommunications and multimedia system, especially a mobile network, users of this system receive data on their consumption in real time. In addition, mobile network providers can inform their users of any over-consumption trend and offer them more suitable services based on

the user's consumption profile. To add such intelligence to the smart grid, the proposed intelligent decision support system must be able to study the consumer behaviour and lifestyles of users.

Conclusions and Recommendations

The development of energy industry and its segments including renewable energy sources penetration and impact, the role and place of market electricity price for all categories of consumers and economy of Latvia as whole is a top priority governmental task. It is reflected in the main guidelines and official policy documents of the Saeima of the Republic of Latvia, the Cabinet of Ministers, the Ministry of Economics and other ministries and departments of the Republic of Latvia with the result-based consistent monitoring at the state level, and of course on the EU level. These documents set goals, determine strategies and activities for the transformation of industry. Nevertheless, there is almost no attention paid to the development of IT technologies with the goal to regulate demand side of electricity.

Therefore, the relevance of the Thesis research is confirmed by author's design of the concept for the development electricity demand side services in Latvia on the basics of the Regional Aggregator.

According to the results of the research, the following main conclusion have been formulated:

1. The analysis of theoretical-methodological and scientific aspects of electricity Demand Management has revealed, that due to the nature of renewable, it is not possible to control or request electricity power when it is needed. The main objectives of DR techniques are reduction of peak load and the ability to control consumption according to generation . Usually, end-users have very little practical knowledge about their flexibility and are unaware of their usage patterns and behaviour. Hence, participants in DR programmes show a lower response than the expected levels.

2. The analysis of programme documents and legislative literature reveals that the more liberalized the market, the more it responds to fluctuations in demand and supply. In an effort to maximize the liberalization of the European energy market, European market decision makers intended to use it as a tool that should provide an ever-increasing, growing and diversified range of offers, which would put downward pressure on prices. The analysis performed by the author reveals that electricity market prices are highly volatile.
3. The analysis of various tools for managing the demand for electricity consumption, as well as functioning demand management programmes in the countries of the world, reveal a significant differentiation and specificity of such tools and programmes in the country context. The author concludes that the Demand Response programmes shown in Table 1.1 are not interchangeable and all of these mechanisms can be used in a complex. That understanding than have been substantiated in development electricity Demand Response model.
4. On the grounds of the genesis in the field of demand management for electricity consumption were proposed, systematized, and substantiated the stages of scientific research on the subject. Results of the research prove that the development of scientific research is influenced by both external factors in relation to the electric power industry, such as economic crises, the spread of information technologies, and internal factors, such as the development and liberalization of energy markets, of technologies for distributed and renewable energy sources, the emergence of new technological trends etc.

5. The author of the Thesis proposes combinatorial optimization for implementation of the concept of regional DR Aggregator, that will allow to solve the problem of reducing electricity consumption and, at the second stage, the choice of active consumers to be switched off for the current hour is optimized if the amount of electricity is not enough, even taking into account a decrease in its consumption.
6. Trends in the production, consumption and export of electricity in Latvia are weak, but upward. The trends in imports and the excess of imports over exports of electricity are of a downward nature, which indicates the dynamics of a slow but decreasing dependence of Latvia on imports of electricity. Cannot be used for a short-term "approximate" forecast of this indicator.
7. The trend of planned wind power consumption for the day ahead in Latvia has a clearly pronounced upward character with a high strength of connection with statistical data (coefficient R2 = 0.7) and indicates a steady annual increase in wind power consumption in Latvia, which corresponds to the goals of increasing the share of RES in final energy consumption should grow and reach its share up to 45 % by 2030. At the same time, the upward trend in the cost of one MWh (wind power consumed in Latvia with a high value of R2 = 0.7) does not correlate with the trend in its consumption. This circumstance, as well as the consequences of the coronavirus pandemic, may require adjusting plans to increase electricity consumption from RES, which will require a more detailed assessment of the volume of wind power imports and, possibly, the implementation of measures to increase the capacity for the production of this energy in Latvia.

8. In developed of a methodology for statistical analysis of wind energy yearly and monthly (2019) data, it was established that for practical use should be applied analysis methods that give not only good quality criteria, but also the values of the considered indicators corresponding to the logical meaning. Multiple (polynomial) regression has proven to be an effective tool for electricity demand forecasting. One of its main strengths is the negligible computational time it takes to perform forecasts without losing much in terms of accuracy. Furthermore, the forecasting model can be improved by certain modifications, the most promising of which has turned out to be subtraction of the model residuals averaged over hour-of-day.
9. During the peak wind power and peaks of electricity price, multiple (polynomial) regression has proven to be an ineffective tool for the analysis of monthly statistical data gave unsatisfactory results, therefore, it is recommended to use the model of sinusoidal dependence of the corresponding indicators on the month number.

   While other modifications (x component and time series filtration) did not produce a consistently beneficial effect over the whole dataset, there were days when their inclusion aided in improving the accuracy. Thus, a model, which automatically selects the features the forecasting program, should consider before each daily forecast is advisable. Additionally, it should consider automatic selection of the training set size, since the optimum look-back horizon tends to vary during the peak wind power.
10. There has been set the task and offered improved economic and mathematical model of optimization of regional electricity aggregator, focused on reduction costs of the PP and electricity consumers. Research reveals that there no such service in Latvia. Although, institutionally everything is ready, technologically it is

necessary to develop electricity smart grid and install smart meters. The method of solving the optimization problem was tested on validation case studies with software Mathcad and demonstrated its appropriateness and effectiveness.

11. Latvia suffers from a shortage of electricity for about 18 % of annual consumption, therefore, the problem of regulating the balance of demand and supply of consumers for its consumption is the most important task of the Aggregator, for the solution of which the author proposes a two-stage optimization procedure as the amount of electricity purchased for the next day on the Nord Pool exchange in the Latvian trade zone. and the choice of groups to be switched off by the AC in case of shortage during the current hours of its consumption. For each stage, the formulation of the problem is developed and methods for their solution with deterministic initial data are considered. Further development of the developed methodology in the future is supposed to be carried out with random initial data.
12. In the given case study, the KP solution of the problem by the exact method (exhaustive search) and the approximate method ("greedy" method) coincides. This coincidence is quite possible for a small number of AC groups. In practice, the number of AC groups can be measured in tens and hundreds, since, for example, different households with different tariff plans for electricity consumption can be divided into dozens of different groups, etc. Therefore, a regional aggregator should have application packages or online calculators for solving the problem in the formulation (2, 3) by both exact and approximate methods, the easiest to use are the brute force search method and the greedy method, taking into account the complexity of the problem.

13. The level of awareness prosumerism of the respondents who participated in the survey is relatively high. Although, the author suggests that those who are not familiar with the term prosumerism simply did not continue to fill out the questionnaire.

It is important to note that the behaviour of electricity consumers testifies to the great potential of Latvian consumers to participate in the electricity generation and sale market. That means the potential to participate in the aggregation of electricity demand.

Therefore, the hypothesis put forward by author is proved, the goal and objectives are fulfilled.

Recommendations

Based on the conclusions made during the work the following suggestions were formulated by the author for the State structures of Latvia, state bodies of education of Latvia, universities of Latvia; enterprises.

To the Ministry of Education of the Republic of Latvia: Acknowledging, there some pretty qualitative study programmes on sustainable development in economic, psychological, environmental, and business education in Latvia, the author of the Thesis recommends to develop and include concept of “electricity prosumerism” to both secondary and higher education.

To the Ministry of Economy of Republic of Latvia: It is suggested to designate the priority of the development of the smart grid in Latvia and to finalize to provision of households with smart meters. That allows after 2025 promptly involve electricity consumers to the demand response aggregation.

To the Central Statistical Bureau of Republic of Latvia: To recognize the topicality of transitional processes of CEEP in the Latvia and to specify the definition of prosumerism and active consumer in energy sector, by the including of the system of evaluation of the interaction between: consumed electricity and average bill for prosumers households. It will ensure ability to study the consumer behaviour and lifestyles of users.

To the High institutions of Republic of Latvia: The author of the Thesis proposes the implementation in Latvia of an expanded intelligent system in order to create a unique energy consumption profile for family members: comparing an electrical system with a telecommunications and multimedia system, especially a mobile network, users of this system receive data on their consumption in real time. In addition, mobile network providers can inform their users of any over-consumption trend and offer them more suitable services based on the user's consumption profile. To add such intelligence to the smart grid, the proposed intelligent decision support system must be able to study the consumer behaviour and lifestyles of users.

To the enterprises, which plan to offer electricity DR services in Latvia: For companies planning to offer electricity PR services in Latvia: extending the proposed “knapsack” method to a stochastic one can provide a rough approximation of future energy consumption trends for a regional aggregator.

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