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"Environmental Science"

ASPECTS OF ENERGY EFFICIENCY AND SMART METERING

Summary of the Doctoral Thesis

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

To be granted the scientific degree of Doctor of Environmental Engineering, the present Doctoral Thesis will be defended on 3 November 2017 at the Faculty of Power and Electrical Engineering, Āzenes Street 12/1, Room 115.

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DECLARATION OF ACADEMIC INTEGRITY

I hereby declare that the Doctoral Thesis submitted for the review to Riga Technical University for the promotion to the scientific degree of Doctor of Engineering Sciences is my own. I confirm that this Doctoral Thesis had not been submitted to any other university for the promotion to a scientific degree.

Uldis Bariss ……………………. (signature)

Date: …………………….

The Doctoral Thesis has been written in English. It consists of Introduction; 2 Chapters; Conclusion; 36 figures; 21 tables; the total number of pages is 90, not including appendices. The Bibliography contains 110 titles.

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INTRODUCTION

Many significant changes have occurred in energy sector during the past few years. Structurally large monopolies have separated electricity and natural gas transmission and distribution networks that now continue to operate as regulated service providers, while energy production and supply operates under the free competition. However, it is not the end of change. Transition to increasing share of renewable energy, CO_2 emission reduction, energy efficiency improvement, as well as increasing involvement of energy consumers are the main tasks in the upcoming years.

By year 2020, approximately 20 % of energy in European Union (EU) should be produced from renewable energy sources. In Latvia the aim is to reach 40 % share by 2020. In turn, the aim for 2030 is to reach at least 27 % renewable energy share in EU, which means that in electricity generation it should reach 50 %. The aforementioned increase will mainly be achieved by wind and solar energy. These sources of electricity production significantly increase both daily and seasonal fluctuations, as well as stochastic fluctuations. Therefore, these factors will increase the value not only of electricity generation reserves but also of customer side solutions that will increase efficiency of energy use and also allow easier adaptation to price changes or facilitate participation in electricity market by selling demand side flexibility.

In order to realize the potential of energy efficiency and electricity consumption elasticity, it is important to create interaction between the production and consumption. By developing the EU electricity market, the link between production and consolidated consumption has been successfully established at a wholesale trading platform level that in Latvia is represented by the Nord Pool. In this market main electricity trading occurs in a day-ahead market that forms hourly electricity price. However, significant step forward is providing individual consumers with information access to these electricity prices that would enable to unlock energy efficiency and demand flexibility potential.

At least two main prerequisites of further involvement of consumers can be identified. First, it is necessary to implement electricity consumption monitoring, also known as smart metering, to provide the consumer with information on actual electricity consumption. Secondly, it is necessary to create energy consumer engagement that provides feedback on electricity price and consequently either changes the consumption amount and patterns or enables the development of various technological solutions to optimize the consumption. All of these changes can be implemented only in close cooperation between electricity suppliers and consumers provided that there is a rollout of smart meters.

Research Topicality

Smart metering is and at the same time is not an energy efficiency improvement measure.

- It is not energy efficiency measure because by implementing a smart meter electricity will not be saved by itself.

- It can be seen as an energy efficiency measure because smart metering provides electricity user with timely and efficient feedback information that encourages the user to reduce energy consumption by changing behaviour or implementing energy efficiency measures.

Therefore, smart metering could be viewed through the perspective of energy efficiency implementation. Smart metering is not only a source of information on actual electricity consumption, it is an energy management tool which allows to analyse and evaluate economic efficiency of energy consumption.

Smart metering that is supplemented by appropriate information feedback to energy user at the beginning raises awareness, which induces behavioural changes later resulting in motivation to implement energy efficiency measures and in long-term more effective energy consumption.

However, introduction of smart metering, especially at its initial stage, is not an easy decision from the economic point of view, because it involves significant investments, where benefits cannot be easily estimated and justified at first. It is therefore important to have a wider understanding of linkage between smart metering and energy efficiency, economic benefits of which can be evaluated easier.

Aim and Objectives

The objective of this research is to analyse smart metering influence on energy efficiency of end users in household sector, as well as assess the role of factors that influence energy efficiency improvement.

In order to meet the objective, the following tasks were performed.

1. Analysis of smart metering effect on energy efficiency improvement by evaluating:
    a) economic feasibility;
    b) potential of electricity consumption reduction;
    c) influence on reduction of CO_2 emissions.
2. Analysis of factors influencing energy efficiency as well as its adoption by taking into account the external factors:
    a) the role of innovation diffusion and human behaviour aspects;
    b) possible development of consumption and energy efficiency of households.

Scientific Novelty

Scientific novelty is based on step by step principle, from the simplest to the most complex task. Scientific novelty is illustrated in Fig. 1.

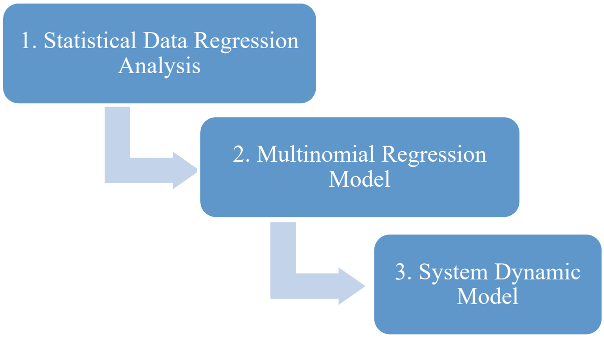

Fig. 1. Methodologies used in the research.

Methodologies are interrelated and integrated into one another.

1. Methodology includes planning and implementation of pilot project, as well as collection and processing of statistical data during smart metering pilot project.
2. Multinomial regression model was developed in order to assess the effect of CO_2 emissions on electricity prices. Multinomial logistic regression model was developed in order to apply goal-framing theory. This analysis was carried out in order to determine how goals frame the behaviour of energy users during energy efficiency activities. This mathematical model of diffusion of innovations was developed based on the survey of households' attitude towards energy efficiency.
3. System dynamic modelling of household electricity end user energy efficiency improvement was used. Two system dynamics models have been created in order to assess:
   a) implementation of efficient lighting by taking into account social and technological aspects;
   b) influence of the development of household income, adoption of more efficient technologies and changing electricity prices on electricity consumption of households.

Research Hypothesis

The rollout of smart meters has significant influence on energy efficiency and CO_2 emissions also under local conditions in Latvia where behavioural aspects of electricity end users play a significant role.

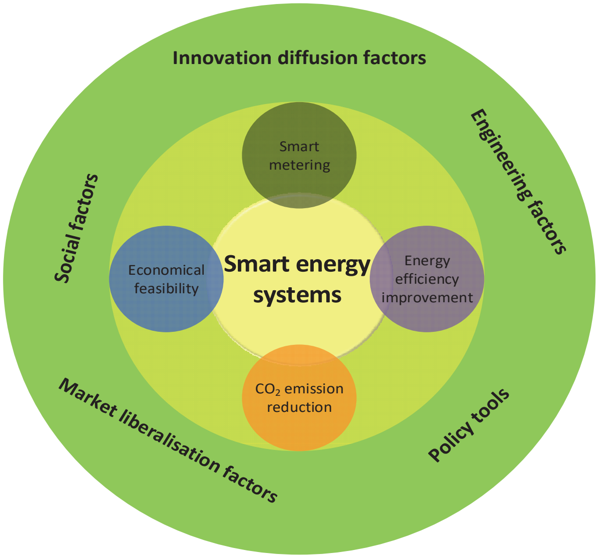

Fig. 2. Graphical illustration of doctoral thesis.

Smart metering is not considered as a direct energy efficiency measure. However, smart metering is a factor that affects energy efficiency because it determines which energy efficiency measure is chosen and implemented, thus simultaneously affecting solutions to various issues. Some of them are as follows:

- climate change mitigation, because electricity production from fossil fuels is related to greenhouse gas (GHG) emission release in the atmosphere;
- implementation of innovative technologies, because energy efficiency measures are related to purchase of innovative technologies;
- money savings, because due to energy efficiency measure implementation, payment for electricity is reduced;
- human behaviour change, because energy management deals with human behaviour change in order to improve their knowledge and awareness on energy efficiency.

The Doctoral Thesis includes the analysis of one element of the smart energy system – smart metering and its interaction with end user under the influence of a number of external factors (see Fig. 2).

Scientific Application

Methodologies that are developed and applied in the research demonstrate interconnection between smart metering and energy efficiency.

- Methodology of smart metering pilot project can be generalized and applied in energy management problem analysis.
- Analysis of the impact of energy efficiency improvement on climate change by developing a methodology for the evaluation of CO_2 emission factor under free market conditions that allows generalizing this methodology for other markets or market conditions.
- Evaluation of technological aspects of energy efficiency measures by applying goal-frame theory for the evaluation of innovation diffusion;
- Development of system dynamics model which forecasts consumption of electricity and incorporates energy efficiency measures, electricity end user behaviour, as well as prosperity, technological and price factors. The model can be developed and applied when assessing the impact of potential policy instruments on household electricity consumption.

Practical Significance

Smart metering has a significant role in energy efficiency improvement; however, it is not possible to directly reduce electricity consumption only by implementing smart metering system. Therefore, it is necessary to involve electricity end user who implements energy efficiency measures based on consumption data from the smart meter.

The main challenges that have been identified in Latvia are relatively low household consumption of electricity and additional material investments into smart metering system. Therefore, the analysis is supplementing arguments for further rollout of smart meters.

In liberalised electricity market smart metering enables customers not only to promptly receive consumption information but also allows adjusting the consumption to actual market prices. Taking into account the fact that electricity price is changing hourly, in the future offers of appliances and services for end user will be developed in order to optimise consumption accordingly.

Approbation of the Research Results

Scientific Publications about the Topic

1. Avotiņš, A., Kuņickis, M., Bariss, U., Apse-Apsītis, P. Smart Metering Cost-Benefit Analysis in Latvia. In: *Proceedings of the 14th International Scientific Conference on Electric Power Engineering (EPE 2013)*, Czech Republic, Kouty nad Desnou, 28–30 May, 2013 (indexed in SCOPUS, Web of Science).

2. Kuņickis M., Dandens A., Bariss U. Justification of the Utility of Introducing Smart Meters in Latvia. *Latvian Journal of Physics and Technical Sciences*, 2015, No. 6, pp. 13–21 (indexed in SCOPUS).
3. Bariss, U., Kamenders, A., Vītoliņš, V., Blumberga, D. Energy Efficiency Results of Smart Metering, Pilot in a Context of Cost Benefit Analysis of Smart Meters in Latvia. In: *Proceedings of the 27th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems (ECOS 2014)*, Finland, Turku, 15–19 June, 2014. Turku: Abo Akademi University, 2014, pp. 2168–2177 (indexed in SCOPUS).
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7. Timma, L., Bariss, U., Blumberga, A., Blumberga, D. Outlining Innovation Diffusion Processes in Households Using System Dynamics. Case Study: Energy Efficiency Lighting. *Energy Procedia*, 2015, 75, pp. 2859–2864 (indexed in SCOPUS, Web of Science).
8. Bažbauers, G., Bariss, U., Timma, L., Lauka, D., Blumberga, A., Blumberga, D. Electricity Saving in Households due to the Market Liberalization and Change in the Consumer Behaviour. *Energetika*, 2015, No. 61, pp. 108–118.
9. Timma, L., Bazbauers, G., Bariss, U., Blumberga, A., Blumberga, D. Energy Efficiency Policy Analysis Using Socio-Technical Approach and System Dynamics. Case Study of Lighting in Latvia's Households. *Energy Policy*, 2017, Vol. 109, pp. 545–554 (indexed in SCOPUS).
10. Bariss, U., Bazbauers, G., Blumberga, A., Blumberga, D. System Dynamics Modeling of Households' Electricity Consumption and Cost-Income Ratio: A Case Study of Latvia. *Environmental and Climate Technologies*, 2017 (accepted for publication).

Other Scientific Publications

1. Ločmelis, K., Bariss, U., Blumberga, D. Latvian Energy Policy on Energy Intensive Industries. *Energy Procedia*, 2017, Article in press, pp. 1–6 (indexed in SCOPUS).
2. Timma, L., Bariss, U., Dandens, Ā., Blumberga, A., Blumberga, D. Framework for the Assessment of Household Electricity Saving by Integrating Behavioural Aspects. *Energy Procedia*, 2016, Vol. 95, pp. 517–521 (indexed in SCOPUS, Web of Science).

3. Burmistre, I., Blumberga, A., Rošā, M., Blumberga, D., Bariss, U. Development of Methodology for the Assessment of Changes in Household Electricity Consumption and Calculation of CO_2 Emissions. *International Journal of Global Warming*, 2015, Vol. 8, No. 1, pp. 114–131 (indexed in SCOPUS, Web of Science).
4. Bariss, U., Dandens, Ā., Blumberga, D. Smart Meters as Enablers for Feedback Information Induced Energy Efficiency and Demand Response: Case Analysis in Latvia. In: *2015 IEEE 5th International Conference on Power Engineering, Energy and Electrical Drives (POWERENG): Proceedings*, Latvia, Riga, 11–13 May, 2015. Riga: Riga Technical University, 2015, pp. 69–73 (indexed in SCOPUS, Web of Science).
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Scientific Conferences

1. Bariss, U., Dandens, Ā., Blumberga, D. Smart Meters as Enablers for Feedback Information Induced Energy Efficiency and Demand Response: Case Analysis in Latvia. In: *2015 IEEE 5th International Conference on Power Engineering, Energy and Electrical Drives (POWERENG): Proceedings*, Latvia, Riga, 11–13 May, 2015.
2. Kuņickis, M., Bariss, U., Dandens, Ā. Smart Meters Implementation Substantiaton in Latvia. In: *International Symposium, Dedicated to the 150 Anniversary of the Faculty of Transport and Mechanical Engineering: Scientific Program and Book of Abstracts*, Riga, 16–20 October, 2014.
3. Bariss, U., Dandens, Ā., Timma, L., Blumberga, A., Blumberga, D. How to Assess Involvement of Electricity End User in Energy Efficiency Improvement. Analysis of Survey Results. In: *Abstracts of 55th International Scientific Conference: Subsection: Environmental and Climate Technologies*, Latvia, Riga, 14–15 October, 2014.

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7. Avotiņš, A., Kuņickis, M., Bariss, U., Apse-Apsītis, P. Smart Metering Cost-Benefit Analysis in Latvia. In: *Proceedings of the 14th International Scientific Conference on Electric Power Engineering (EPE 2013)*, Czech Republic, Kouty nad Desnou, 28–30 May, 2013.

Structure of Doctoral Thesis

The doctoral thesis has been created as a collection of scientific publications that have been written during doctoral studies.

In this thesis, research on smart metering pilot project and energy efficiency improvement has been implemented. The research was performed with a step by step approach. The structure of the Thesis is shown in Fig. 3.

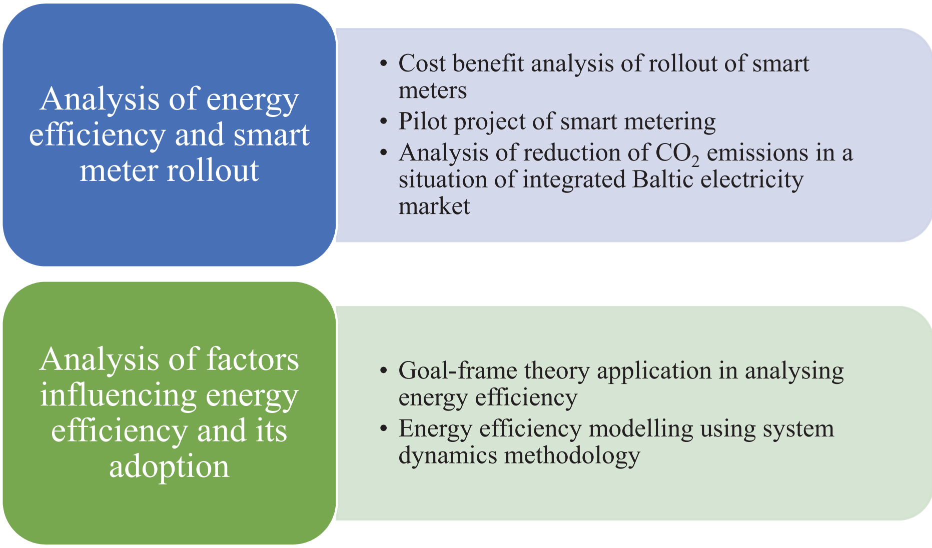

Fig. 3. Structure of doctoral thesis.

The first chapter presents the cost benefit analysis of smart meter rollout with an aim to justify the optimal implementation scenario. In order to validate the assumptions included in CBA, analysis of smart metering pilot assessing electricity consumption changes is carried out. In addition, analysis of reduction of CO_2 emission is carried out taking into account significant structural change due to liberalisation of electricity market.

The second chapter presents the analysis of factors that influence the energy efficiency decision of end users. That includes adaptation of goal-frame theory in analysing the motivation of end user. Two system dynamics models have been developed to analyse technology diffusion issues and forecast changes in electricity consumption of households.

1. Analysis of Energy Efficiency and Smart Meter Rollout

1.1. Cost Benefit Analysis of Smart Meter Rollout

The most important step towards the rollout of smart meters was the Directive 2009/72/EC concerning common rules for the internal market in electricity that required Member States to ensure implementation of intelligent metering systems at least for 80 % of customers by 2020, where the rollout of meters is assessed positively.

Smart metering system is defined as an electronic system that can measure energy consumption adding more information than a conventional meter, and can transmit and receive data using a form of electronic communication. The purpose of this regulation is not only to facilitate energy efficiency but also to ensure that customers are able to actively participate in the electricity supply market. This directive was a part of the so called 3rd Package aimed at further liberalization and integration of electricity and gas markets in EU. However, the implementation of smart meters is subject to an economic assessment that should be carried out in each country taking into account all costs and benefits characteristic to the local market and individual consumers.

In Latvia the main challenges were relatively low average household consumption, unclear potential benefits from energy efficiency and additional network investment for smart meters.

Cost benefit analysis (CBA) of smart meter rollout was carried out according to the guidelines of the Joint Research Centre of European Commission. According to the guidelines a base case has to be fixed which represents the current situation and a number of scenarios have to be defined for the implementation of smart meters and systems by varied penetration, speed of rollout, functionality, technology solutions and other factors. Accordingly, six scenarios were developed which are described in Table 1.1.

Table 1.1

The Scenarios of the Rollout of Smart Meters

Scenario	Short description of scenario
A	Continuation of maintenance of existing meters
B	80 % smart meters installed by 2020 and the remaining 20 % by 2022, according to minimal rollout set in the directive
C	Smart meters installed for all objects where annual consumption is above 600 kWh reaching 74 % penetration, and prioritisation according to the consumption taking into account technical restrictions
D	Smart meters installed without prioritisation according to the consumption and technical replacement plan for old meters reaching 90 % penetration
E	Smart meters installed for all objects where annual consumption is above 2500 kWh using GSM technology reaching 23 % penetration of smart meters
F	Smart meters installed for all objects where annual consumption is above 2500 kWh using PLC technology reaching 23 % penetration of smart meters

In the CBA required capital expenditure and operational costs associated with implementation scenario were calculated. The gains from the implementation of such system for a distribution network and society at large were assessed.

The assessment of potential benefits for customers and electricity market was a significant challenge due to the fact that besides energy efficiency benefits there might be gains from electricity supply quality and development of customer side flexibility. However, taking into account the complexity of measuring such benefits, CBA has focused on the gains from energy efficiency improvement and corresponding reduction of CO_2 emissions.

The results, showed in Fig. 1.1., identified that only Scenario F delivers positive benefits to society in the amount of EUR 4.4 million over a ten year period and assumes installation of smart meters for all objects where annual consumption is above 2500 kWh using PLC technology and reaching 23 % penetration of smart meters. The rollout of smart meters is planned for the period from 2015 to 2017. The positive balance of this scenario was largely due to the external factors – customer gains of EUR 20.9 million based on energy efficiency improvement and EUR 3.9 million from environmental gains based on reduced energy consumption and corresponding reduction of CO_2 emissions.

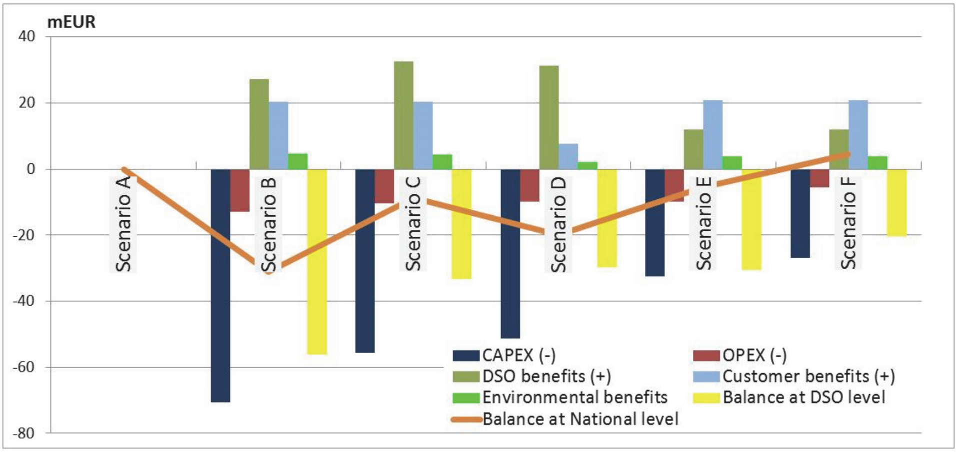

Fig. 1.1. The first cost benefit analysis of smart meter rollout in electricity distribution network.

At the distribution operator level the balance of costs and benefits is determined by capital expenditure on the one side and possibilities to reduce operating costs on the other side. Despite the fact that in CBA there was assumption of declining prices for smart meters, the balance for the distribution network was significantly negative – EUR 20.4 million.

It was taken into account that the customer gains from energy efficiency improvement and reduction of CO_2 emissions account for the most of total gains in the CBA and are largely based on the assumption of 5 % energy savings potential. This level was chosen based on the experience of other countries; however, because of diverse results and different market conditions smart meter rollout pilot project was started in Latvia.

1.2. Analysis of Smart Metering Pilot Project

Smart meters provide customers with opportunity to promptly and conveniently receive information regarding actual energy consumption which is affecting energy efficiency.

The role of feedback is to make energy consumption visible, thus creating the knowledge of residential consumers about how much energy is consumed and how much they actually pay for it. There are a number of pilot projects and studies exploring potential energy savings which provide better information and feedback on consumption to households. The feedback about usage enables consumers to reduce their electricity demand through conservation activities, through changing behaviour or making energy-efficiency investments in lighting or household appliances.

The research in this area has been carried out for a relatively long period. For example, the review carried out by Darby suggests that the norm for savings from direct feedback and the feedback associated with actual consumption time, is in a range from 5–15 %. There is also an indication that high energy consumers may respond more to the direct feedback. Indirect feedback is when information is provided either via billing or web service solutions and is disconnected from the consumption time. The savings in this case have ranged from 0 to 10 %, but they vary according to the quality of information provided[1]. The feedback study carried out by Ehrhardt-Martinez et al. in 2010, which comprised 57 initiatives in general, supports these findings; however, it shows an average household energy savings of roughly 4 to 12 % that is a slightly tighter range[2]. For direct feedback types this study reports average household electricity savings of 5.5 % for enhanced billing, 6.8 % for estimated feedback and 11.0 % for daily/weekly feedback. Later report of consultancy company VaasaETT, comprising data from about 100 pilots stated 8.7 % energy savings for in-house displays, of which 6 % are for detailed invoices and 5.1 % for webpage feedback[3].

The wide range of energy efficiency effects of reported feedback results could be explained by different evaluation methodologies, ex-ante versus ex-post evaluation, definition of target and control groups, by different duration of pilots which involve long-run versus short run-effects. Additionally, there are a number of local factors, such as the distribution of household consumption in a region, weather conditions, local energy usage habits and stock of appliances, feedback content in its relevance within a particular market. Therefore, taking into account those factors and relatively dispersed results for energy efficiency potential, it is necessary to validate the assumptions regarding energy efficiency and CO_2 emissions.

The smart metering pilot project was carried out by JSC *Latvenergo* with the help of financing from the Climate Change Finance Instrument. The pilot project included installation of smart meters in 500 households, development of meter reading and management system,

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[1] S. Darby, "The Effectiveness of Feedback on Energy Consumption: a Review for DEFRA of the Literature on Metering, Billing and Direct Displays," Environmental Change Institute, University of Oxford., 2006.

[2] K. Ehrhardt-Martinez, K. A. Donnelly and J. P. Laitner, "Advanced Metering Initiatives and Residential Feedback Programs: A Meta-Review for Household Electricity-Saving Opportunities. Report No. E105," American Council for an Energy – Efficient Economy, Washington D. C., 2010.

[3] VaasaEET, "The Potential of Smart Meter Enabled Programs to Increase Energy and Systems Efficiency: A Mass Pilot Comparison – Empower Demand. Report for European Smart Metering Industry Group," 2011.

provision of hourly consumption information via customer portal, as well as billing based on actual consumption.

The participants of the pilot were selected in three steps. First, initial list of 20 000 potential customers was randomly selected identifying the respondents in set consumption groups by the energy utility from their billing system. Secondly, more than 1000 computer-assisted telephone interviews were conducted with households randomly assigned to the target group and control group. The interviews comprised questions about household appliances, energy usage and socio-demographic characteristics. The target group participants were asked for consent to participate in the study and install a smart meter. In the target group households 107 single phase induction type meters and 393 three phase induction type meters were replaced with smart meters which provided automated power consumption reading. The control group households received information about the study on energy consumption; however, they were not informed about smart meter pilot. Thirdly, smart meters were installed in the target group households and binding participation and acceptance of a privacy agreement was signed.

In order to identify effect from the feedback on actual consumption for the target group, year by year consumption changes of customers with smart meters were compared with energy consumption changes in the control group. The data from the control group was used to exclude effect from such factors as changes in weather conditions, seasonality factors, growth of economy and other factors that similarly influence both groups. It should be also noted that electricity prices for households have not varied during the study period and there have not been significant price changes two years before the study. Therefore, it can be assumed that the identified relative reduction can be attributed to the effect of installation of smart meters and provided feedback for actual consumption. The households within the target and control groups where sorted into six subgroups based on the annual amount of electricity consumed considering as equal representation as possible in each subgroup. Additionally, it should be taken into account that one of the aims of the pilot was to explore energy efficiency potential in the households with high energy consumption. Therefore, representation of such consumers in the pilot was much higher than that of general households. Additionally, distribution of customers in the pilot was effected by willingness of respondents to participate in the study.

Implementation of the pilot project began in April 2013 and relative changes in electricity consumption for a respondent in the subgroup of target and control groups ($E_{i(\%)}$) are calculated according to equation

$$E_{i(\%)} = \frac{(E2013_i - E2012_i)}{E2012_i} \cdot 100, \%, \tag{1.1}$$

where $E2013_i$ and $E2012_i$ is electricity consumption in the period from April to November in year 2013 and 2012 respectively.

Taking into account that during the case study there could be respondents who might have moved out of premises or for other reasons have extreme consumption changes thus distorting the results for the whole subgroup, significant outlying data identification was carried out. This test was performed separately for each consumption subgroup; the upper and lower limits for minimal and maximal values were calculated according to equation

$$\text{Upper limit} = Q_3 + 2.2(Q_3 - Q_1), \tag{1.2}$$

$$\text{Lower limit} = Q_1 + 2.2(Q_3 - Q_1), \tag{1.3}$$

where

Q_1 lower quartile of the data in a subgroup;

Q_3 upper quartile of the data in a subgroup;

2.2 multiplication factor.

In total 4 % of data were eliminated. Higher variability was presented in the control group were data from 30 respondents were outside limits. The target group contained 2 % of data that were outside those limits and were eliminated from further analysis.

Relative electricity consumption changes in a subgroup $E_{\text{subgroup}(\%)}$ were calculated according to equation

$$E_{\text{subgroup}(\%)} = \frac{\sum_{i=1}^{n} E_{i(\%)}}{n}, \tag{1.4}$$

where $E_{i(\%)}$ are relative consumption changes for a respondent in the subgroup calculated in equation (1.1).

The results of the pilot are shown in Table 1.2. Significant reduction of consumption was identified in all groups. However, it should also be noted that there were significant variations in data and they did not correspond to normal distribution in subgroups. Therefore in the analyses mean and median of consumption were used.

The reduction of consumption in the target and control group could be attributed to changes in weather conditions during the compared periods. Therefore, the group difference should be assessed as a result of information feedback.

In the analysis it was assumed that only those differences of groups were included which satisfied the statistical significance test with p value smaller than 0.05. Additionally, the subgroup results should be included according to their representation in the consumption distribution of all households in Latvia. The results of this analysis are presented in Table 1.3.

Table 1.2

Electricity Consumption Changes in Corresponding Periods of 2013 and 2012 Subdivided in Groups Based on Annual Electricity Consumption

Consumption subgroup, kWh annually	Target group				Control group			
	Number of participants	Median of consumption reduction, %	Mean of consumption reduction, %	Std Error of the mean, %	Number of participants	Median of consumption reduction, %	Mean of consumption reduction, %	Std Error of the mean, %
0 to 2500	47	–11.2	–11.7	3.7	70	1.1	5.6	4.1
2501 to 4800	96	–9.9	–6.4	2.7	133	–3.8	–1.8	2.4
4801 to 8400	102	–11.7	–11.7	2.5	175	–6.1	–3.5	2.2
8401 to 18 000	86	–16.2	–17.1	2.6	46	–2.3	1.2	6.0
18 001 to 22 800	81	–26.3	–22.7	3.4	56	–2.8	–1.8	4.1
Above 22 800	70	–29.9	–28.4	3.0	51	–2.3	0.0	4.0

Based on the pilot results and normalising data according to distribution of consumption in population it can be concluded that there is a statistically significant reduction of 11.4 % for an average and 8.6 % for median of consumption. However, for CBA validation purpose the median reduction value should be used as it reduces the effect from distribution factors in subgroups.

Table 1.3

Electricity Consumption Related Changes Based on Electricity Consumption Distribution between Subgroups

Subgroup annual consumption, kWh	Subgroups from total HH consumption, %	Median of consumption reduction, %	Mean of consumption reduction, %	Median of consumption reduction, %	Mean of consumption reduction, %
0 to 2500	46	–12.3	–17.3	–5.7	–8.0
2501 to 4800	29	0.0	0.0	0.0	0.0
4801 to 8400	14	–5.6	–8.2	–0.8	–1.1
8401 to 18 000	5	–13.9	–18.3	–0.6	–0.8
18 001 to 22 800	4	–23.5	–20.9	–1.0	–0.9
Above 22 800	2	–27.6	–28.4	–0.6	–0.6
Total	100			–8.6	–11.4

Important issue in evaluating these results is whether the data from relatively short study can be used when assessing the gains from provision of feedback information in cost benefit analysis that spans over a ten year period. Despite the fact that it was not possible to do it within the scope of the pilot project, there are indications, for example in the Vaasa ETT report and in the smart metering pilot in Ireland, that long term effects could be even higher than short ones. It could be due to the fact that short term effects are driven by changes in customer behaviour that might fade over time. Whereas, long-term effects offset that as they are associated with acquisition of more efficient lighting and household appliances.

It should be also noted that the pilot project is still continuing as it is required by Climate Change Finance Instrument financing conditions and the results confirm that the consumption of target group is still 10 % lower in comparison with the control group.

1.3. Analysis of Reduction of CO_2 Emissions in a Situation of Integrated Baltic Electricity Market

The positive result – EUR 4.4 million in the Scenario F in cost benefit analysis of smart meter rollout, was partially due to the environmental gains from the reduction of CO_2 emission. That has contributed EUR 3.9 million to the positive balance of cost benefit analysis. The savings are achieved due to the fact, that increased energy efficiency requires less electricity generation. In order to satisfy the demand in Latvia, generation on fossil fuel has to be run almost all the time, therefore, savings can be estimated based on CO_2 emissions from marginal generation that is needed to meet the demand. The smart meter analysis assumed CO_2 emission intensity of 0.397 tCO_2/MWh that corresponds approximately to electricity generation in *Latvenergo* thermoelectric power plants. Nevertheless, the actual emission factor is stipulated by government regulation No. 441 on calculation of reduction of CO_2 emissions.

However, due to integration of the Latvian electricity market in the Baltic and Nordic markets the situation can significantly change because hydropower generation exceeds 50 % in the Nordic market and generation from fossil fuels accounts for 22 % from total generation. At the same time, marginal generation cannot correspond to the average generation. It can be the effect of competition or of commodity prices, for example, prices of CO_2 emissions. Therefore, it is important to assess the effect on the assumed CO_2 emissions reduction after integration in much decarbonised Nordic electricity market.

To estimate the carbon market effect on power prices in the Nordic and Baltic markets, multiple regression analysis has been performed. Based on literature and test the optimal regression framework is calculated according to the following equation:

$$Y = \beta_0 + \beta_1 \cdot prd + \beta_2 \cdot cnp + \beta_3 \cdot coal + \beta_4 \cdot CO_2 + \beta_5 \cdot hyd + \epsilon, \qquad (1.5)$$

where

prd	total Nordic internal electricity production amount;
cnp	total Nordic internal electricity consumption amount;
coal	closing coal market price;
CO_2	closing of the CO_2 emissions trading contract with a delivery in December 2015;
hyd	total Nordic electricity production from hydro power plants;
ϵ	residual values.

The analysis was run on the data spanning from August 2010 to May 2015 where factors that represent accumulative values, such as supply and demand, were taken as the absolute monthly total amount, while changing variables, such as the CO_2 emissions price, were taken as the monthly average of daily closing prices to match the electricity market format. The results are presented in Fig. 1.2. and are characterised with value 0.85 of adjusted R^2.

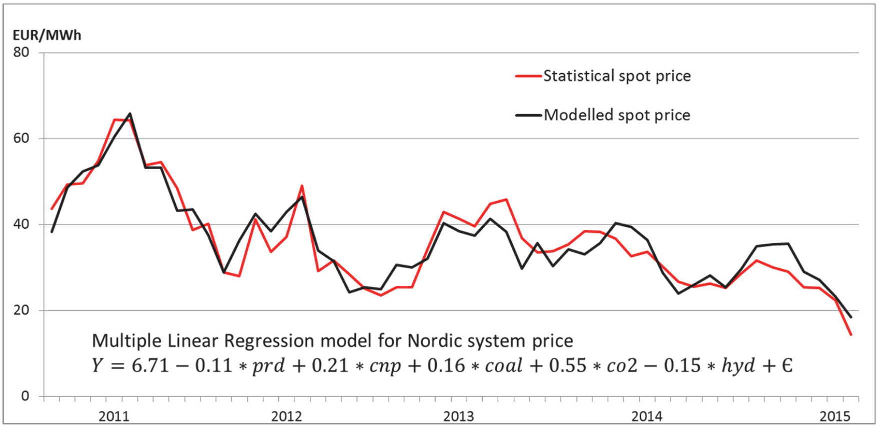

Fig. 1.2. Multiple regression model for the Nordic system price.

Therefore, we can conclude that the price of CO_2 emissions is a significant predictor of the Nordic electricity price and this phenomenon is more significant than it could be expected from the generation mix during the period of analyses where generation from fossil fuels constituted about 20 %. That could be explained by the fact that Nordic hydropower plants possess large accumulation capability and therefore can optimize generation over extended time period. That allows to price in replacement of fossil generation also during periods when such generation physically is not present on the market.

Taking into account that the Baltic electricity market is linked with Finland, Sweden and Poland, the regression model was used for the analysis of these price areas.

Table 1.4

Effect of the Price of CO_2 Emissions on Electricity Prices in Different Nordic and Baltic Price Areas

Selected region	Percentage of the explained response variable variation within the model (adjusted R^2), %	Increase in electricity price by 1 EUR increase in CO_2 price, EUR	Standard error, EUR
Nordic system	85	0.55***	0.21
Sweden	77	0.58*	0.28
Finland	59	0.62*	0.34
Poland	48	0.67***	0.24
* Significant at $p < 0.10$; ** Significant at $p < 0.05$; *** Significant at $p < 0.01$.			

At the regional level correlation between CO_2 and electricity prices still persist; however, it is to a lesser extent expressed, see Table 1.4. Possibly the difference is due to congestions between the price areas that is common on the border of Norway, where 98 % generation is from hydropower plants, as well as in Sweden and Finland. In Poland, the generation is almost completely dominated by coal power plants and the model did not capture the price changes very well due to the market specifics – relatively closed market with domination of bilateral agreements. Due to the power exchange the trading is less than 20 % of all generation and the fundamental factors have less effect on prices.

Taking into account the fact that the Baltic electricity market is in the formation stage, which is driven by interconnections with neighbouring markets, it is not possible to use the statistics to assess market reaction in the future. Therefore, in order to assess the Latvian electricity market and the effect from CO_2 emissions, generation forecast in form of merit order in hourly granularity was developed. Using this forecast annual mix of marginal generation or source of electricity import was created (see Table 1.5.). CO_2 emission factor for imported electricity was derived from CO_2 price impact factor for each relevant electricity price area.

Table 1.5

Marginal Electricity Sources at the price of 7.5 EUR per ton of CO_2 Emissions According to the Market Conditions in Latvian Price Area in 2017

Marginal generation or import sources	Marginal sources as %	Price analyses		Sensitivity analyses	
		CO_2 emission factor, tCO_2/MWh	Weighted CO_2 emission factor, tCO_2/MWh	CO_2 emission factor, tCO_2/MWh	Weighted CO_2 emission factor, tCO_2/MWh
Oil shale	2	1.01	0.020	1.01	0.02
Gas cogeneration	10	0.27	0.027	0.27	0.03
Sweden	36	0.58	0.209	0.37	0.13
Finland	36	0.62	0.223	0.37	0.13
Poland	9	0.67	0.060	0.84	0.08
Other	7	0.37	0.026	0.37	0.03
Total	100		0.566		0.419

For every generation type its emission factor was identified and correspondingly for import sources the CO_2 price sensitivity factor was used. Emissions from gas cogeneration were based on actual emission factor in 2016 for *Latvenergo* gas power plants, which comprises also the same fraction of condensing. For other sources gas condensing emission factor was used as it is mostly imported from Kaliningrad.

Assessing marginal emission with this methodology, we can conclude that the benefits from the reduction of 1 MWh of electricity demand would result in the reduction of 0.566 tCO_2 that is significantly higher than 0.397 tCO_2/MWh set by the government regulation.

Additionally, sensitivity scenario was developed where emission factors for import from Sweden and Finland were replaced by the emission factor of electricity generated in gas condensing power plant.

That could be justified because gas condensing generation will be next marginal generation after coal in merit order. Such situation might arise due to the increase of CO_2 emission price or due to administrative restrictions enforced on coal generation.

At the same time it would be reasonable to replace electricity import from Poland with emission factor for electricity generation from coal because with improvements in electricity market in this price area electricity generation from coal will always be marginal generation. In case of this sensitivity scenario, reduction of 1 MWh of electricity demand would result in the reduction of 0.419 tCO_2 that still is higher than the assumption in CBA.

It was identified, that in this type of analysis the absolute level of CO_2 emission is a significant factor as it will switch in the generation merit order between coal and cogeneration. As demonstrated in Fig 1.3., at low levels of CO_2 emission that correspond to actual 2017 prices, the marginal electricity generation most often is gas cogeneration. At the same time oil shale power plants are running as a base load with emission factor 1.01 tCO_2/MWh. It clearly demonstrates that current emission trading price does not optimise generation scheduling from environmental perspective. The distribution of generation shown in Fig. 1.3. represents merit order of an average hour during winter months excluding night hours and weekends.

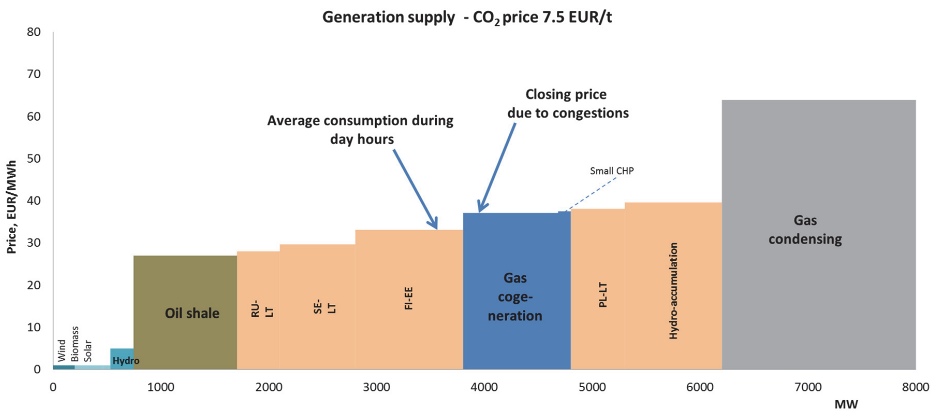

Fig. 1.3. Forecast of merit order of generation in 2017 at CO_2 price 7.5 EUR/t.

In addition, a forecast of merit order of generation for 2017 at CO_2 price 7.5 EUR/t was developed where the prices of primary energy resources were kept at the same level. The results demonstrate that at this CO_2 price level 1 MWh of electricity demand would result in the reduction of 0.492 tCO_2 as shown in Table 1.6. As CO_2 emission price increases, the weight of cogeneration percentage in electricity generation supply accordingly increases and squeezes out generation with higher emissions. The sensitivity analysis for this price scenario, replacing emission factors for import from Sweden and Finland with emission factor of electricity generated in gas condensing power, demonstrates the emission factor of 0.458 tCO_2/MWh that is still higher than used in CBA.

Table 1.6

Marginal Electricity Sources at the Price of 20 EUR per ton of CO_2 Emissions According to the Market Conditions in Latvian Price Area in 2017

Marginal generation or import sources	Marginal sources as %	Price analyses		Sensitivity analyses	
		CO_2 emission factor tCO_2/MWh	Weighted CO_2 emission factor tCO_2/MWh	CO_2 emission factor tCO_2/MWh	Weighted CO_2 emission factor tCO_2/MWh
Oil shale	15	1.01	0.152	1.01	0.15
Gas cogeneration	47	0.27	0.127	0.27	0.13
Sweden	17	0.58	0.099	0.37	0.06
Finland	5	0.62	0.031	0.37	0.02
Poland	8	0.67	0.054	0.84	0.07
Other	8	0.37	0.030	0.37	0,.03
Total	100		0.492		0.458

Figure 1.4. demonstrates that the change of CO_2 emission price from 7.5 to 20 EUR/t is sufficient for an oil shale power plant to become a marginal cost producer. The analysis does not take into account possible scenarios of commodity prices. However, assuming that the relation between coal and gas would remain about the current level, CO_2 price level will be the main factor in the competition of those generation sources.

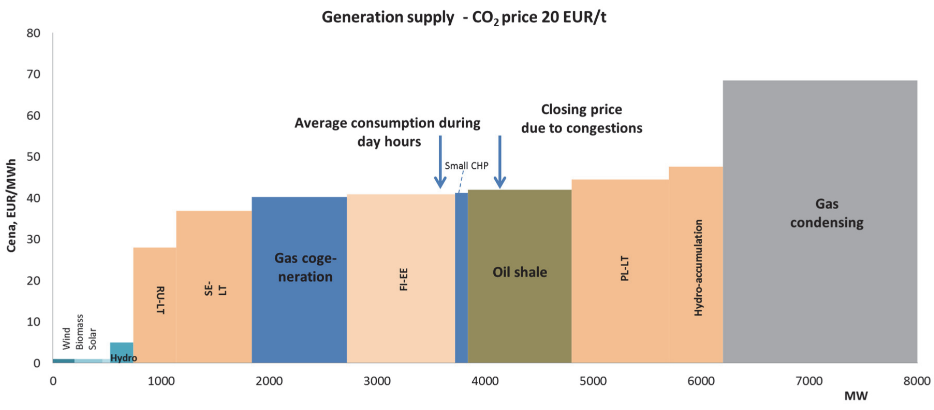

Fig. 1.4. Forecast of merit order of generation in 2017 at CO_2 price 20 EUR/t.

In summary, the analysed scenario and sensitivity analysis demonstrated that the benefits from the reduction of 1 MWh of electricity demand would result in the reduction of emissions in a range of 0.419 tCO_2 to 0.566 tCO_2. Therefore, it can be concluded that even higher CO_2 emission factor could be used in cost benefit analysis of smart meters where currently 0.397 tCO_2/MWh is used based on government regulation.

2. Analysis of Factors Influencing Energy Efficiency and its Adoption

2.1. Goal-Framing Theory Application in Energy Efficiency Analysis

In order to explore the process of energy efficiency adoption, diffusion of innovation framework developed by Rogers[4] can be used. There are five stages of an individual adopting the innovation:

- gaining of knowledge about the innovation through social networks;
- formation of an attitude towards it;
- decision on adopting or rejecting it;
- implementation of it;
- conforming with the decision.

In order to promote energy efficiency, general practice is to inform society about available energy efficiency measures in lighting and efficient household appliance. At the same time, despite the widely available information, the uptake of efficiency solutions is significantly lagging. It can be explained by innovation diffusion theory that predicts that after the information stage an individual should form an attitude and make a decision. There is a number of psychology theories that can be used in order to analyse pro-environmental attitudes and behavioural aspects. One of such framework for pro-environmental behaviour is the goal-framing theory developed by Lindenberg and Steg[5].

Goal-framing theory is a cognitive attitude that develops under specific context which forms the choices of an individual. In the goal-framing theory in the context of a particular situation goals become focal and the rest has a background role.

In order to investigate the factors influencing energy efficiency adoption in Latvia, a survey was developed to determine residential customer attitudes to adoption of energy efficiency measures. The survey was based on goal-framing theory and three main elements of goal-framing were analysed:

- hedonic ("enjoying" the energy efficiency measures);
- gain (cost savings through energy efficiency measures);
- normative (energy efficiency measures to reduce impact on the environment).

The overall design of survey was taken from Ozaki (*Ritsuko Ozaki*), where it is used in the research of the behaviour of consumers adopting green electricity tariffs[6]. According to Rogers' framework of diffusion of innovations, individuals should first gain knowledge of an innovation and then, during the second stage – an attitude towards the innovation develops. Therefore, the survey was distributed via e-mail to the employees of utility company *Latvenergo* providing

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[4] E. M. Rogers, Diffusion of Innovations, 5th edition, New York: Free Press, 2003.

[5] S. Lindenberg and L. Steg, "Normative, Gain and Hedonic Goal Frames Guiding Environmental Behavior," Journal of Social Issues, vol. 63, no. 1, pp. 117–137, 2007.

[6] R. Ozaki, "Adopting sustainable innovation: what makes consumers sign up to green electricity?," Business Strategy and the Environment, vol. 20, pp. 1–17, 2011.

energy supply and distribution services, assuming that among this population information about energy efficiency solutions is well disseminated.

In general, answers were received from 407 respondents, 387 questionnaires were completely filled and were used in further data analysis. Since the survey was carried out among utility employees, the sample group consisted mostly of male respondents, people with higher education and average income per household member, see Table 2.1.

Table 2.1

Demographics of Population Survey and Comparison With Average in Latvia

Parameter, unit	Statistics from questionnaire	Average in Latvia, (year)
Age, years on average	41.50	41.60 (2011)
Gender, % male	68.49	45.82 (2014)
Income per household member, EUR/month	491.03	319.90 (2012)
Household size, persons per household	3.07	2.43 (2013)
Education		
% higher	79.69	23.10 (2011)
% secondary	20.31	53.99 (2011)
Housing type, % living in flat	62.24	70.00 (2013)
Language spoken at home, % speaks Latvian	85.16	56.27 (2011)

These biases could affect representativeness of the survey. However, the intention of study was to explore the attitudes only of those people, who have good knowledge about energy efficiency and are in the network of such people in order to analyse how in these circumstances attitudes towards energy efficiency are formed. Additionally, pilot studies have not identified correlation between the gender and education level from one side and engagement into energy saving behaviour from the other.

The aim of goal-framing theory is to conduct logistic regression analysis in order to use the acquired results in system dynamics modelling. Correlation analysis was performed to explore how goal frames might affect energy efficiency behaviour. The answers from the questionnaire where grouped as follows: normative, hedonic, gain and mixed goals. Correlation analysis was carried out between the answer to whether the respondent is actively engaged in energy saving activities and all other answers of the questionnaire (independent variable). The correlation coefficient (R) and mean value was calculated for each independent variable at 95 % confidence level for both groups who are and who are not involved in energy saving, thus allowing to compare statistically different answers across the two groups.

Logistic regression analysis was performed to determine the combination of factors, which explain the intention to use or not to use energy efficiency measures. Only the statistically significant at the confidence level of 95 % combinations of answers from each of normative, hedonic, gain and mixed goals groups where then combined into one logistic regression model. For logistic regression analysis a model was created, where dependent variable describes events with two possible stats – the respondent is engaged in energy saving activities or not. For logistic regression analyses also respondents who stated that they are using energy efficiency measures but are not actively involved in this activity were included as it provided better predictability for the model. Possible outcomes were modelled as a function of the predictor variables, using a logistic function, expressed by equation 2.1.

$$\log\left[\frac{P(X)}{1-P(X)}\right] = \mathrm{e}^{(\beta_0+\beta_1 X_1+\beta_2 X_2+...+\beta_k X_k)}, \tag{2.1}$$

where

P outcome probabilities if independent variable is X;

β_0 constant of the fitted model;

$\beta_1, \beta_2, \ldots, \beta_k$ estimated coefficients.

Stepwise backward factor selection was chosen with p-value to enter 0.05. To estimate the accuracy of the fitted model the percentage of deviance explained by model (R^2) was calculated according to equation 2.2.

$$R^2 = \frac{\lambda(\beta_1, \beta_2, ...\beta_k \,|\beta_0)}{\lambda(\beta_0)}. \tag{2.2}$$

Adjusted deviance (R^2_{adj}) was calculated in similar manner to R-squared, see equation

$$R^2_{\mathrm{adj}} = \frac{\lambda(\beta_1, \beta_2, ...\beta_k \,|\beta_0) - 2p}{\lambda(\beta_0)}, \tag{2.3}$$

where p equals the number of coefficients in the fitted model, including constant term.

The results of the logistic regression models fitted for individual motivations show that there is no single clearly dominating motivation. The final model "Energy efficiency motivation" (which combines normative, gain, hedonic motivation and other variables) explained 51.4 % of deviance and 13.0 % of adjusted deviance (see Table 2.2.).

Table 2.2

Analysis of Deviance and Residuals for the Logistic Regression Model "Energy Efficiency Motivation"

The model	The sum of squared deviations explained by the model, %	The sum of squared deviations explained by the model, adjusted, %
Normative motivation	29.0****	5.2
Gain motivation	21.1**	2.3
Hedonic motivation	20.1****	5.9
Other variables	21.2****	7.0
Energy efficiency motivation	51.4****	13.0

** Significant at $p < 0.01$; *** Significant at $p < 0.001$; **** Significant at $p < 0.0001$.

These results can be due to the fact, that the context of the survey was embracing all energy efficiency activities applicable to households and this scope might be too broad. The goals can change not only due to underlying values but also due to situational cues that imply that reactions are very context specific. The goals can become focal as an automatic reaction to cues and when some of them become focal, they change our behaviour affecting what we focus at, what information we are sensitive to, what information we neglect, what knowledge and what concepts are activated at a given moment, what we like and dislike, what we expect others to do. Consequently, it might be that the respondents were not placed in a specific enough context in order for all of them to form more definite attitude towards expected behaviour that resulted in more scattered results among different goals.

2.2. Energy Efficiency Modelling Using System Dynamics

The system dynamics modelling was used as method in the study due to its ability to provide a modeller with well-suited and convenient instruments for the analysis of dynamics of complex systems with inclusion of feedbacks and delays.

Two system dynamics models were developed. The study analysed the dynamics of household electricity consumption, which depends on two important feedbacks – the feedback from electricity consumption to electricity cost-income ratio (and further to a motivation to save electricity) and the feedback from electricity consumption to electricity price, affecting electricity cost-income ratio as well (see Fig 2.1.).

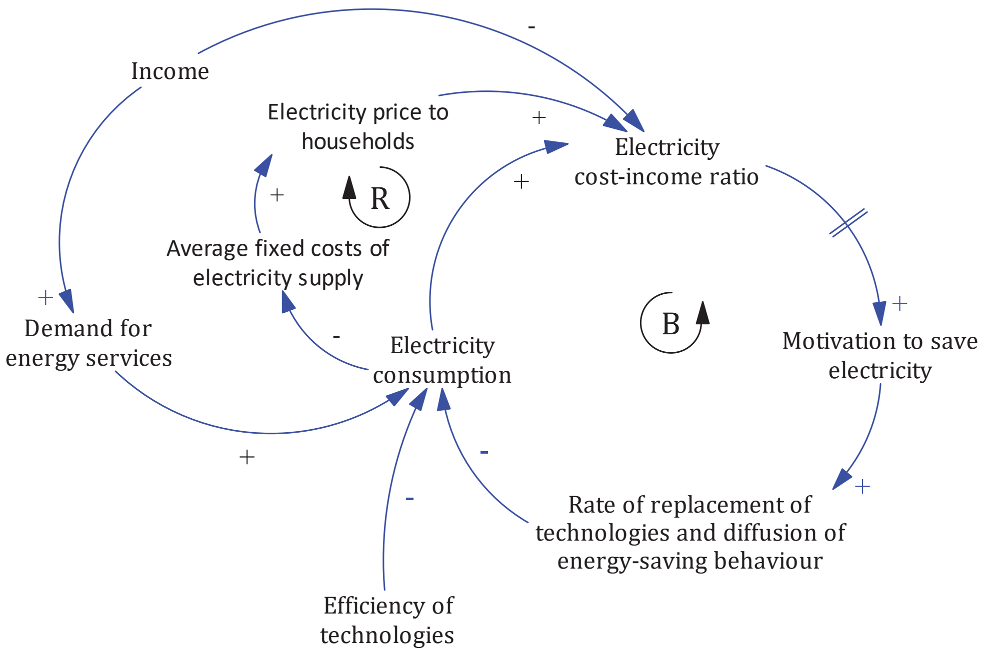

Fig 2.1. Dynamic hypothesis – a causal loop diagram (CLD) illustrating the main feedback processes.

In addition, a household survey regarding the relation of implemented electricity saving measures and the electricity cost-income ratio was carried out and the functional relationship was used in the model to characterize the link between the electricity cost-income ratio and the motivation to save electricity (see Fig 2.1). A dynamic hypothesis is based on the assumption that the motivation to save electricity is driven by electricity cost-income ratio, which, in turn, depends on electricity consumption, electricity price and income.

The structure of the studied system can be represented by one reinforcing and one balancing loop. Decreasing electricity consumption as the result of the increased motivation to save electricity, reduces the electricity cost-income ratio and thus balances-out the effect of motivation. The balancing loop illustrates the re-bound effect of energy savings. On the other hand, decreasing electricity consumption increases the average fixed costs of electricity supply, which, in turn, drives up electricity price for households and electricity cost-income ratio, thus reinforcing the motivation to save electricity. The increased motivation feeds back to electricity consumption by decreasing it even more and increasing the price of electricity further *ceteris paribus.* The income growth has two effects (Fig 2.1).

1. It increases the demand for energy services, i.e. lighting, heating, cooling.
2. It decreases the electricity cost-income ratio, thus pushing electricity consumption upwards.

The electricity consumption is reduced by increasing the efficiency of technologies, leading to reduced electricity consumption per unit of energy service provided.

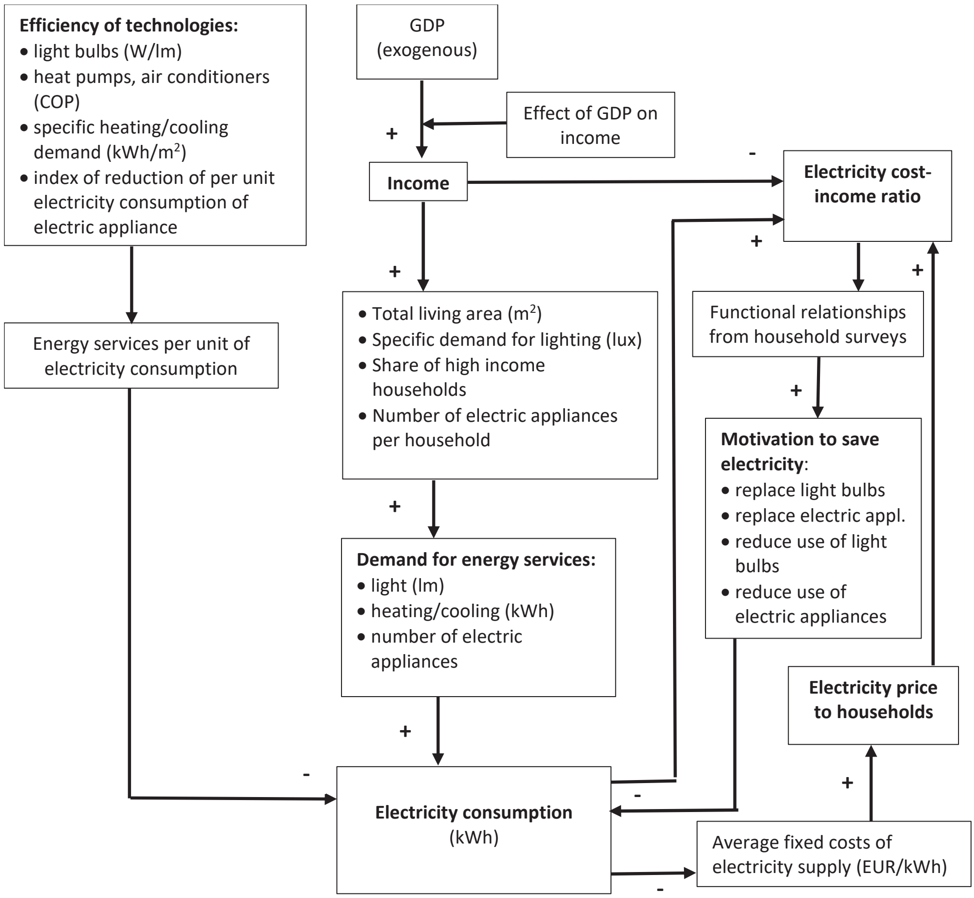

Fig. 2.2. Structure of the model – a sector diagram.

The model is organized (Fig. 2.2) according to the structure reflected by the causal loop diagram. A gross domestic product (GDP) is taken as an exogenous parameter for determination of the dynamics of income. The data regarding GDP increase, household characteristics (living area, types and number of lighting, heating, cooling equipment, electric appliances and hot water heaters) were obtained from statistical databases [8]. The data of household electricity consumption and the prices for the years 2014–2016 were obtained from electricity company JSC *Latvenergo*. The average fixed costs of electricity supply were calculated based on the assumption that the initial total fixed costs of electricity supply to end-users do not change. Thus, with calculating change of the electricity consumption, the variation of electricity price to households can be determined endogenously. Functional relationship between the electricity cost-income ratio and motivation to save electricity was obtained from the household survey in Latvia.

The modelling period was January 2014 to December 2020, assuming gradual replacement of old equipment – light bulbs, electric appliances, heat pumps and air conditioners. Efficiency of the new equipment was modelled assuming the "goal seeking" behaviour, which may be a good assumption considering a diminishing return of efforts invested in the development of a particular technology. The decrease of electricity cost-income ratio would create an opposite motivation.

In order to assess how varying electricity cost-income ratio also influences the motivation to reduce the use of light bulbs and electric appliances, i.e. change the behaviour of use, there was a survey among 700 households in Latvia during 2015. The aim was to quantify the relation between the electricity cost-income ratio and motivation to save electricity, as included in the dynamic hypothesis, and what electricity saving measures were actually implemented by the households in response to the increase of electricity cost-income ratio.

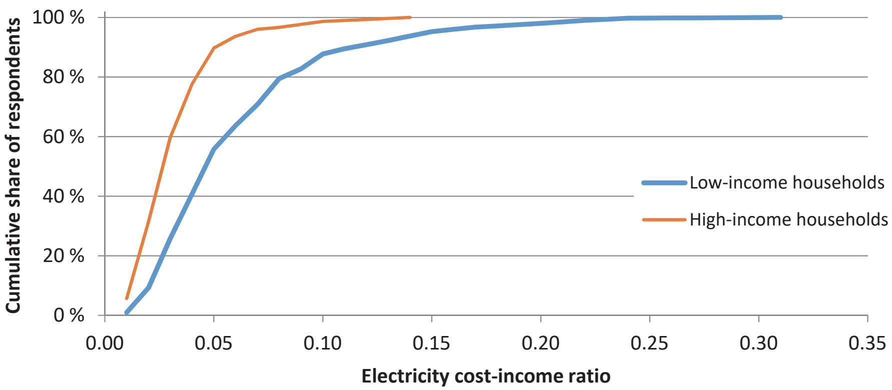

Fig. 2.3. Relation between the cumulative share of respondents and electricity cost-income ratio in low and high-income households.

Analysis of survey data revealed two groups, i.e. low-income and high-income households can be distinguished by higher electricity cost-income ratio among larger fraction of the first group. Therefore, it was decided to model these two groups as separate parts where cost-income ratio is shown in Fig. 2.3. At the beginning of the modelling high-income households accounted for 20 % of the total.

The model was validated using structural and behavioural tests. Both data of actual electricity consumption and calculated results show initial decline of electricity consumption, although the calculated consumption does not exhibit the same extent of decline as the actual. That could be due to active public communication during market opening that highlighted price increase.

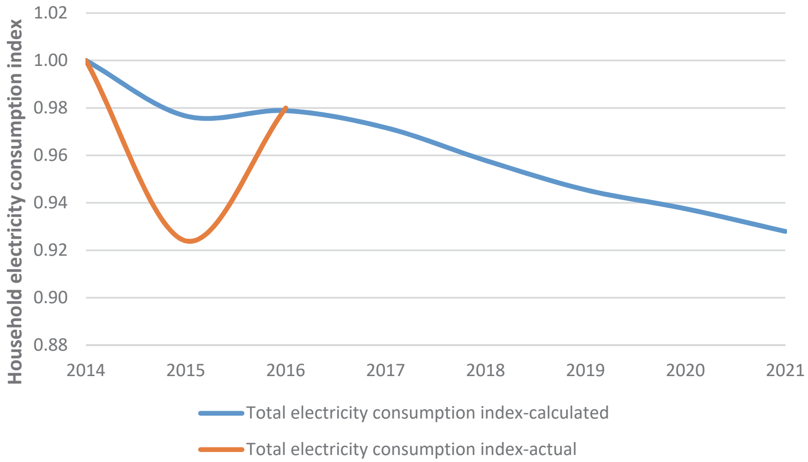

Fig. 2.4. Total household electricity consumption index – calculated results and actual data (the initial consumption: 1887 GWh per year).

The calculated and the actual indexes coincide during the year 2016 and the results of the model indicate the applicability of the model for forecasting of consumption trends.

Results of the model show that under the current assumptions and dynamic hypothesis the total residential electricity demand may decline from 1887 GWh to 1751 GWh annually that corresponds to 1.1 % cumulative annual reduction rate, see Fig. 2.4.

Although the indexes of change of the electricity-cost income ratio and the resulting indexes of the motivation to replace light bulbs (the trend is similar for the motivation to replace electric appliances and change behaviour) in both household groups decrease beyond the year 2016, these indexes still remain above value 1, see Fig. 2.5. and Fig. 2.6. It can be noticed that a considerable increase of the electricity price, resulting in similar increase of the electricity cost-income ratio and motivation to replace light bulbs, does not lead to a drastic drop of electricity consumption. This can be explained by the rate of increase of energy efficiency of technologies being larger than the rate of increase of demand for the energy services.

It is expected that reduced time of replacement of old light bulbs and electric appliances with the new ones would lead to even more rapid decrease of electricity consumption due to higher efficiency of the new equipment.

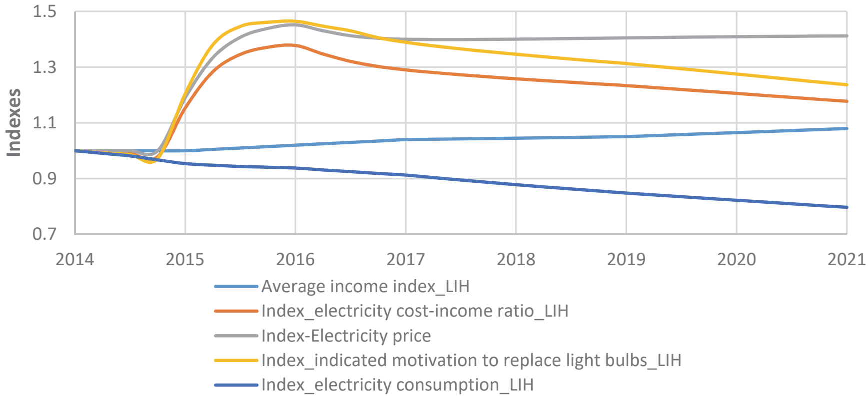

Fig. 2.5. Indexes of electricity price and low-income household (LIH) electricity consumption.

The index of electricity consumption (see Fig 2.5.) of high-income households increases because of the increasing share of high-income households due to economic growth. If in the model the share of the high-income households remained constant, the electricity consumption decreases would be observed in both groups.

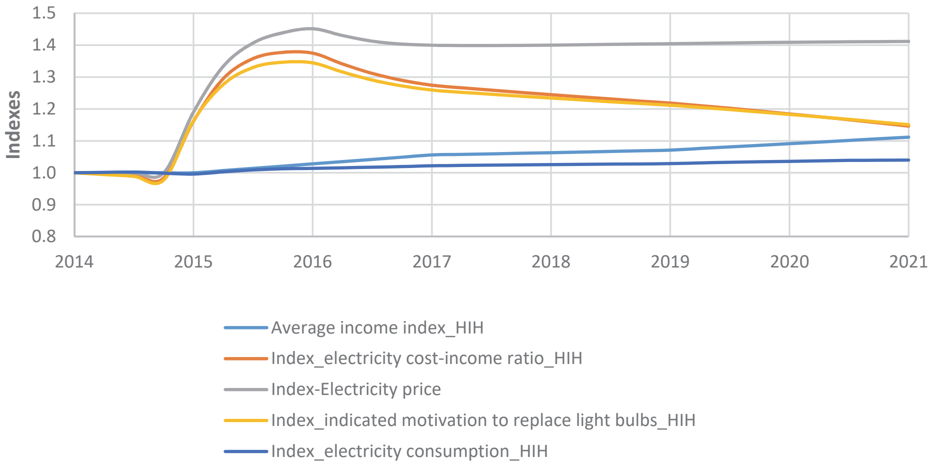

Fig. 2.6. Indexes of electricity price and high-income household (HIH) electricity consumption.

To explain the obtained results several scenarios were developed in addition to the reference or base case. First, by increasing the efficiency of technologies, behaviour of use and demand for energy services constant, the model can have an additional validation test since electricity consumption should remain constant under these assumptions, as it does. Figure 2.7. shows the results if the efficiency of technologies and behaviour of use remains constant but the demand for energy services increases due to the increase of income.

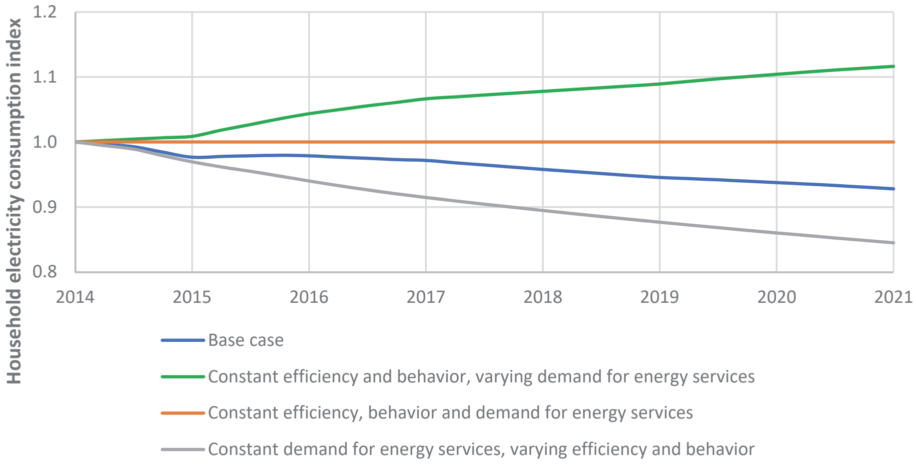

Fig. 2.7. Total household electricity consumption index in different scenarios.

In this situation, the consumption index increases almost by 10 % which is generated by income growth in households and consequently generates electricity consumption growth. The household consumption increase corresponds to 1.6 % cumulative annual growth rate and accounts for 1627 GWh over the modelling period. When the electricity price is constant, the resulting electricity consumption is slightly larger but the difference with the base case is not profound.

When the electricity price is set constant along with a constant demand for energy services, the results show that a difference in the scenario with constant demand for energy services but with varying electricity price (see Fig. 2.8.) is very little, i.e. electricity consumption is only by circa 1 % larger in the case of constant electricity price. It is probably worth noting, that no difference of electricity consumption in the base case and in the case with constant electricity price until the 3rd quarter of 2015 is due to an information delay between the electricity cost-income ratio and motivation to replace light bulbs, willingness to replace electric appliances and electric water heaters, as well as reduce the use of light bulbs and electric appliances. The information delay is used for technical reasons, i.e. to avoid circular references, but may as well be justified by reality, since an increase of the electricity cost-income ratio may be perceived and trigger some action with a time delay.

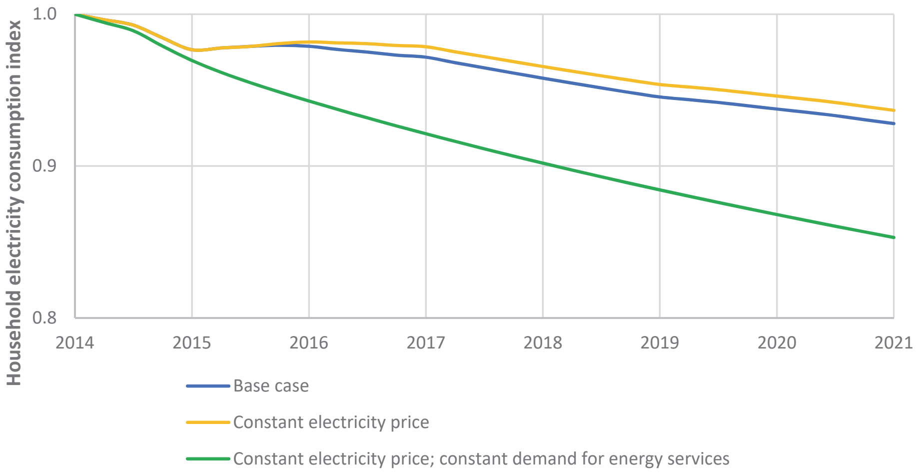

Fig. 2.8. Total household electricity consumption index for different price scenarios.

In addition, a potential to further reduce consumption forecast was identified in case there is a possibility to minimise diffusion of new energy efficiency technologies. The model based on current input data assessed this effect as 593 GWh further consumption reduction that corresponds to 0.9 % cumulative annual reduction rate, see Fig. 2.9.

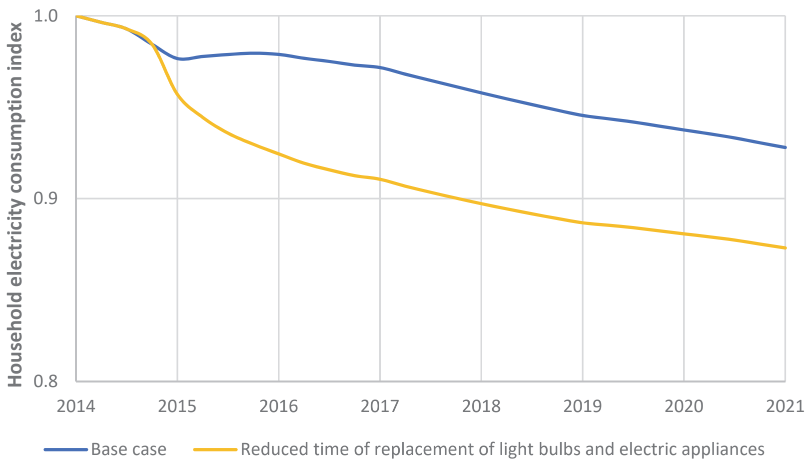

Fig. 2.9. Total household electricity consumption index and the case with time of replacement of light bulbs and electric appliances being nearly 0.

There are several directions for future research and improvements of the model. First, one of the deficiencies of the model, which could be eliminated, is a more accurate modelling of efficiency attributes of equipment. In the present model, the efficiency of all new equipment of the same type is assumed to be the same and equal to the current level of technological development. It would be more correct to account that the new equipment is a mix of units with differing energy efficiency characteristics, which depend on the time of "purchase" by a household. Secondly, considering that a "goal-seeking" character of efficiency change leads to a quite rapid increase during the initial time periods, it is important to assess the sensitivity of electricity consumption to assumptions regarding the values of goals and time to reach those goals. In addition to those "technical" aspects, the research could be extended by including additional social factors, which may lead to changes of consumer behaviour. Namely, integration of the results from sociological studies on impact of environmental awareness, information level, "behaviour of neighbours and friends", etc. in addition to economic factors, in system dynamics modelling would provide more insight in potential future energy savings. Considering the influence of specific factors, e.g. income and electricity price level, climatic conditions, etc., which depend on the region under study, it would be worthwhile to expand similar studies to other regions.

CONCLUSION

Analysis of Energy Efficiency and Smart Meter Rollout

- The first cost benefit analysis of smart meter rollout has demonstrated that economic benefits to a society are achievable by limited rollout program that assumes installation of smart meters only in objects with annual consumption above 2500 kWh that results in 23 % penetration of smart meters. This scenario demonstrates EUR 4.4 million positive return over a 10-year period at society level where the implementation of the limited rollout is planned from 2015 to 2017. The positive outcome of the scenario is mainly due to external factors where EUR 20.9 million come from customer savings generated by energy efficiency improvements and EUR 3.9 million come from the reduction of CO_2 emission resulting from lower electricity consumption. The prerequisites for further economical penetration of smart meters are the reduction of costs of technology as well as improvement of operation efficiency in distribution networks.
- In order to validate the cost benefit analysis of smart meter rollout, a smart metering pilot project was carried out. Based on the results of the pilot project and applying them to the distribution of electricity consumption of households in Latvia, it can be concluded that statistically significant 8.6 % electricity reduction has been observed in the case of installation of smart meters and provision of appropriate feedback information. The reduction is materially above 5 % assumption used in cost benefit analysis. It could be assumed that in case of higher gains from energy efficiency also penetration of smart meters can be increased. That is supported by the fact that the subgroup of households with annual consumption of electricity under 2500 kWh has demonstrated savings even above average level. However, such assumption would require further testing because there is a possibility that over a longer period the saving effect reduces.
- Reduction of CO_2 emission has contributed EUR 3.9 million to the positive balance of cost benefit analysis. The savings are achieved due to the fact, that increased energy efficiency requires less electricity generation. The analysis assumed CO_2 emission intensity of 0.397 tCO_2/MWh that approximately corresponds to electricity generation in *Latvenergo* thermoelectric power plants. In parallel to the rollout of smart meters electricity market of Latvia is rapidly integrating in the Nordic market that is characterized as very low carbon intensity market. Therefore, a multiple regression analysis was carried out to assess the impact of CO_2 emissions on electricity prices.
- The regression analysis demonstrates that the price of CO_2 emissions is a significant predictor of electricity price in the Nordic market and it is significantly above the level that could be expected from the share of generation from fossil fuels, which during that time was slightly above 20 %. The price impact was 0.55 for the Nordic system price, which means that an increase of the CO_2 price by 1 EUR would increase the electricity price by 0.55 EUR. That could be explained by the fact that hydropower plants in the Nordic system possess large accumulation capability and therefore can optimize generation over an

extended time period. That allows to price in replacement of fossil generation also during periods when such generation physically is not present on the market.

- In order to assess the CO_2 emissions factor of electricity in Latvia, where it is formed not only by local generation but also by different import sources, analysis of marginal costs of generation for 2017 was carried out by simulation of merit order on hourly bases. Based on this analysis marginal generation or import sources over the year that determine CO_2 emissions factor in Latvia was determined. Assessing marginal emission using this methodology we can conclude that benefits from the reduction of 1 MWh of electricity demand would result in the reduction of 0.566 tCO_2 where emission price is 7.5 EUR/t which is close to current market conditions. Additionally, a scenario of the case with the emission price 20 EUR/t was developed, where no price changes were assumed for primary fuel. In this scenario, the reduction of 1 MWh of electricity demand would result in the reduction of 0.492 tCO_2.
- In summary, the analysed scenario and sensitivity analysis demonstrate that benefits from the reduction of 1 MWh of electricity demand would result in the reduction of emissions in the range of 0.419 to 0.566 tCO_2. Therefore, it can be concluded that even higher CO_2 emission factor could be used in cost benefit analysis of smart meters where currently in accordance with government regulation 0.397 tCO_2/MWh is used. Consequently, higher emission factor could be used assessing impact of other energy efficiency activities resulting in reduced electricity consumption. Finally, it can be concluded that integration of the Latvian electricity market into the Nordic market does not imply the risk of diminishing environmental gains from energy efficiency measures.

Analysis of Factors Influencing Energy Efficiency and its Adoption

- The process of implementation of energy efficiency measures can be analysed by applying innovation diffusion concept, which assumes that an individual is forming its attitude and forming a decision after receiving information regarding available solutions of energy efficient lighting and other appliances. In order to analyse the stage of formation of attitude and decision, the goal-framing theory was selected. Accordingly, a survey was carried out and multi nominal logistic regression model was developed. The results did not identify one dominating goal; however, in the answers of respondents, who were active in energy savings in correlation analysis, normative goal was more evident. The motivation model for energy efficiency, which combines normative, gain, hedonic motivation and other variables, explained 51.4 % of deviance and 13.0 % of adjusted deviance that is lower if compared with similar studies on intention to adopt eco-innovations. This might be due to broad survey setting; therefore, the predictability of this methodical approach could be improved by narrowing the survey to a very specific energy efficiency activity where respondents are engaged in purchasing only LED or A+++ white appliance.
- In order to assess long term effects from energy efficiency, system dynamics model has been developed which in addition to motivation to implement efficiency measures included electricity price changes, development of household income and assumptions on technology

improvements. The system dynamics approach was chosen as it is a convenient instrument for analysis of dynamics of complex systems with inclusion of positive and negative feedbacks and delays. In addition, a survey was carried out in order to assess how cost and income relation affects energy efficiency motivation in households.

- The results of system dynamics model based on current input data and the proposed dynamics hypothesis forecast that total household consumption by 2020 would reduce from 1887 GWh to 1751 GWh per annum that corresponds to 1.1 % cumulative annual reduction rate. It can be concluded that energy efficiency activities fully offset the consumption increase generated by income growth. The model incorporates household consumption increase that corresponds to 1.6 % cumulative annual growth rate and accounts for 1627 GWh over the modelling period. In addition, a potential to further reduce consumption forecast was identified in case there is a possibility to minimise the diffusion of new energy efficiency technologies. The model based on current input data assessed this effect as 593 GWh further consumption reduction that corresponds to 0.9 % cumulative annual reduction rate.
- In summary, it can be concluded that the rollout of smart meters has significant positive influence on energy efficiency and CO_2 emissions also under local conditions in Latvia where behavioural aspects of electricity end users play a significant role.