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Distributed Electricity Generation and its Possibilities for Meeting the Targets of Energy and Climate Policies

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Declaration:
Hereby I declare that this doctoral thesis, my original investigation and achievement, submitted for the doctoral degree at Tallinn University of Technology has not been submitted for any academic degree.

Reeli Kuhi-Thalfeldt

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ENERGEETIKA. ELEKTROTEHNIKA. MÄENDUS D57

Elektrienergia hajatootmine ja selle võimalused energia- ja kliimapoliitika eesmärkide täitmiseks

REELI KUHI-THALFELDT

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KIRJASTUS

TABLE OF CONTENTS

ABBREVIATIONS AND SYMBOLS

List of abbreviations

CHP	Combined Heat and Power
CO_2	Carbon Dioxide
EEK	Estonian crown
energyPRO	Modeling software for cogeneration projects
EUR	European monetary unit euro
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GWh	Gigawatt hour
LEAP	long-term energy planning model, abbreviation of Long-range Energy Alternatives Planning
MARKAL	long-term energy planning model, abbreviation of MARKet ALlocation
MW	Megawatt
NU	Nuclear Power
OS	Oil Shale
PJ	Petajoule
PV	Solar Photovoltaic
RE	Renewable Energy
SO_2	Sulfur Dioxide
WP	Wind Power

Conversion factors

1 EUR	15,6466 EEK
1 GWh	3600 GJ

Unit prefixes

k	kilo, 10^3
M	Mega, 10^6
G	Giga, 10^9
T	Tera, 10^{12}
P	Peta, 10^{15}

LIST OF ORIGINAL PAPERS

The present doctoral thesis is based on following publications, which are referred to in the text using Roman numbers I-VIII:

[I] **Kuhi-Thalfeldt**, **R**., Valtin, J. The potential and optimal operation of distributed power generation in Estonia. Oil Shale, Vol. 28, No. 1S, 2011, Estonia, pp. 240-252.

[II] **Kuhi-Thalfeldt, R**., Valtin, J. Influence of distributed generation development on national targets and electricity price in Estonia. 8th International Symposium "Topical Problems in the Field of Electrical and Power Engineering", Doctoral School of Energy and Geotechnology II. Pärnu, Estonia, January 11-16, 2010, pp. 75-81.

[III] **Kuhi-Thalfeldt, R**., Valtin, J. Combined heat and power plants balancing wind power. Oil Shale, Vol. 26, No. 3 Special, 2009, Estonia, pp. 294-308.

[IV] **Kuhi-Thalfeldt, R**., Kuhi-Thalfeldt, A., Valtin, J. Estonian electricity production scenarios and their CO_2 and SO_2 emissions until 2030. WSEAS Transactions on Power Systems, Issue 1, Vol. 5, 2010, pp. 11-21.

[V] **Kuhi-Thalfeldt, R**., Valtin, J. CO_2 and SO_2 emissions in Estonia in the period 2000-2030. 7th International Symposium "Topical Problems in the Field of Electrical and Power Engineering", Doctoral School of Energy and Geotechnology. Narva-Jõesuu, Estonia, June 16-19, 2009, pp. 47-56.

[VI] **Kuhi-Thalfeldt**, R., Valtin, J. Possibilities of stabilising fluctuating wind power with cogeneration power plants. 5th International Symposium "Topical problems in the field of electrical and power engineering“. Doctoral school of energy and geotechnology, Kuressaare, Estonia, January 14-19, 2008, pp. 140-144.

[VII] **Kuhi-Thalfeldt, R**., Valtin, J. Economic analysis of a biogas-fuelled cogeneration power plant. 4th International Symposium "Topical problems of education in the field of electrical and power engineering", Doctoral school of energy and geotechnology, Kuressaare, Estonia, January 15-20, 2007, pp. 164-168.

[VIII] **Kuhi-Thalfeldt, R**., Kuhi-Thalfeldt, A., Valtin, J. The effect of Estonian electricity production scenarios on CO_2 and SO_2 emissions in 2000-2030. In: Recent Advances in Electric Power Systems, High Voltages, Electrical Machines: Proceedings of the 9th WSEAS/IASME International Conference on Electric Power Systems, High Voltages, Electric Machines (POWER '09): University of Genova, Italy, October 17-19, 2009, pp. 182-187.

In the Appendix B, copies of publications I-V are included.

Author’s own contribution

The contribution by the author to the papers included in the thesis is as follows:

- [I] Reeli Kuhi-Thalfeldt is the main author of the paper. She is responsible for literature overview and data collection, performed calculations and modeling. She had a major role in writing.
- [II] Reeli Kuhi-Thalfeldt wrote the paper and is the corresponding author. She is responsible for literature overview, data collection, modeling, calculations and analyses. She had a major role in writing. She made the presentation of the paper at 8th International Symposium "Topical Problems in the Field of Electrical and Power Engineering", Pärnu, Estonia.
- [III] Reeli Kuhi-Thalfeldt wrote the paper and is the corresponding author. She is responsible for literature overview, data collection, modeling and analyses. She had a major role in writing.
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INTRODUCTION

The development of Estonian electricity generation is greatly influenced by the climate- and energy policies of European Union. Europe is more and more moving towards a carbon free power generation and increased use of renewable energy. In 2008 the European Union (EU) adopted an energy and climate change policy called Europe 2020, which targets 20% lower greenhouse gas (GHG) emissions compared to 1990, 20% of energy consumption from renewables and 20% increase in energy efficiency [1].

The development of member states is conducted through directives, such as 2009|28|EC on promotion of renewable energy, directive 2004|8|EC on promotion of cogeneration and directive 2010|75|EU on industrial emissions. Having been a member of EU since 2004, Estonia has taken several commitments, of which most relevant regarding this thesis are [4,43]:

- 25% share of renewable energy in final energy consumption in 2020,
- 15% share of renewable energy in electricity gross consumption[1] in 2015,
- 20% share of cogeneration in gross electricity consumption in 2020,
- 7,85 million tons of CO_2 emissions from the energy sector in 2020, of which 5 million tons from electricity generation.

The installed capacity of power plants in Estonia is currently about 2 500 MW, of which 1 600 MW are oil shale production units which are over 50 years old and which does not comply with sulfur emission standards. In 2010 about 13 000 GWh of electricity was generated, of which 89% from oil shale, 2% from natural gas, 1% from peat and 8% from renewable energy [2]. Electricity generation from renewable energy is increasing and it is mainly produced from wood and wind power. Renewable energy formed 10,8% and cogeneration 13,7% of gross electricity consumption. Estonia is a country that exports electricity more than it imports, 34% of the produced electricity was exported in 2010.

The GHG emissions in Estonia have decreased about 50% from 40,8 million tons of CO_2 equivalent in 1990 to 20,5 in 2010. CO_2 contributes currently 89% of the total GHG emissions. Electricity and heat production account for 77% of total GHG emissions in 2010, of which majority comes from power plants [3]. But the CO_2 emissions are currently almost at the same level as in the year 1993. Most of the emission reduction took place in the years 1991 and 1992 due to regaining independence from the Soviet Union in 1991 and transition from planned economy to market economy. Therefore additional efforts in the electricity generation are required for further emission reduction.

During the next ten years a significant share of production capacities will be replaced. The current Development Plan of the Estonian Electricity Sector until 2018 includes basically three options for electricity generation: oil shale, nuclear power and wind power with gas turbines [4]. The scenarios with other renewable

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[1] Gross electricity consumption is domestic electricity production, plus imports, minus exports.

energy sources or distributed generation are not included, since these areas have not yet been adequately studied in Estonia. This thesis contributes to the development of this particular area.

Energy system planning models are very useful for evaluating weather it is possible to reach the goals of development plans and limitations of directives. Energy system planning model MARKAL has been previously used by Liik *et al*, Agabus and Landsberg for prognosis of CO_2 emissions in Estonia [5-7]. For the studies related to this thesis LEAP (Long range Energy Alternatives Planning System) model is used and in addition to CO_2 also SO_2 emissions are predicted. Dementjeva has investigated different energy planning models and used LEAP for CO_2 emission forecast [8].

When planning new generation capacities, the investment decision should be made taken into account the impact of future EU policies, as the lifetime of investments is long. In the end of 2011 European Commission published a long term energy strategy Energy Roadmap 2050, which aims reduction of GHG emissions to 80-95% below 1990 level by 2050 [9]. The CO_2 emissions from electricity production are expected to reduce by 99% due to increased use of renewable energy, nuclear power and carbon capture and storage. For Estonia this target means, that the GHG emissions should be decreased to 2,0-8,2 million tons. Among several other targets, Energy Roadmap 2050 suggests use of energy storage and smart grid solutions for distributed generation. Even though the primary energy consumption is aimed to decrease, electricity will have an even higher importance in the future due to partially replacing fossil fuels in transport and heating through electrification of these sectors.

Several countries of EU have announced very ambitious energy sector development plans. German government has decided to phase out nuclear power by 2022, to reduce greenhouse gases from the 1990 level by 80% by 2050 and increase the share of renewable energy in the gross electricity consumption to 80% [10]. Denmark's energy policy has set an aim that 50% of electricity in 2020 is generated from wind power and by 2035 all electricity and heating will be generated using renewable sources. By 2050 all energy supply – electricity, heat, industry and transport – will be covered by renewable energy [11]. United Kingdom has adopted a plan to reduce GHG emissions by at least 80% below 1990 level by 2050 [12], which foresee major changes in electricity generation including small and micro production.

Wind energy will have a high importance on the move towards to a low CO_2 development, but also distributed generation units like small hydro and wind, solar photovoltaic panels and CHP plants using biomass and biogas can be used to replace fossil fuels.

There is an international trend towards an increase of distributed generation. The term of distributed generation, also called as dispersed generation, embedded generation or decentralized generation means producing electricity close to the consumer. In the central energy system the electricity generation takes place in large thermal power plants and electricity is transported to the consumers through power lines. The electricity distribution and especially the generation (if cogeneration is not used) is related to high energy losses, which can be reduced using cogeneration of heat and power (CHP) and producing electricity close to the consumer. In addition to CHP plants distributed generation includes small-scale wind, solar and hydro power. Also storages are sometimes considered as distributed generation. Through use of production with high efficiency and use of renewable energy remarkable energy savings and emission reductions can be achieved.

According to World Survey of Decentralized Energy in 2005, the world's average share of distributed generation in power generation was 10% and by 2025 it could reach 20%. Countries with a highest distributed generation share are Denmark (52%), Finland and Netherlands (48%) [13]. These are countries with considerable cogeneration. As the EU aims at further increased use of cogeneration and renewable energy, the share of distributed generation in Europe will grow also in the future. It is estimated that by 2020 the installed capacity of small-scale renewable electricity generation in Europe could increase over three times and reach 105 GW, of which about half would form photovoltaic, but also biogas and small biomass CHP-s will have a growing importance [14].

Distributed generation is defined differently depending on the specifics of a country. It is not yet adequately studied in Estonia and there is no general understanding what is called distributed generation and what is not. Is it only electricity production for a household, producers connected to the distribution network or producers with an electrical output below 5 MW? In the master thesis, Kivipõld has estimated the potential of distributed generation in Estonia, which largely consists of wind power [15]. The potential distributed electricity generation of the study is assessed by multiplying the primary energy of available resources with the efficiency of power generation. But as the distributed generation should use locally available fuels, the assessment should include evaluation of available resources in smaller areas, not for the whole Estonia. There is already research done for biomass and biogas resources per county in Estonia [16,17].

High penetration of renewable energy in the electricity generation includes usually high shares of wind and solar power, of which generation is fluctuating depending on weather conditions. In the conventional electricity system the power plants are operated according to the electricity demand. But generation of wind turbines and solar panels cannot be operated according to electricity demand and therefore the electricity system needs some balancing capacities. Palu has analyzed the balancing impact of thermal power plants in Estonia [18]. In this thesis the balancing ability of gas engine and availability of heat storage is investigated.

The purpose of the thesis

The main purpose of this thesis is to analyze the potential of distributed electricity generation and its possibilities for meeting the targets of energy and climate policies. This thesis presents extended knowledge and new solutions in addition to the above-mentioned research work. The purpose of the work performed during the doctoral studies was:

1. to make a proposal for definition of distributed generation in Estonia and to investigate its current state,
2. to assess the potential of distributed generation in Estonia taking into account the potential for cogeneration and location of consumers and resources.
3. to analyze the ability of gas engine CHP plant for balancing the fluctuating wind power production.
4. to estimate the need for balancing measures in an electricity system containing only CHP plants, wind and solar power.
5. to compare the possibilities of different electricity generation scenarios for meeting the targets of national development plans.
6. to make a proposal for additional electricity generation scenarios in the development plan of electricity sector.

This doctoral thesis is based on eight already published research articles written by the author of this thesis. The study was carried out during the years 2005-2012 in Estonia while the author took part in the research projects Optimization of the structure of distributed electricity production, Dissemination strategy on electricity balancing for large scale of renewable energy and Assessing the impact of electricity and heat production scenarios for the National Development Plan of the Energy Sector until 2020.

Outline of the thesis

The current thesis includes a summary chapter and appended five published articles. In the summary chapter the related author's publications, methods and results are described. Thesis also includes additional analyses, which have not been previously published.

In Chapter 1 *Material and Methods* the background information, calculation methods, assumptions and description of software is given. The different possibilities of defining the distributed generation, its advantages and disadvantages are shortly described. The principles and data sources for estimating the distributed generation capacity in Estonia are presented. The overview of support schemes in Estonia for promotion of renewable energy and cogeneration is given. The potential of renewable energy resources and cogeneration and limitations on their usage is provided. Formulas for simple distributed generation potential calculation are introduced. Assumptions for calculating the distributed generation based on location of resources and consumption are also described. The overview of electricity and heat generation simulation software energyPRO and its modeling assumptions is given. Finally energy-environment modeling tool LEAP and the principles of Estonian energy sector model are presented.

In Chapter 2 *Results* the outcomes from calculations and simulation models are introduced. The definition of distributed generation in Estonia is formed. It is assessed how much distributed generation there is currently in Estonia and the potential for future developments is analyzed. The potential is examined also based on several resource use and plant operation restrictions. A graphical overview of location of renewable energy resources and electricity demand is presented. The renewable energy based production capacities are calculated, if all required electricity in Estonia would be produced in CHP plants, wind turbines, hydro power plants and solar panels. The same capacities are inserted into the energyPRO model to see, which will be the electricity and heat generation, fuel consumption and need for balancing capacities if the plants are operated according to hourly electricity and heat demand. The need for balancing measures is also thereby assessed. The possibilities of balancing wind power generation with gas engine CHP plant are also summarized. The predicted CO_2 and SO_2 emissions, electricity and heat generation, primary energy consumption of Estonia are given in case of several electricity generation and consumption scenarios in LEAP.

In Chapter 3 *Discussion* the issues arising from the study are analyzed and the critical assessment of results is made.

Data used for the analysis includes statistical data from the database of Statistics Estonia, national development plans, articles published in scientific journals, results from research works, annual reports from national transmission network operator Elering, legal acts of Estonia, master and doctoral thesis, etc. The study was carried out performing calculations in Excel and using modeling and simulation software energyPRO and LEAP.

Network connection and power quality issues of distributed generation are not included in this thesis. Economical aspects have also been outside the framework of the current research, though the impact of distributed generation development on electricity price is evaluated in one of the author’s articles.

Contribution of the thesis

This thesis includes theoretical approaches, methodological and practical recommendations considering the future development of distributed generation. The originality of thesis consists of theoretical and practical results.

Theoretical originality includes methodological recommendations for planning the development of distributed generation. The results expand the existing knowledge on the definition of distributed generation and on the estimation of its potential. The optimal operation objectives show different ways of distributed generation development aims. Theoretical methodology also includes developed approach for balancing the wind power with CHP plant and for considering the distributed generation development impact on national targets.

Practical originality of the thesis includes results from the need for balancing and the impact on the environment. The results of the thesis can be used for preparing new support schemes for promotion of renewable energy and cogeneration. The practical originality includes a comprehensive model in LEAP for Estonian energy system, which can be used to provide reliable estimates of various scenarios. The model can be used for preparing the analyses for development plans, simulation of several future scenarios, emission and energy usage prognoses, etc

The current relevance of the thesis is related to fast development of distributed generation in Estonia as well as in the whole world supported by the European climate policy. The developed methodologies help to solve problems in energy planning. The results will be useful for energy planners, ministry officials and researchers. Currently a new long-term energy sector development plan is under a preparation and also the subsidies for electricity generation are being amended. Due to closing down of old oil shale power plants there is a need for decisions which fuels and production types will be replacing this generation. At the same time the uncertainty regarding the profitability of new investments is depending on environmental targets. One possibility of reducing the risks is through development of distributed generation, which has a low environmental impact.

Acknowledgments

During the seven years of work that has resulted in thesis, many people have contributed in one way or another.

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Finding time for performing the research and writing the articles and this thesis has been a great challenge besides having small children. I would like to thank my family and parents for support and understanding during all this time. Thank you, mother for taking care of my children. Special thank goes to my husband Aron for supporting me during critical moments. I hope that this will encourage you to pursue your PhD thesis.

Finally, the Estonian science Foundation and Development Foundation of Tallinn University of Technology are gratefully acknowledged for their financial support of this work.

1. MATERIAL AND METHODS

1.1 Definition and potential of distributed generation

In the articles [I] and [II] the definition, potential and optimal operation of distributed generation in Estonia is analyzed. The influence of distributed generation development on electricity price and on national targets is also assessed in these articles.

Distributed generation can be classified based on the voltage level of network connection, their unit size, technology or fuel used. Some countries define it as production units connected to the distribution network, others have limits for the production capacity or include only renewable energy based production [II]. It also depends on which issues of distributed generation are observed. For example, if the electricity network problems are studied, then the focus is on producers connected to the distribution grid.

But the main purpose of distributed generation is to produce electricity close to the consumer. The production units can be connected to the transmission grid, distribution grid or on the customers' side of the meter [19]. They can produce electricity for a town, village, industrial site, commercial building or one household. The size of distributed generation units can be very different, which could be in some cases even up to 300 MW. The producers are classified by the production capacities as micro (< 5 kW), small (5 kW–5 MW), medium (5 MW–50 MW) and large (50 MW–300 MW) producers [20].

Distributed generation comprises all kind of production technologies and the assortment depends rather on availability of technology in required size. Possible technologies are gas and steam turbines, internal combustion engines, micro turbines, biomass gasification technologies, wind turbines, small hydro power, photovoltaic panels, fuel cells and storage units [20]. The choice of fuel depends on what is locally available, like biomass, biogas, peat, household waste, natural gas, wind, water, solar etc.

The advantages of distributed generation are emission reductions and energy savings through the use of production units with high efficiency and renewable fuels. Use of locally available fuels, like biogas, landfill gas and biomass, improves independence from imported fuels. Also the network losses are reduced, power quality and supply reliability is improved. In addition distributed generation could help with peak load shaving and avoid investments into new transmission and distribution capacity. The construction time of small production units is short and a wide range of technologies allows selecting the suitable unit for a specific purpose [21].

Disadvantages are related with grid connection of distributed generation units. The production units are not always located where the distribution network would mostly need them. Distribution network is designed usually for only one-directional power flow, therefore connection of distributed generation can cause power quality problems and may require rebuilding of the grid protection system [20].

1.1.1 Data about distributed generation in Estonia

In Estonia there are no special reports on distributed generation capacity and its generation. Therefore the data must be collected from annual reports and statistical databases. Unfortunately the data available in statistical databases is not detailed enough for this purpose. But each year the transmission network operator Elering publishes reports on sufficiency of production units [22], security of supply [23] and annual review of power system [24], which provides additional information. The reports give a detailed overview of electricity generation, available and planned production capacities.

As most of the distributed generators are receiving subsidies, the table of paid subsidies per month for each producer [25] is very useful source of data. But not all subsidies are paid to distributed generation producers. When examining the subsidies paid to producers, it is seen that in 2011 subsidized generation was 1 213 GWh, but 308 GWh formed generation from thermal power plant [25], which is co-firing of oil shale with wood chips. This plant operates with not efficient cogeneration or even in condensing regime, therefore this generation is not distributed generation.

The existing production units can be divided to distributed and central producers according to following principles:

- Hydro power plants are distributed generation, as their unit size is very small, from few kilowatts to 1,1 MW.
- Wind power plants on shore are distributed generation.
- Offshore wind power plants are central generation.
- Solar photovoltaic panels are distributed generation.
- Micro-, small- and medium-scale CHP plants are distributed generation as they are operated at the high efficiency cogeneration[2] regime [26]. These plants use renewable (biogas, wood) and fossil (natural gas, peat) fuels.
- Thermal power plants, which operate at the condensing or low efficiency cogeneration regime, are central producers irrespective what fuels are used.

1.1.2 Support for the development of distributed generation

The Electricity Market Act regulates the generation, transmission, distribution and sale of electricity. The development of renewable energy and cogeneration is promoted using the feed-in-tariff, which producers will receive in addition to price of selling electricity to the market. Producer receives a subsidy of 53,7 €/MWh if electricity is produced from renewable energy or from biomass using cogeneration. A subsidy of 32 €/MWh is paid for production from high-efficient cogeneration using waste, peat or oil shale gas or with a high-efficient cogeneration with a production units with capacity up to 10 MW. For wind power there is an annual limit of 600 GWh, after which subsidy is not paid [27].

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[2] High efficiency cogeneration – heat and power cogeneration providing at least 10% primary energy savings compared to separate production

In the beginning of year 2012 the Ministry of Economic Affairs and Communications has proposed a new support scheme, by which the subsidies would be depending on electricity market price.

In addition to subsidies, some small- and micro-producers have received investment support. Estonian Environmental Investment Centre has supported the investments into CHP plants and wind parks, which were financed from CO_2 quota sales. The investment support is 37,8 million € and as a result 11,8 MW small scale CHP-s and 24,9 MW wind power are built. Estimated annual electricity generation of these plants is 136,2 GWh, of which 76 GWh from CHP plants and 60 GWh from wind power [28].

Estonian Ministry of Economic Affairs and Communications has a similar investment support program for households to buy a small wind turbine or solar panels with a maximum capacity of 11 kW. The total support is 1 million €, which could raise the distributed generation capacity by 0,5-0,6 MW [29]. But this is only the first, introductive support plan before wider support schemes for micro-generation.

1.1.3 Potential of renewable energy resources and cogeneration

Previous research on the potential of renewable sources and cogeneration has shown that:

- Wood resources based on annual renewal of forests in Estonia is estimated to be 21 600 GWh (77 PJ) [17] of primary energy, but when excluding the merchantable wood (for woodworking industry, furniture industry etc), only 30% of the resource remains for electricity generation. Based on the Estonian Forestry Development Plan until 2020 the energy sector could use up to 8 300 GWh (30 PJ) of wood annually [30] and electricity production could be about 2 600 GWh.
- Straw and reed resources could be an alternative for wood. Its potential is 3 451 GWh (12 PJ), which allow producing 1 035 GWh of electricity[16].
- Biogas resources produced from animal and biological waste, landfills, wastewater treatment plants and from herbaceous biomass are 2471 GWh (8,9 PJ) and their electricity generation could be 1 024 GWh [16].
- Wind and solar potential exceeds the national electricity demand many times, but their production is depending on favorable weather conditions, which can occur also in a moment of low electricity consumption. Their usage is also related to electricity grid limitations. Estonian electricity grid currently allows connecting only 575 MW of wind turbines, if Estlink 2 starts operating in 2014 the limit is 850-1 100 MW and the potential electricity generation could be up to 3 000 GWh. But with wind power curtailment[3] the limit is 3 200-3 400 MW [31]. Current connection proposals have given for total over 3 000 MW wind power plants [22], with the potential generation of 7 500 GWh.

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[3] Reduction of wind power production for maintaining the electricity system stability.

- Technical potential of solar power is estimated to be 150-600 GWh of electricity [32], but there are no investigations made which are the grid limitations if there is already wind power connected to the network.
- Hydro power potential is 300 MW and their generation 2 000 GWh, but technically available potential is only 30 MW and 200 GWh [33].
- Cogeneration potential in Estonia is estimated to be 397 MW and electricity generation of these plants could be 2 095 GWh [26]. This evaluation is based on assumption that 45% of the heat demand is covered with CHP plants and heat to power ratio is 3. In Denmark, which has the highest share of cogeneration in Europe, over 80% of heat and 60% electricity has been produced in CHP plants [34].

1.1.4 Calculation of distributed generation potential

The assessment of distributed generation potential in Estonia made so far has been looking only at the available resources and possible electricity generation efficiencies. The potential of generation is calculated by multiplying the available renewable energy resources with the efficiency of power generation.

$$W_E = \sum_{i=1}^{n} W_{E,i} = \sum_{i=1}^{n} R_{E,i} \cdot \eta_{E,i} = R_{E,1} \cdot \eta_{E,1} + R_{E,2} \cdot \eta_{E,2} + \ldots + R_{E,n} \cdot \eta_{E,n}, \quad (1)$$

where W_E – Potential distributed electricity generation

$W_{E,i}$ – Electricity generation by fuel, i=1,….,n

$R_{E,i}$ – Primary energy resource by fuel

$\eta_{E,i}$ – Electrical efficiency of power unit

There are several resources available for distributed generation – fossil and renewable; solid, gaseous and liquid, etc. The electrical efficiency depends on the technology, which in turn uses certain type of fuel. One resource can be used in different electricity generation technologies.

Heat generation from CHP plants can be calculated with a formula:

$$W_H = \sum_{i=1}^{n} W_{E,i} \cdot C_i = W_{E,1} \cdot C_1 + W_{E,2} \cdot C_2 + \ldots + W_{E,n} \cdot C_n, \quad (2)$$

where W_H – heat generation of CHP plants, i=1,….,n

C_i – heat to power ratio[4]

Based on electricity generation quantities the production capacities are calculated according to following formula:

$$P_E = \sum_{i=1}^{n} P_{E,i} = \sum_{i=1}^{n} \frac{W_{E,i}}{T_{\max,i}} = \frac{W_{E,1}}{T_{\max,1}} + \frac{W_{E,2}}{T_{\max,2}} + \ldots + \frac{W_{E,n}}{T_{\max,n}}, \quad (3)$$

where P_E – Potential distributed electricity generation capacity

$P_{E,i}$ – Electricity generation capacity by fuel, i=1,….,l

$T_{max,j}$ – Annual full load operating hours[5] of a particular generation capacity

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[4] Heat to power ratio shows how much heat is generated per one unit of electricity.

Annual full load operating hours constraint:

$0 \leq T_{max} \leq 8760$ (4)

For wind turbines, solar panels, hydro power plants the annual operating hours depend on availability of the resource. For combustion power plants the load factor is linked to type of generation (e.g. peak, base load or medium load covering). The operation of CHP plant is dependent on heat demand. In the electricity market conditions working hours are also dependent on the production price. If the production price is higher than the market price in certain hours, then the production unit cannot operate and therefore the annual full load working hours will be lower.

1.1.5 Assumptions for distributed generation calculation based on renewable energy sources.

Estonia's territory is divided into 15 counties. The calculation based on Formulas 1 and 2 was made for each county to see how much the result will differ compared to calculation made for the whole country. This issue was also derived from the principles of energy efficiency. Minimization of energy losses and emissions should be aimed throughout the entire supply chain, from resource extraction until the consumption. Therefore it is important that distributed generation units use locally available fuel. If it is necessary to transport fuels over long distances, then additional fossil fuel (for example diesel) usage of transporting vehicles and thereby emitted emissions will reduce the positive effect of distributed generation. Also the fuel costs are thereby increased, which by ever-rising oil prices could form a substantial part of operational expenditures. For example, it was concluded in a master thesis that it is economically not feasible to transport reed and straw further than 50 km [35].

The assessment of potential renewable energy based distributed generation is based on following assumptions:

1. Electricity demand including grid losses is 8 500 GWh.
2. Heat demand including network losses is 10 000 GWh.
3. Maximum share of CHP in heat production is 80%.
4. The available renewable energy resources for CHP plants are biogas (8,9 PJ), straw (12,4 PJ) and wood (30 PJ). 30% of wood is gasified and used in gas engines and the rest is used in steam turbine CHP plants.
5. Technical parameters of CHP plants are presented in the Table 1.
6. Potential electricity generation of hydro power plants is 200 GWh, from solar power 900 GWh and wind power 6 500 GWh [15].
7. Wood, biogas and straw resources are divided between the counties based on performed studies [16,17]. Hydro resources are summed for each county based on the location of the potential hydro power plants [33]. Solar resources are divided per capita based on population distribution between

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[5] Full load operating hours are calculated when the annual generation is divided with rated power output.

the counties. Wind resources inland are divided according to wind atlas [36] and availability of land in coastal areas [37].

8. Electricity and heat consumption are divided between 15 counties according to following assumptions: consumption in households per capita and in other sectors per GDP based on population and GDP distribution between the counties [2]. The calculated electricity and heat consumptions per county are presented in Appendix A, Tables 7 and 8.

Table 1. *Technical assumptions for CHP plants*

Fuel	Electrical efficiency (%)	Thermal efficiency (%)	Working hours (h)	Heat to power ratio
Wood Steam	30	60	6 500	2,2
Wood Gas	35	43	6 500	1,2
Straw	23	67	6 500	2,9
Biogas	40	50	8 000	1,2

In the investigation process four resource usage and generation restriction strategies were studied:

- Alternative 1, where electricity generation is based on locally available renewable fuels in a county and the operation of plants is not limited and all resources are used up.
- Alternative 2, where electricity generation is based on locally available renewable fuels in a county and the operation of CHP plants is restricted to 80% of heat demand. The CHP production units are prioritized in the order that at first the heat demand is covered with biogas produced from animal, biological waste, wastewater and landfills, then with wood, thereafter biogas produced from herbaceous biomass and as a last with straw. The remaining local electricity demand is at first covered with local hydro power. Thereafter in the areas with remarkable wind resources wind power is prioritized and as last solar power is used. In inland solar power is prioritized before wind power. The electricity generation in a county cannot exceed the local demand.
- Alternative 3, where electricity generation is based on locally available fuels and operation of CHP plants is restricted to 80% heat demand, but wood is transported to counties with high electricity demand. In this scenario heat demand is covered at first with biogas, then with straw and thereafter with wood. The remaining electricity demand is fulfilled using the same priorities as in the Alternative 2.
- Alternative 4, where electricity generation is not restricted to local electricity demand, but to total demand in the whole country. Compared to Alternative 3 the CHP generation priorities are the same, but coastal wind power plants are allowed to produce more than it is locally needed.

1.2 Simulation of electricity and heat generation in energyPRO

In this doctoral thesis energyPRO software was used to simulate the operation of CHP plants, wind and solar power. It was also used for analyzing the capability of CHP plant to balance the fluctuating wind power and the essence of heat storage, which results are presented in articles [III] and [VI]. In the article [VII] the same software was used for modeling the operation and performing the profitability analysis of CHP plants using biogas collected from the landfill. Also the impact of availability of biogas and heat storages on the flexibility of CHP plant operation was investigated.

energyPRO is a software for design, optimization and analysis of energy projects developed by Danish company Energi- and Miljødata. The user is able to input a wide range of data on different energy plant types, external conditions such as demands, operating strategies, tariff structures, revenues and operating costs, investments and finance arrangements. CHP plants, boilers, biogas plants, geothermal plants, solar collectors, solar photovoltaic and wind farms can be analyzed using this software. It includes also different types of storages – for thermal energy, biogas, compressed storages, batteries, electric vehicles. Based on the inputs energyPRO optimizes the operation of the plant against technical and financial parameters and provides graphical overviews about hourly generation and demand curve for the whole year. Software also provides operating results, report for the emissions and detailed financial reports [38].

energyPRO is an input/output model for calculating annual production in steps of one hour. In this thesis inputs are capacities, efficiencies, fuel data, hourly outdoor temperatures, wind speed and solar radiation data. It is necessary for the optimization to define hourly demands for electricity and heat. For this purpose the total consumption, its dependency on outdoor temperatures, hourly variation of demand during a day and period of heating is needed to define.

The optimization in energyPRO is based on calculation periods and it is dependent on operational strategy. Based on inserted data, the model constructs for the whole planning period an hourly time series for electricity demand and similar curve for heat. The production units are given priorities, and additionally it is defined whether the partial load, production to storages and restrictions related to electricity and heat demand are allowed or not.

1.2.1 Simulation of electricity and heat generation in an electricity system containing only CHP plants, wind and solar power.

For the simulation of electricity and heat generation in Estonian energy system containing CHP plants, wind and solar power, the following assumptions are used:

- Production capacities are the same as shown in Table 4. In addition heat boilers are available.
- Technical data of CHP plants is the same as in Table 1. In addition it is assumed, that the minimum load of CHP plants is 30% of their rated output and then their efficiency is reduced by 10%.

- Electricity demand including grid losses is 8 500 GWh, hourly electricity demand and wind power production for the year 2011 is used [39]. Wind power hourly values are converted in energyPRO so that the maximum output is 1 667 MW.
- Heat demand including network losses is 10 000 GWh, which is dependent on hourly outdoor temperatures for the year 2011 [40]. Heating period is from 1st September to 31st May. Daily profile demand from 06:00-20:59 ratio is 10, from 21:00-05:59 ratio 8.
- Production priorities for heat generation are: CHP biogas 1, CHP wood 2, CHP wood gas 3, CHP straw 4, Boilers 5. For electricity generation wind power and solar power is prioritized before CHP plants.
- There are no balancing measures or storages applied. Generation of CHP plants is depending on heat demand and they are not allowed to produce more heat than needed. The generation from wind and solar power is not limited; the balance between demand and production is achieved through electricity export and import.

1.3 Energy system modeling in LEAP

LEAP software was used for the whole Estonian energy system modeling and for prediction of emissions and primary energy consumption. The articles [IV, V, VIII] present the assumptions for the study which was performed in relation to strategic environmental assessment of the Estonian Development Plan of Energy Sector until 2020. In the article [IV] the Estonian electricity production scenarios and CO_2 and SO_2 emissions from electricity generation were analyzed. The emissions from the whole Estonian energy system are assessed in the article [VIII]. The study also included the influence of heat production scenarios, but as their share in the total emissions is low [41], these are not separately analyzed. In the article [I, II] LEAP was used to compare the emissions of central and distributed energy scenarios and their capability to meet the national targets were evaluated.

LEAP is a software tool for energy policy analysis and climate change mitigation assessment developed at the Stockholm Environment Institute. The software is used in over 190 countries worldwide. It is a scenario-based energy-environment modeling tool, which can be used to create models of different energy systems where each requires its own unique data structures. LEAP supports a wide range of different modeling methodologies: on the demand side these range from bottom-up, end-use accounting techniques to top-down macroeconomic modeling. LEAP also includes a range of specialized methodologies including least cost optimization and stock-turnover modeling. On the supply side, LEAP provides a range of accounting and simulation methodologies for modeling electricity generation and capacity expansion planning [42].

LEAP allows simulating the whole energy system – final energy consumption by sectors, primary energy resources, resource production, electricity and heat generation by different technologies; it calculates the energy balance and emissions. Electricity generation is modeled using the data about the production capacities, efficiencies, cogeneration capacities and maximum availability. The prognoses of future development are also important inputs, which include building of new and closing down of power units, changes in the efficiencies, availability etc.

Compared to energyPRO, LEAP does not include simulation on hourly basis. The electricity generation operation is based on user-defined system load curve and dispatch rules. Model takes into account the electricity demand, network losses, own consumption of power plants, electricity import and export and calculates the annual electricity production by production unit taking into account the dispatch rules (base, medium and peak load covering).

1.3.1 Electricity generation scenarios in LEAP

In addition to simulations, which results are presented in articles, additional LEAP model was created. This model includes statistical data until the year 2010 and nine electricity generation and consumption scenarios. The updated LEAP model includes following assumptions:

1. The planning period is from 2000-2040, where 2000-2010 is based on historical data and from 2011 the data is either predicted by LEAP based on historical numbers or is user-defined as changes in the production capacities, building of new plants, changes in the oil shale mining and shale oil production (produced from oil shale) etc.
2. The final energy consumption in different sectors will grow according to gross domestic product (GDP) prognosis taking into account the elasticity coefficient, which is calculated based on historical data. The long term GDP prognosis is +3,5%/year.
3. The electricity consumption growth and export quantities are based on three scenarios: low (-L), medium (-M) and high (-H), which are described below.
4. Three electricity generation strategic choices were included: oil shale (OS), nuclear (NU) and renewable (RE). All scenarios were constructed taken into account currently available production capacities, their closing down and the new plants under construction as stated in the report [23]. Overview of production capacities common for all scenarios, is presented in Figure 1. From the year 2025 the production capacity of existing power plants is 1 500 MW, of which 950 MW is available on peak load hours (wind power and gas turbines are excluded).
5. The evaluation is given on total emissions, which means also emissions from other sectors besides electricity production. The variable part of emissions of different scenarios will be from electricity and heat production, emissions from other sectors will remain the same.
6. The emission coefficients are taken from LEAP's database.
7. Electricity import is assumed to be at the same level. Three scenarios in combination with demand growth are used for electricity export.
8. District heating consumption will decrease 0,1% per year.

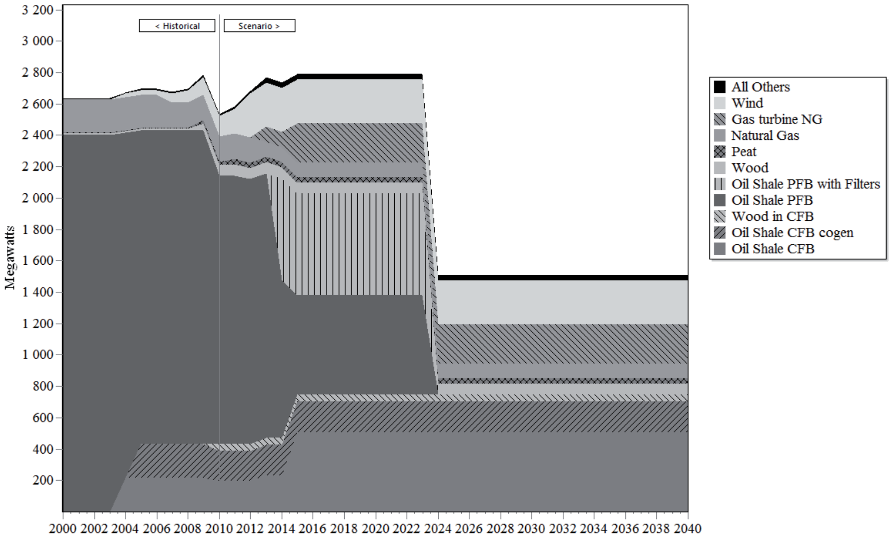

Figure 1. *Available electricity production capacities common for all scenarios*

Electricity demand during the last 10 years has been increasing in average 3,2% per year. Annual growth of 2,5% until 2020 and 1,3% until 2040 [23] was considered as the moderate consumption growth prognosis.

Due to increasing energy efficiency of electric appliances, replacing of incandescent lamps and energy efficiency improvements in the industry, the electricity consumption could also grow slower. Therefore consumption growth of +1,5% until 2020 and thereafter +0,8% was assumed in low growth scenario.

On the other hand the plans of wider use of electric vehicles and heat pumps, like several European countries are planning to do for balancing the wind power generation, will increase the electricity demand. In 2010 private persons consumed 10,4 PJ (238 thousand tons) of vehicle fuel [2]. It was calculated that if electric vehicles would be used instead, these cars would consume 600 GWh of electricity. In 2010 households consumed 20,5 PJ of fuels for heating purposes. The use of heat pumps instead could increase the electricity consumption by 1 400 GWh. In total, the use of electric vehicles and heat pumps could increase the electricity consumption by 2 000 GWh. If this transition takes place during a 10-year period, this would mean an annual consumption growth of +2,7%. When adding also the fuel consumption in commercial and public sector and also partly the transport and industrial sector, the electricity consumption could increase even up to 3 500 GWh. For the rapid electricity consumption growth it was assumed +3,5% until 2020 and +1,8% until 2040.

Electricity export has had a significant influence on energy balance and emissions during the last years. Therefore the three above-mentioned electricity consumption growth scenarios were combined with export scenarios – low consumption growth includes an annual export of 1 500 GWh, medium 3 000 GWh and high 5 000 GWh.

2. RESULTS

2.1 Definition and potential of distributed generation in Estonia

There are different objectives how the distributed generation plants could be operated. In the electricity market conditions the producers are maximizing their profit. In the perspective of electricity network operators the aim could be to maximize the supply reliability and energy security. In the national perspective environmental emission reduction could be relevant. More detailed description of the objectives is given in article [I].

In this thesis the basis for forming the definition is that distributed generation should meet the targets of energy saving, increased use of renewables and reduction of GHG emissions. Distributed generation in Estonia is defined as production units generating electricity close to the point of consumption. The connection point of producer is not relevant as long as the size is suitable to cover the local demand. In case of fuel combustion technologies, the production should take place at high efficiency cogeneration regime. Preferably the renewable energy sources should be used.

In Estonia distributed generation currently comprises production units with a capacity up to 25 MW of electricity. This includes all high efficiency CHP plants, wind turbines, hydro power plants and solar photovoltaic panels. Overview of estimated number of production units, electrical capacities and their electricity generation in 2011 is presented in Table 2. The capacity of distributed generation has grown from 108 MW [II] in 2008 to 279 MW in 2011 and their production forms currently about 12% of the gross electricity consumption.

Table 2. *Distributed generation in Estonia in 2011*

	Number of units	Electrical capacity (MW)	Electricity generation (GWh)
Biogas	3	4	16
Hydro	~40	5	31
Natural Gas	8	20	77
Peat	3	66	71
Wood			439
Wind	85	184	365
Total	**~140**	**279**	**998**

Distributed electricity is generated mainly from wood and wind power, but includes also fossil fuels like natural gas and peat. About 200 GWh of the electricity generation comes from producers connected to the distribution network [23]. In addition in 2010 power producers with a total capacity of 33 MW produced 107 GWh of electricity and 567 GWh of heat for self consumption and this was generated from natural gas, wood, shale oil gas, oil shale and wind [2]. The statistical data does not include off-grid micro-producers like small wind turbines and photovoltaic panels. Their total capacity is less than 200 kW and they are producing electricity for households, lighthouses and weather stations. Also some industrial companies have installed distributed generation, for example ABB Estonia has a 25 kW of PV panels [44]. Therefore, the share of distributed generation is actually even little higher when taking into account the electricity produced for self consumption and in off-grid solutions.

2.1.1 Potential of distributed generation in Estonia

It is estimated that by the year 2020 distributed generation in Estonia could reach 900 MW of electricity and 1 100 MW of heat and it could cover 40% of electricity and 65% of heat gross consumption. This capacity includes 400 MW of wind power, 490 MW CHP plants on wood, peat, natural gas, biogas and household waste and 10 MW hydro power. Most of these producers would receive subsidies for their electricity generation, which are paid by the end-consumer as renewable energy fee. In the year 2012 it is 9,7 €/MWh and due to distributed generation development the fee is raised to 20 €/MWh [I].

The distributed generation potential based on location of consumers and resources is presented in Table 3. The evaluation was made based on renewable energy resources and electricity and heat demand per county. Assumptions for these calculations were described in chapter 1.1.5. More detailed information regarding electricity generation can also be found in Appendix A, Tables 9-12.

Table 3. *Electricity generation of renewable energy based scenarios in GWh*

Fuel	Alternative 1	Alternative 2	Alternative 3	Alternative 4
Biogas	988	699	988	988
Hydro	200	200	200	200
Solar	900	551	578	500
Straw	1 035	221	635	697
Wind	6 500	1 776	1 669	3 500
Wood	2 599	1 458	2 497	2 615
Total	**12 222**	**4 904**	**6 567**	**8 500**

Alternative 1 shows that in case the operation of distributed plants is not limited and all potential resources are used up, the total electricity generation is 12 222 GWh. This is higher than the gross electricity consumption (8 500 GWh). The graphical overview of potential electricity generation and consumption per county is visualized in Figure 2. In case the operation of plants is restricted to local electricity and heat demand and only local fuels are used (Alternative 2), the electricity generation is only 58% of the gross consumption. This is due to lack of local resources, the reasons of which are analyzed below. If wood resources can be used in other counties (Alternative 3), the share in gross electricity consumption increases to 77%. If wind power plants are allowed to produce more than locally needed (Alternative 4), it is possible to cover the whole electricity demand with renewable energy based generation.

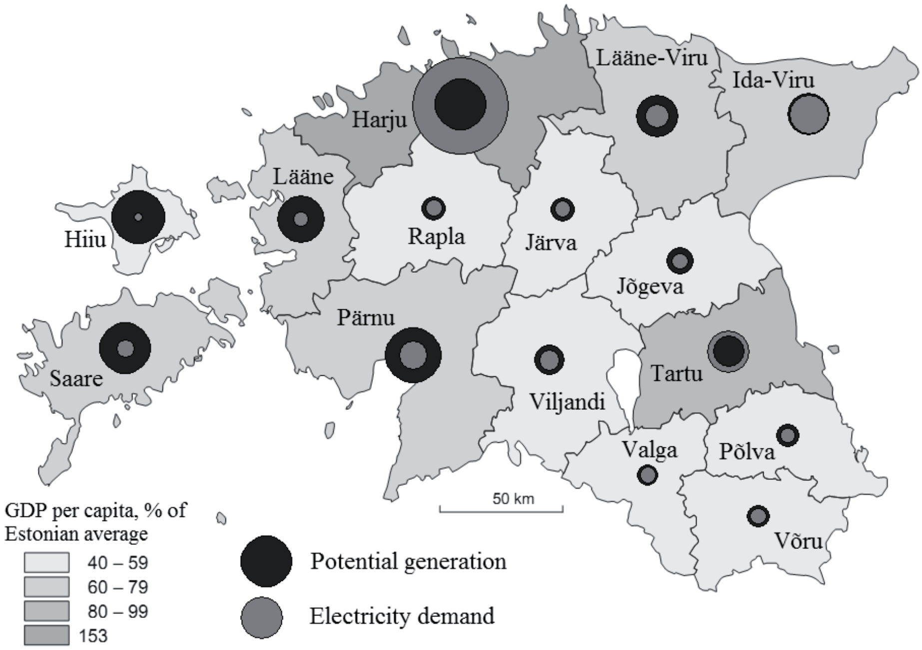

Figure 2. *Overview of location of renewable resources and electricity demand in Estonia*

From the Figure 2 and Tables 9-12 in Appendix A it is seen, that:

1) Approximately half of the total electricity and heat consumption is situated in Harju county.
2) Pärnu, Hiiu, Saare, Harju and Lääne counties have the most resources.
3) Hiiu county has the biggest surplus of energy having 30 times more resources than it is locally needed.
4) Harju and Tartu counties are the only counties with local generation deficit, as there are not sufficient renewable energy sources in these counties.
5) Harju county can produce only 30% of the electricity it requires and can generate only 25% heat with CHP plants. In case of Alternative 3 and 4, where wood from other counties is transported there, it is possible to supply CHP plants with needed biomass. But there is still 35% of electricity demand not covered.
6) Tartu county can satisfy 60% of its local demand. Tartu has enough resources for CHP plants, but in lack of other generation, as its hydro, wind and solar resources are rather limited.
7) Ida-Viru county has not enough resources for CHP plants, but its hydro and wind resources can compensate this deficit.
8) Hiiu, Lääne and Saare counties have outstanding resources, but low electricity consumption. This is due to large wind power resources, but also plenty of wood.

9) Comparison with currently available production capacities show, that the capacity of existing wind parks in Lääne county is 110 MW [48], which already produce more electricity than it is locally needed.
10) The existing CHP plants in Harju, Tartu and Pärnu counties are already using about 80% of the wood resource available for electricity generation in these counties.
11) Solar power, as the most expensive electricity generation units should be promoted mainly in bigger towns – in Harju and Tartu counties. In Lääne, Hiiu, Saare, Pärnu, Ida-Viru and Lääne-Viru there is no need for solar power, as there is enough wind power and cogeneration available.
12) Based on principles of distributed generation, to produce electricity close to the consumer, the extensive wind power development in Hiiu, Saare and Lääne counties should be avoided and instead the wind parks should be located in Harju county.

Calculated electrical capacities, primary energy consumption, and electricity and heat generation of alternative, which satisfies the current electricity demand (Alternative 4) is seen on the Table 4.

Table 4. *Calculated electricity and heat generation based on renewable sources and cogeneration*

Fuel	Resource (PJ)	Electricity generation (GWh)	Electrical capacity (MW)	Heat generation (GWh)
Biogas	8,9	988	124	1 186
Straw	10,9	697	107	2 021
Wood Gas	9,0	872	134	1 046
Wood Steam	20,9	1 743	268	3 747
Total CHP	**49,7**	**4 300**	**633**	**8 000**
Wind	12,6	3 500	1 667	0
Solar	1,8	500	500	0
Hydro	0,7	200	30	0
Boilers	8,0	0	0	2 000
Total	**72,8**	**8 500**	**2 830**	**10 000**

According to calculations described in Chapter 1.1.4, 633 MW of CHP plants and 2 197 MW wind, solar and hydro power plants could provide the electricity currently required in Estonia. In this case CHP production would form 80% of heat and 50% of electricity generation. Full potential of wood, biogas and straw resources is used to provide this electricity and heat. Based on the assumptions on resources about 80% of the heat in boilers should be produced from fossil fuels as there are not enough of renewable fuels. Also, quite a significant amount of wind and solar power is needed, as their generation together with hydro power will cover 50% of the electricity demand.

2.2 Balancing the energy system with high share of wind power and cogeneration.

The results in article [III] showed that a 3 MW gas engine CHP plant is able to balance the production of a wind park which is about the same size as the CHP or to balance a 20% forecasting fault of 18,4 MW wind park. But already in this case the CHP production is reduced by 30% of the normal annual production. Building of heat storage will improve the CHP operation as it will allow producing more electricity than the heat demand would allow at the moment. The biggest effects are achieved with smallest storage sizes and the investment payback time is 4 years. The heat storage is most useful from April to October, as there is no excess heat in the winter, because the heat demand is high, CHP is running on full load and boiler is used to cover the peak heat consumption. But for the CHP technology with other heat to power ratio and with a different adjustability of power generation, the results could be different.

In the article [VI] the balancing capability of two CHP plants instead of one were investigated. In this case there would be a 1,5 MW CHP unit in addition to 3 MW CHP. Compared to article [III] the electricity consumption is 10 GWh higher, which means that the results of the two articles are not fully comparable. In the article [VI] it was concluded that CHP units alone can cover the heat and electricity demand quite well even though the plant is operating according to the heat demand. This means that most of the wind power is not consumed locally. When the operation of CHP units is dependent on wind power generation, then the plant has to reduce its production by half and second CHP unit is used rarely. The availability of heat storage will increase the CHP production by 10%. The simulation of different operational strategies and availability of storages proved that the lowest electricity export and import is from the alternative, in which the operation of CHP plants is related to wind power production and there is a bigger heat storage available. As in this case the electricity generation is 40% lower than in the normal operation, the incomes from electricity sale or downward regulation must compensate the reduction of electricity generation.

In Estonian central power plants the excess heat is mostly not used for district heating as there are not sufficient heat consumers nearby. Based on energy efficiency principles it is not reasonable to waste the surplus heat and therefore electricity generation in CHP plants should be favored. According to the same principle, also the CHP plants should not use waste heat chillers. In the article [VII] it is shown that in case of biogas plant, waste heat chillers can be allowed as the landfill gas production is almost constant throughout the year and there is usually no gas storage. The environmental issues regarding biogas require that the gas generated in landfills, wastewater treatment plants and bigger farms has to be collected. If the gas is emitted to the air, it will contribute to global warming as methane, the main component of biogas is one of the greenhouse gases. The impact of methane emissions on global warming is 21 times higher than the CO_2 emissions which are emitted when burning the biogas. If the collected gas is simply burned in a flare, the energy is wasted, but using it in the

CHP plant reduces the environmental effect even more through reducing the electricity production of fossil power plants. As their generation is constant throughout the year, it will not require balancing like the fluctuating wind power.

The availability of biogas storage was discussed in the article [VII] as a possibility to reduce the need for natural gas which is sometimes used in peak load boiler if there is not enough biogas available. The heat storage could be useful in spring and autumn, when the heat demand is only slightly higher than the heat production from CHP plant.

2.2.1 Simulation of renewable and cogeneration based electricity and heat generation

The electricity generation capacities presented in Table 4 were used as inputs in energyPRO and their simulation was made on the basis of hourly data for the year 2011. The summary of simulated electricity and heat generation and primary energy consumption in energyPRO is given in Table 5.

Table 5. *Simulated electricity and heat generation based on renewable sources and cogeneration*

Fuel	Resource (PJ)	Electricity generation (GWh)	Electrical capacity (MW)	Heat generation (GWh)
Biogas	8,9	985	124	1 242
Straw	7,9	500	107	1 479
Wood Gas	12,3	1 170	134	1 465
Wood Steam	19,7	1 645	268	3 289
Total CHP	**48,9**	**4 300**	**633**	**7 475**
Wind	12,6	3 500	1 667	0
Solar	1,8	500	500	0
Hydro[6]	0,7	200	30	0
Boilers	10,0	0	0	2 525
Total	**74,0**	**8 500**	**2 830**	**10 000**

The simulation showed that in case of the same production capacities as presented in Table 4, CHP plants would produce 75% of heat and 50% of electricity. Although it is possible to produce the same amount of electricity by CHP plants, the share of fuels is a little different. The generation from wood gasification plants is higher and from straw lower. It is also seen that compared to calculated primary energy consumption, the simulated consumption is 1,2 PJ higher. This is due to reason that CHP plants operate also on partial load, where efficiency is lower.

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[6] Hydro power production was not simulated in energyPRO therefore the same data as in Table 4 is used.

An important outcome of the hourly simulation is that energyPRO also shows the monthly and annual electricity import and export quantities. The annual electricity generation equals the gross electricity consumption, but actually 16% (1 350 GWh) of electricity generation appears in the time when the consumption is not so high and therefore this electricity is exported. Similarly, 16% of electricity consumption cannot be covered with local generation and this electricity is imported. The graphs about hourly electricity and heat generation during selected months are given in Appendix A, Figures 10-14. The monthly electricity consumption, production, export and import quantities are presented in Figure 3.

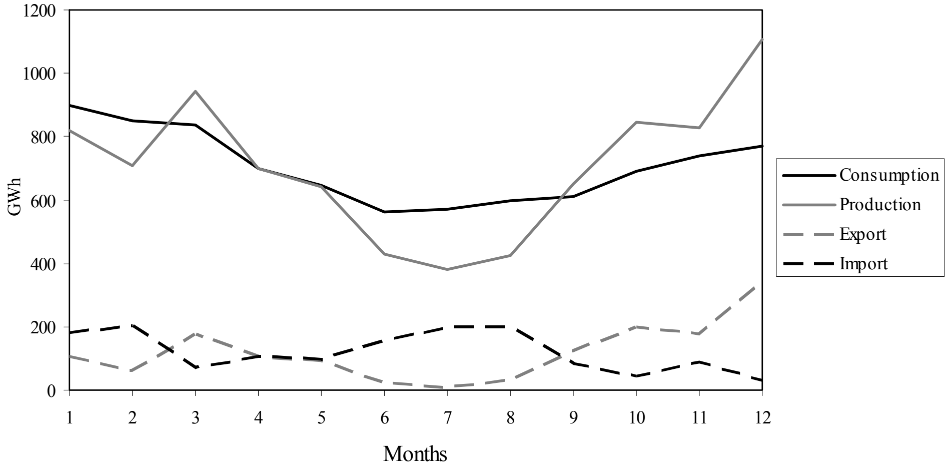


Figure 3. *Monthly electricity consumption, production, export and import of simulation results in energyPRO*

From Figure 3 it is seen that the largest part of export occurs in March, October, November and December and high import during the summer months and in January, February. Hourly electricity generation in selected months is seen in Appendix A, Figures 12, 13 and 14.

The hourly electricity generation and consumption is seen in the Figure 4. For the comparison a similar graph without electricity consumption is presented in Appendix A, Figure 11. As seen from the Figure 4, the maximum electricity generation is 2 100 MW, whereas the maximum demand is 1 600 MW. During the analyses it was observed that the maximum required export capacity is 1 200 MW and import capacity 900 MW. But usually there is a need for 500-600 MW of balancing capacities.

In an electricity system containing of only CHP plants, wind and solar power, there can sometimes be several days with very low wind power generation (Appendix A, Figure 12), and therefore substantial part of electricity consumption relies on electricity import. There are also situations where during a one day there could be a need to import 500 MW and few hours later the export of 500 MW is required.

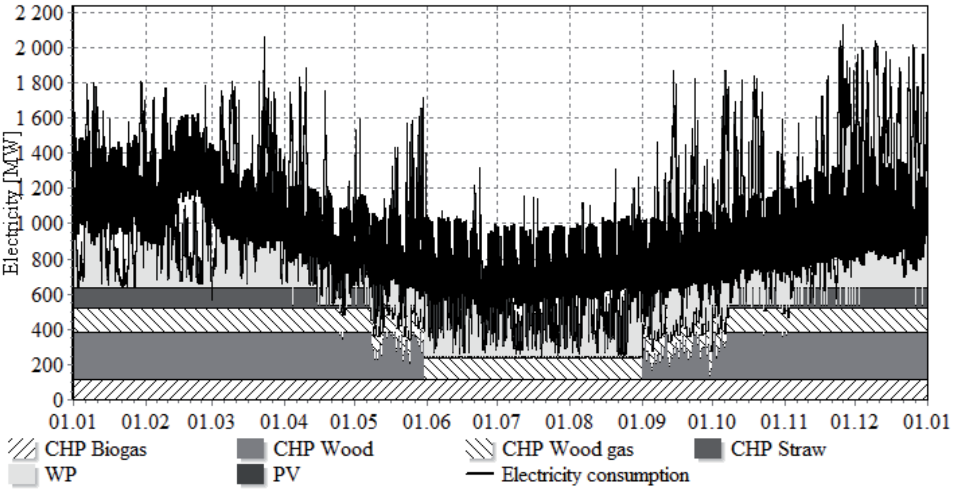


Figure 4. *Annual electricity consumption and simulated electricity generation*

In December (Appendix A, Figure 14) about half of wind power production is exported, as the wind conditions are very favorable. Solar power is useful for covering the peak demand from April to September. In summer its daily peak production ranges between 50-500 MW (Appendix A, Figure 13), but in winter its production is very small, usually 10-20 MW and reaching only in very few days 50-100 MW.

In summer the heat demand is low and therefore CHP plants can cover about 30% of the electricity consumption (Appendix A, Figure 13). The minimum electricity demand in June is 550 MW, which all could be covered with CHP plants. But Figure 10 in Appendix A shows, that the simulated heat demand in summer is only 300 MW. The electricity generation can be increased if CHP plants could provide cooling, which tri-generation CHP plants are able to do. In the tri-generation plant the cooling is produced from the waste water using an absorption chiller.

2.3 Influence of electricity production scenarios on national targets

Different electricity generation scenarios and their emissions have been analyzed in several articles. The results of the article [IV] showed that all electricity production scenarios of development plan have a decreasing CO_2 and SO_2 emissions starting from the year 2016, when the old oil shale units were assumed to be closed down. This will have a significant impact especially on SO_2 emissions as the SO_2 emissions of new oil shale power units are over 100 times lower. But it is still important to limit the oil shale mining and extensive oil shale power production, as the oil shale scenarios have the highest CO_2 emissions. The predicted CO_2 emissions from electricity generation in 2030 could be between 3,5 and 9,5 million tons depending on which scenario will be realized. SO_2 emissions could be from 2 to 55 thousand tons. The best scenarios regarding the pollution level are nuclear and wind power. In the nuclear scenario a large electricity import is expected during a ten year period as by 2016 the old oil shale power units were assumed to be closed down, but the nuclear power plant could start operating in 2025. The CO_2 emissions of wind power scenario are a little bit higher than of nuclear power, because of natural gas used for balancing the wind power.

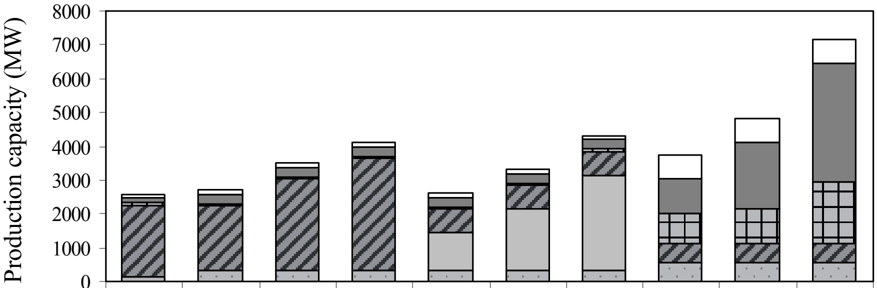
In the article [IV] the emissions from electricity generation were assessed, whereas the article [V] examines the total emissions of Estonia. The total CO_2 emissions in 2030 could be between 15 and 23 million tons and SO_2 emissions from 10 to 60 thousand tons. From the study it was concluded that none of the scenarios meets the target of the development plan to reduce the CO_2 emissions two times. It was also stated that the CO_2 emissions have a growing trend, which is mainly resulting from the use of oil products in the transport sector. SO_2 emissions of the most scenarios are after 2016 in the same, low level, as the difference in oil shale based generation will not affect the results in a significant way.

Comparison was also made between distributed and central electricity generation scenario. In the article [II] it was concluded that the development of distributed generation will reduce the CO_2 emissions of electricity and heat generation three times. Distributed generation will have an important role to meet the national targets. Whereas the central generation scenario proved that not all national goals are fulfilled. In case of development of central power generation the use of cogeneration is hindered and therefore the target of CHP generation share in electricity gross consumption will be not be met. Also, the CO_2 emission of central generation scenario is higher than the target.

2.3.1 Comparison of oil shale, nuclear and renewable energy scenarios

In this section the results from the updated LEAP model are presented, which are based on assumptions in Chapter 1.3.1. Comparison of electricity generation capacities in 2010 and 9 scenarios in 2040 is given in Figure 5. Other production capacities in Figure 5 are biogas, hydro, peat, solar and waste. For the renewable energy scenario it is assumed that the new oil shale power units are co-firing 50% oil shale and wood. Therefore the oil shale production capacity of this scenario is lower than in nuclear scenario. The total production capacities of the renewable energy (RE) scenarios are higher than for oil shale (OS) and nuclear (NU) scenarios, as this includes wind and solar power, which have low availability and cannot be considered available during the peak load hours.

As seen from Appendix A, Figure 15, the electricity demand of different consumption growth and electricity export scenarios is rather different. In case of low growth scenario the electricity demand (including consumption, network losses, own consumption and export) in 2040 is 13 200 TWh and peak power requirement 2 500 MW. But in high growth scenario consumption is 22 000 GWh and peak load 4 200 MW, which is over 1,5 times higher than of the low growth scenario. This means that very different amount of investments into electricity production capacities are needed.



	2010	OS-L	OS-M	OS-H	NU-L	NU-M	NU-H	RE-L	RE-M	RE-H
☐ Wood	110	110	110	110	110	110	110	700	700	700
■ Wind	130	280	280	280	280	280	280	1000	2000	3500
⊟ Other	70	70	70	70	70	70	70	880	1000	1800
▨ Oil Shale	2100	1900	2700	3300	700	700	700	580	580	580
▢ Nuclear	0	0	0	0	1100	1800	2800	0	0	0
▢ Natural Gas	160	340	340	340	340	340	340	560	560	560

Figure 5. *Comparison of electricity generation capacities in 2010 and 2040*

The total Estonian CO_2 emissions in Figure 6 shows that the emissions from renewable and nuclear scenario in 2040 are between 12 and 14 million tons, of which 3,5 to 4,5 million tons is from electricity and heat production. The emissions are in low level regardless of whether consumption is growing rapidly or slowly, as most of the renewable and nuclear electricity generation scenarios are CO_2 free. The emissions from oil shale scenarios are from 21 to 29 million tons and are greatly depending on the demand growth. Thus different electricity consumption growth and export scenarios impact the emissions of oil shale scenario significantly.

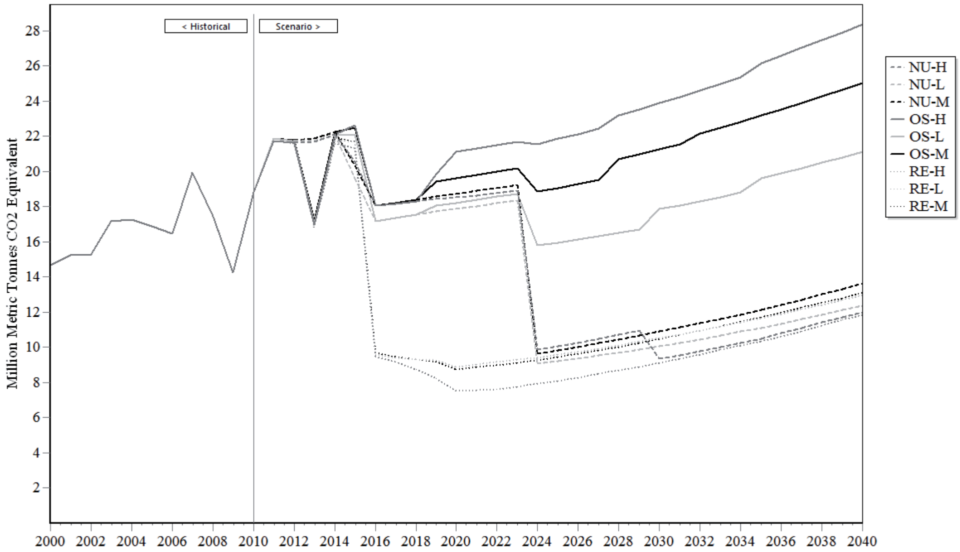


Figure 6. *Total CO_2 emissions of different electricity generation scenarios in million tons*

SO_2 emissions presented in Appendix A, Figure 16 are decreasing due to closing down and renovating the old oil shale based power units, which form a majority of current emissions. It is also seen from the Figures 6 and 16 that the reduction of emissions takes place later than predicted in the articles [IV, V]. This is due to EU Directive 2010|75|EU, which allows to operate the old oil shale power units without filters with limited (17 500) working hours during the period 2016-2023. It has also now become clear that sulfur-capturing filters will be installed to 4 power units. This will also increase SO_2 emissions compared to the initial assumption where these production units were assumed to be closed down in 2016.

In case of renewable energy scenarios it was still assumed, that the old oil shale power units will not be used from 2016. This will have a significant emission reduction compared to oil shale and nuclear scenarios, which use the old power units with limited working hours until 2023. Figures 6 and 16 show that due to closing down of oil old shale power units the CO_2 and SO_2 emissions of renewable energy scenarios will be two times lower than in other scenarios.

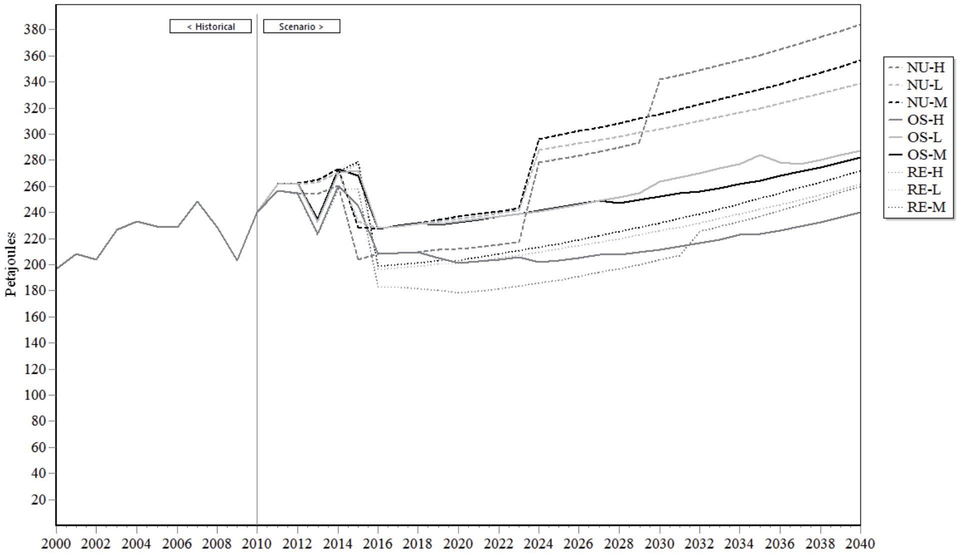


Figure 7. *The total primary energy consumption of different electricity generation scenarios in PJ*

The primary energy consumption has grown from 200 PJ in 2000 to 240 PJ in 2010. Figure 7 shows that by the year 2040 primary energy consumption will reach 240 to 380 PJ. Nuclear power scenario has the highest primary energy consumption. The use of renewable energy and cogeneration for electricity and heat production can reduce the total primary energy consumption by 30-35% compared to nuclear scenario.

The primary energy consumption by fuel type of RE-M (renewable, medium growth) scenario is seen in Appendix A, Figure 17. It is seen from the figure that it is possible to cover 35-45% of the primary energy consumption by renewable energy. For the low electricity demand growth scenario it is possible to reach even a share of 55%.

In the year 2010, 160 PJ (44 490 TWh) of primary energy was used for electricity and heat production in Estonia [2]. Overview of consumed fuels, produced useful energy and losses is given in Figure 8. Currently only 44% of consumed primary energy reaches the consumer (if considering also electricity export as consumption), which means that 56% of energy is lost during the electricity and heat production and distribution processes. The biggest losses appear during the electricity generation process, which has therefore the highest potential for energy saving.

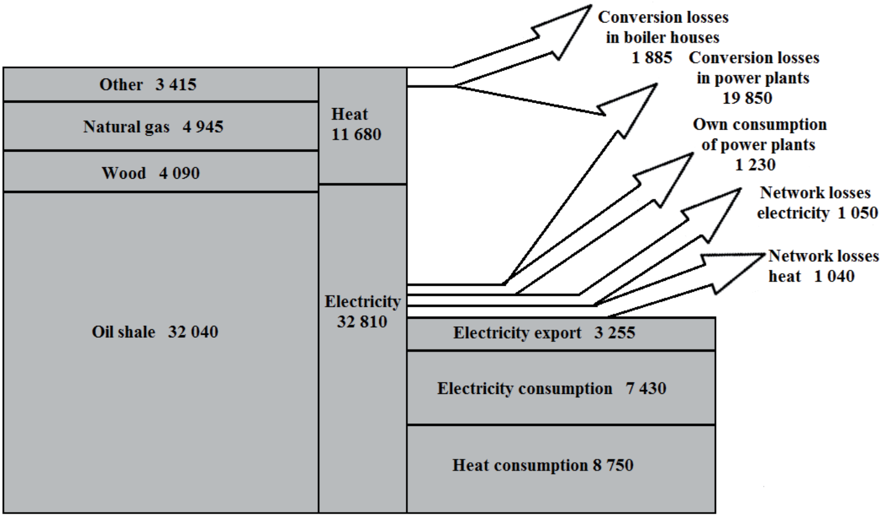


Figure 8. *Energy balance of electricity and heat generation in 2010 in GWh*

Comparison can be made with primary energy consumption of renewable energy based electricity generation. Simulation results presented in 5 show that only 74 PJ of energy is used to produce electricity and heat in CHP plants and from wind, solar and hydro power. Thus it is possible to reduce the current energy consumption by 86 PJ when using renewable energy and cogeneration for electricity and heat production and limiting the electricity export.

In 2010 electricity and heat generation formed 71% of the total CO_2 emissions [3]. With the renewable energy based electricity and heat generation the emissions can be reduced by 83% compared to 1990 level. Share of electricity and heat production in the primary energy consumption was 68% [2]. Simulations and calculations have shown that primary energy consumption can be reduced by 35% by using cogeneration and renewable energy for electricity and heat production. The share of renewable energy in the primary energy consumption in 2010 was 14% [2] and this can be increased to 55%. Renewable energy formed 10,8% [2] of the electricity gross consumption and this should be then increased to 100% to meet the above-mentioned targets. In 2010 CHP plants produced 35% [2] of the heat and this should be then increased to 80%.

3. DISCUSSION

In the Chapter 2.1 it was shown that theoretically it is possible to cover 50% of the current electricity and 80% of heat demand by CHP plants. The question arises if it is realistic to reach such a high share of CHP generation. The heat demand is currently approximately 10 000 GWh, which has a slightly decreasing trend. But the additional potential of local CHP plants in industry and commercial sector have not been taken into account in these calculations. Also, household consumers could have micro-CHP plants in the future. Based on statistical data on fuel consumption in these sectors, their heat consumption could be an additional 5 500-6 000 GWh. Thus there is a great potential for CHP plants in buildings in which heat is currently produced with a boiler or furnace.

The share of cogeneration in electricity production depends on CHP technology, which determines the heat to power ratio. The smaller the heat to power ratio, the more electricity is produced and the higher the CHP share in electricity consumption is. The results presented in Table 5 are based on an assumption that approximately half of electricity generation in CHP plants is produced with gas engines, which have a heat to power ratio of almost 1. An additional benefit of gas engines is their excellent balancing capability. But their usage is limited as they use gaseous or liquid fuels. Typical fuel for this type of CHP-s could be natural gas or biogas. In Estonia the main renewable energy resource is wood, which can be used in a steam turbine CHP with a heat to power ratio from 2 to 5. This means that less electricity is produced per 1 MWh of heat. The development of gasification technologies has provided the possibility to also use biomass in gas engines, but as a drawback the gasification is related to losses.

The second point of discussion is the preciseness of electricity and heat consumption estimation per county, which is seen in appendix A, Tables 7 and 8. As the consumption is not given in so detailed form in statistical databases or annual reports, the consumption has been divided between counties according to assumptions in Chapter 1.1.5. The only available data for the comparison of electricity consumption is for the year 1999 [45]. The change in percents compared to this data is presented in Figure 9. Lääne county is not represented in this figure, because the study [45] did not include data for this county. In average the electricity consumption has risen 1,5 times during the last 12 years. Figure 9 show that consumption has increased the most in Harju and Tartu counties. The comparison with statistical data indicates the same tendencies, as according to statistics people have moved from neighboring counties to these two counties and also the GDP has grown faster there.

Also comparison of electricity and heat consumption can be performed with research works made for Võru and Põlva counties. The electricity consumption in Võru county in 2009 was 145 GWh and heat consumption approximately 230 GWh [46]. In the current thesis the consumption was calculated in the year 2011 to be 140 GWh of electricity and 212 GWh of heat. The electricity consumption in Põlva county in 2005 was 89 GWh and heat production in boiler houses 178 GWh [47] and calculated numbers for the year 2011 are 109 GWh and 168 GWh. Compared to year 2005 the electricity consumption in Estonia has increased 14% and heat consumption decreased 5%, so based on these two examples it can be concluded that the preciseness of calculations is quite good.

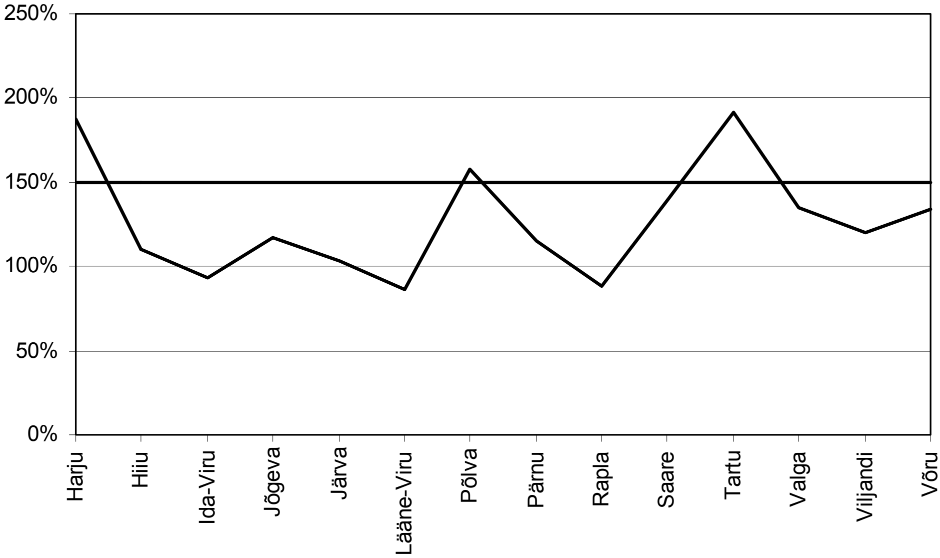


Figure 9. *The calculated electricity consumption per county compared to the year 1999*

In the articles [III, VI] the capability of gas engine CHP plant to balance wind power production was analyzed. For this purpose CHP plants have to reduce its production and this will affect the profitability investment. The purpose of using local CHP plants for balancing is to avoid investments into transmission capacities. But the effect of balancing wind power production with locally available CHP plants in Estonia is rather low. The best wind resources in Estonia are situated in the coastline and islands of western Estonia, where the transmission capacity is not sufficient. Calculations based on data in Appendix A, Table 7 show that the electricity consumption in Lääne, Hiiu and Saare counties is low and the maximum potential for local CHP plants is about 30 MW of electricity. But the installed capacity of already available wind power in this area is almost 120 MW [48]. Therefore even if the full potential of CHP is applied in these counties, their balancing effect is limited. Palu has also shown that regulating activities of CHP will result in increased fuel consumption and extra costs for starting and stopping the plant, increased maintenance costs, reduced lifetime and higher air emissions [18].

There are also several other possibilities for balancing the fluctuating electricity generation. In the open electricity market electricity export and import can be used to balance the fluctuating production. In Scandinavia the hydro power plants are used to balance the wind power production. But the transmission capacities to neighboring countries are limited. In Estonia the planned 500 MW pumped hydro plant could provide the same task. Smart grid is also highly related to the development of distributed generation. Demand side management can be used by changing the demand through switching off and on the consumers' appliances. Also electricity storages such as batteries, super capacitors, compressed air storages, production of hydrogen and its usage in the fuel cells, etc can be used.

The articles [III, VI, VII] showed that the flexibility of CHP production can be improved through heat storage, heat blow-off and biogas storage. But the heat storage is useful mostly in spring and autumn. In addition the heat storage could have electric water heater or a heat pump, which produces hot water during the time of low electricity price. In Estonia the winter is much colder than in Denmark, where heat storages are typically used. Therefore higher heat storage losses in winter can reduce the profitability of the storage. Østergaard has compared the impact of heat, biogas and electricity storages with energyPRO and energyPLAN models, which showed that electricity storages give significantly better integration of wind power, but it is associated with significant costs [49]. Scandinavian countries are also planning electrification of transport and heating sector by large scale use of electric vehicles and heat pumps, which would allow storage and balance the wind power production. Therefore other options for balancing should be also investigated further.

In the articles [IV,V,VIII] CO_2 and SO_2 emissions were predicted until the year 2030, for which study was carried out in 2008. The prognoses in the LEAP model were based on statistical data of the years 2000 to 2006. Currently there is full statistical data available until the year 2010, which allows comparing the prognoses made for the years 2007-2010 to actual numbers.

Table 6. *Comparison of prognoses in LEAP and actual statistical data*

	2007	2008	2009	2010
Electricity generation (GWh)				
Prognosis in LEAP	9 520	9 539	9 611	9 843
Actual	12 189	10 581	8 779	12 964
CO_2 emissions (mill.t)				
Prognosis in LEAP	16,2	16,3	16,4	16,5
Actual	18,9	17,4	14,2	18,2
New calculation in LEAP	19,8	17,5	14,3	18,8
SO_2 emissions (th.t)				
Prognosis in LEAP	69,1	68,3	68,0	68,2
Actual	88,0	69,4	54,8	82,1
New calculation in LEAP	92,4	72,7	52,6	79,9

As seen from the Table 6, the actual electricity generation in 2007, 2008 and 2010 has been considerably higher than the prognoses. Reason for that is higher electricity export as 22-34% of the total electricity production was exported. The modeling was based on assumption that the electricity export will stay on the same level as in 2000-2006, which was about 1 500 GWh. But actually during the years 2007-2010 the export was up to 4 350 GWh. This had also an effect on the emissions, especially on SO_2 emissions. During the comparison it was also discovered that for the years 2000-2006 the emissions in the statistical database of Estonia have been revised afterwards due to of change in the emission calculation methodology. The actual CO_2 emissions were about 10% lower than before and the SO_2 emissions 2% higher. That was also the main reason for updating the LEAP model. In Table 5 new results from LEAP model are presented in the row "new calculation in LEAP". It can be concluded that the prognosis with model for Estonian energy system in LEAP are precise, but the results depend on external conditions. The predictions are based on assumptions and steady growth or reduction prognosis. In reality the electricity consumption and export are dependent on political and economical decisions, which are rather difficult to predict. Therefore in chapter 2.3 new prognoses in LEAP were made based on different consumption growth and export scenarios.

Comparison of Estonian CO_2 emission prognosis with results from other authors is also a subject for discussion. Based on comparison of different energy planning models Dementjeva found LEAP to be suitable for elaborating the energy sector scenarios [8]. But results are not comparable as the LEAP model was simplified. MARKAL model has been used by Liik *et al* [5], Landsberg [6] and Agabus [7], but its scenarios are related more to economic growth, emission limitations or taxes on emissions, not to certain production capacities like in LEAP. The MARKAL model optimizes the energy system according to least costs and decides which energy carriers are used for demand, which power plants are built and calculates the emissions of the energy system. In the year 1999 Liik *et al* has predicted that the CO_2 emissions in 2030 could be between 10 and 18 million tons [5]. Agabus *et al* forecasted the emission for the same year to be from 14 to 23 million tons [50]. The prognosis made with LEAP in article [V] showed that the total CO_2 emissions in 2030 are between 15 and 23 million tons. Chapter 2.3.1 presented the emissions of different electricity consumption and export scenarios, which could be from 9 to 24 million tons. It does not mean that the preciseness of predictions in LEAP is low, rather that the different future prognosis of inputs and several electricity generation options influence the outcomes in a significant way.

The aim of this thesis was to investigate the possibilities of distributed generation to meet the targets of energy and climate policies. Taking into account the aim of energy savings, emission reductions and increased use of renewable energy, the results prove that scenario with CHP plants, wind, solar and hydro power is the only scenario that meets all the policy objectives. Burning fossil fuel in a condensing power plant will not reduce CO_2 emissions, will not increase the use of renewable energy and will not give significant improvements in energy efficiency. Nuclear power production reduces the emissions, but share of renewables and energy efficiency will not be improved. Co-firing of biomass with fossil fuel will reduce the emissions and increase the use of renewable energy, but energy efficiency target will be not met. Use of renewable energy and cogeneration has a great potential for meeting the targets of energy and climate policies.

CONCLUSIONS AND FUTURE WORK

Distributed generation means electricity production close to the consumer with a production unit suitable for covering the local demand. In Estonia the distributed generation consists of wind, solar and hydro power and CHP plants using wood, peat, natural gas and biogas. It also includes electricity produced for self consumption and in places without grid connection. The capacity of distributed generation is currently a little below 300 MW and their generation is about 12% of the electricity gross consumption. Approximately 1/5 of this generation is connected to the distribution grid, the rest to the transmission network. From the assessment of current Estonian distributed generation capacities it can be concluded that distributed generation is not the same as renewable energy generation, although largely they coincide. When producing electricity close to the consumer, local energy sources should be used and this can also include fossil fuels.

Based on the potential of renewable resources in Estonia it is possible to produce all electricity and most of the heat with distributed generation plants. But the evaluation for each county showed that less than 60% of electricity demand can be covered when only local renewable resources in a county are used. The renewable energy sources are not equally distributed over the country and neither is the consumption. Half of the electricity and heat consumption is located in Harju county, but renewable energy sources are there rather small compared to the demand. The calculations showed also that there is no need for extensive wind power development if the aim is to produce electricity from locally available resources. If the whole electricity consumption will be covered with renewables, then the fluctuating production will have to cover half of the consumption as the potential for CHP plants and biomass is limited.

The use of cogeneration should be promoted as their generation coincides significantly better with electricity demand than of wind power. Wood would be the main fuel for CHP plants, but its use in steam turbine is related to low electrical efficiency compared to gas engines. Straw could be an alternative fuel in areas where the wood resources are insufficient. Biogas use should be favored because of additional environmental benefits. Use of gas engines provides also good balancing capability and high electricity generation per one unit of heat. Hydro resources in Estonia are very limited compared to wind and solar power resources. Solar panels could be installed on rooftops of industrial and commercial buildings in bigger towns, as in other areas there are plenty of other resources available.

If whole electricity would be generated with CHP plants, wind and solar power, then the Estonian electricity system would currently require up to 1 200 MW of balancing capacities either as connections to neighboring countries or as balancing units. It is possible to use CHP plants for balancing purposes, so that in times with high wind power production CHP plants stop producing and heat is then produced by boilers. 3 MW CHP plant could balance the wind power production in about the same size or a 20% forecasting error of an

18 MW wind park. This kind of operation will reduce working hours of CHP plant, which will affect the profitability of investment.

For estimating the potential generation of distributed generation simulation models like energyPRO are very useful. The simple calculations do not take into account the alteration of demand and availability of production units on hourly basis. Also the fuel consumption cannot be calculated based on electrical efficiency, as the efficiency of CHP plants is changing depending on actual load. In case of wind and solar power generation it should be taken into account, that they are not producing electricity when it is needed.

The electricity generation, CO_2 and SO_2 emissions and primary energy consumption of different electricity production scenarios were predicted with LEAP software. In addition to scenarios presented in the development plan of electricity sector additional renewable energy scenarios were added. The scenarios were assessed also in case of different consumption growth and electricity export strategies, which have a significant impact on the results of oil shale scenario. The prognoses of LEAP model were assessed to be quite accurate, but the result depends on assumptions, which are rather difficult to predict.

Use of cogeneration and renewable energy for electricity and heat generation will contribute to meet the energy and climate targets. Currently electricity and heat generation forms about 70% of the Estonian CO_2 emissions and primary energy consumption. With the use of cogeneration and renewable energy the CO_2 emissions can be reduced by 80% compared to 1990 level. In primary energy consumption energy saving of 35% can be achieved. The share of renewable energy in primary energy consumption is increased from 15 to 35%.

Comparison of different electricity generation scenarios proved, that use of renewable energy and cogeneration is the only way to meet all goals of policies – to reduce emissions, improve energy efficiency and increase use of renewable energy. When planning the development of electricity and heat generation, the available production units should be taken into account and the transition should take place gradually. Also other sectors of economy could contribute for meeting the targets.

The development of distributed generation depends on European energy and climate policies and national support schemes. Also the electricity market price and investment costs of production technologies are important factors for future growth. As distributed generation involves considerably larger number of producers, also the importance of education and guidelines is high.

The future work should continue with economical assessment of distributed generation. Although the analysis in this thesis was related to Estonia, the findings of the work and used calculations and models can be used also in other countries. LEAP model should be made for the Baltic countries and also for Baltic and Scandinavian region. In energyPRO the different balancing options should be simulated, for example use of electric vehicles and heat pumps for balancing the wind power generation. Also literature about distributed generation in Estonian language is needed.

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LIST OF PUBLICATIONS

[I] **Kuhi-Thalfeldt**, **R**., Valtin, J. The potential and optimal operation of distributed power generation in Estonia. Oil Shale, Vol. 28, No. 1S, 2011, Estonia, pp. 240-252.

[II] **Kuhi-Thalfeldt, R**., Valtin, J. Influence of distributed generation development on national targets and electricity price in Estonia. 8th International Symposium "Topical Problems in the Field of Electrical and Power Engineering", Doctoral School of Energy and Geotechnology II. Pärnu, Estonia, January 11-16, 2010, pp. 75-81.

[III] **Kuhi-Thalfeldt, R**., Valtin, J. Combined heat and power plants balancing wind power. Oil Shale, Vol. 26, No. 3 Special, 2009, Estonia, pp. 294-308.

[IV] **Kuhi-Thalfeldt, R**., Kuhi-Thalfeldt, A., Valtin, J. Estonian electricity production scenarios and their CO_2 and SO_2 emissions until 2030. WSEAS Transactions on Power Systems, Issue 1, Vol. 5, 2010, pp. 11-21.

[V] **Kuhi-Thalfeldt, R**., Valtin, J. CO_2 and SO_2 emissions in Estonia in the period 2000-2030. 7th International Symposium "Topical Problems in the Field of Electrical and Power Engineering", Doctoral School of Energy and Geotechnology. Narva-Jõesuu, Estonia, June 16-19, 2009, pp. 47-56.

[VI] **Kuhi-Thalfeldt**, R., Valtin, J. Possibilities of stabilising fluctuating wind power with cogeneration power plants. 5th International Symposium "Topical problems in the field of electrical and power engineering“. Doctoral school of energy and geotechnology, Kuressaare, Estonia, January 14-19, 2008, pp. 140-144.

[VII] **Kuhi-Thalfeldt, R**., Valtin, J. Economic analysis of a biogas-fuelled cogeneration power plant. 4th International Symposium "Topical problems of education in the field of electrical and power engineering", Doctoral school of energy and geotechnology, Kuressaare, Estonia, January 15-20, 2007, pp. 164-168.

[VIII] **Kuhi-Thalfeldt, R**., Kuhi-Thalfeldt, A., Valtin, J. The effect of Estonian electricity production scenarios on CO_2 and SO_2 emissions in 2000-2030. In: Recent Advances in Electric Power Systems, High Voltages, Electrical Machines: Proceedings of the 9th WSEAS/IASME International Conference on Electric Power Systems, High Voltages, Electric Machines (POWER '09): University of Genova, Italy, October 17-19, 2009, pp. 182-187.

ABSTRACT

The main purpose of this thesis is to analyze the potential of distributed electricity generation and its possibilities for meeting the targets of energy and climate policies.

The strategic objectives of the European Union are to improve energy efficiency, reduce greenhouse gas emissions and increase use of renewable energy. By the year 2050 the goal is to reduce the greenhouse gases by 80% compared to 1990 level. Although Estonia has achieved 50% greenhouse gas savings, the emissions have remained to the 1992 year level and primary energy consumption has a growing trend. Despite that the share of renewables in primary energy and electricity gross consumption have increased in recent years, the issues of emission and primary energy consumption have to be addressed. One way to do this is through use of distributed generation.

In this thesis the definition of distributed generation was investigated and the definition for Estonia was formed. Distributed generation is production of electricity close to the consumer and it involves mainly renewable, but also fossil fuels. The main objective is to provide energy savings, emission reduction and increased use of renewable energy. In 2011 the capacity of distributed generators in Estonia was little less than 300 MW and they account for 12% of electricity gross consumption. Theoretically it would be possible to produce all required electricity using renewable energy sources, but in this case the weather-dependent wind and solar power would form half of electricity generation.

The evaluation was made on resources and electricity and heat consumption for each county, which showed that the resources and consumption are not equally distributed over Estonia. Half of the consumption is in Harju county, but the renewable energy resources there are limited. By using only local renewable energy resources it is possible to produce only 60% of needed electricity.

Large-scale deployment of solar and wind power causes problems in achieving the balance between consumption and production, which must be guaranteed at all times. Balancing issues were studied with energyPRO software, where based on 2011 year data the hourly simulation of electricity and heat consumption and production of CHP plants, wind and solar power was made. The results showed that up to 1 200 MW of balancing is needed either through electrical connection to neighboring countries or as balancing units. energyPRO software was also used to investigate the balancing of wind power production with gas engine CHP plant. It was found that 3 MW CHP plant is capable of balancing wind power plant about the same size or 20% forecasting error of wind turbine with an 6 times higher output. However, this results in reduced profitability of CHP plant.

The CO_2, SO_2 emissions and primary energy consumption of different electricity generation scenarios were predicted using energy planning model LEAP. Comparison of oil shale, nuclear and renewable energy scenarios showed that the scenarios with CHP plants, wind, solar and hydro power are the only scenarios that meet all the energy and climate policy objectives.

KOKKUVÕTE

Antud doktoritöö peamiseks eesmärgiks on analüüsida elektrienergia hajatootmise potentsiaali ning selle võimalusi energia- ja kliimapoliitika eesmärkide täitmiseks.

Euroopa Liidu strateegilisteks eesmärkideks on kasutada energiat säästlikult, vähendada kasvuhoonegaase ning suurendada taastuvenergia osakaalu energiatarbimises. 2050.aastaks on eesmärgiks vähendada kasvuhoonegaase 80% võrra võrreldes 1990.a tasemega. Eesti on küll saavutanud 50%-lise kasvuhoonegaaside kokkuhoiu, kuid emissioonid on jäänud 1992.a tasemele ning primaarenergia tarbimisel on kasvav trend. Kuigi taastuvenergia osakaal primaar-energia lõpptarbimises ja elektri kogutarbimises on viimastel aastatel kasvanud, tuleb leida lahendus ka emissioonide ja primaarenergia tarbimise vähenemiseks. Üks võimalus selleks on läbi hajutatud elektritootmise.

Töös uuriti hajatootmise definitiooni ning defineeriti hajatootmine Eestis. Hajatootmine tähendab elektri tootmist tarbija lähedal ning see hõlmab endas peamiselt taastuvaid, kuid ka fossiilseid kütuseid. Peamine eesmärk on tagada energiasääst, emissioonide vähenemine ja taastuvenergia kasutuse kasv. 2011.a oli hajatootmisvõimsusi Eestis veidi vähem kui 300 MW ning nende toodang moodustab 12% elektri kogutarbimisest. Teoreetiliselt oleks võimalik kogu vajaminev elekter toota ka taastuvatest energiaallikatest, kuid sellisel juhul moodustaks tuule- ja päikeseenergia poole elektri toodangust.

Vaadeldid ka taastuvenergia ressursse ning elektri ja soojuse tarbimist maakondade kaupa, millest selgus, et ressursid ja tarbimine ei ole üle Eesti ühtlaselt jaotatud. Pool tarbimisest asub Harju maakonnas, kuid taastuvenergia ressursid on seal piiratud. Vaid maakonna kohalikke taastuvenergia ressursse kasutades oleks võimalik toota 60% vajaminevast elektrist.

Tuule- ja päikeseenergia laialdane kasutuselevõtt tekitab aga probleeme tarbimise ja tootmise tasakaalu saavutamisel, mis peab olema tagatud igal ajahetkel. Tasakaalustamise küsimusi uuriti energyPRO tarkvara abil, kus 2011.a andmete näitel modelleeriti elektri ja soojuse tarbimist ning koostootmisjaamade, elektrituulikute ja päikesepaneelide toodangut tunni kaupa. Tulemused näitasid, et oleks vaja kuni 1 200 MW tasakaalustavaid võimsusi, seda kas läbi elektriühenduste naaberriikidega või eraldi tootmisvõimsustena. energyPRO abil uuriti võimalust tasakaalustada elektrituulikute toodangut gaasimootoriga koostootmisjaama abil. Leiti, et 3 MW koostootmisjaam suudaks oma toodangut vastavalt suurendades või vähendades tasakaalustada umbes sama suure elektrituuliku toodangut või 6 korda suurema tuuliku 20%-list ennustusviga. Kuid selle tulemusena väheneb koostootmisjaama toodang ning see mõjutab investeeringu tasuvust.

Erinevate elektri tootmise stsenaariumide CO_2, SO_2 emissioone ja primaarenergia tarbimist prognoositi energiasüsteemi arengu planeerimise mudeli LEAP abil. Võrreldes erinevaid põlevkivi, tuuma- ja taastuvenergia stsenaariume leiti, et koostootmisjaamade, elektrituulikute, päikesepaneelide ja hüdroenergiaga stsenaariumid on ainsad, mis täidab kõiki energia- ja kliimapoliitika eesmärke.

ELULOOKIRJELDUS

1. Isikuandmed

Ees- ja perekonnanimi: Reeli Kuhi-Thalfeldt
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Kodakondsus: Eesti

2. Kontaktandmed

Aadress: Paldiski mnt. 48-9, Keila, Eesti
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3. Hariduskäik

Õppeasutus (nimetus lõpetamise ajal)	Lõpetamise aeg	Haridus (eriala/kraad)
Tallinna Tehnikaülikool	2005	Elektroenergeetika, Tehnikateaduste magistri kraad
Tallinna Tehnikaülikool	2003	Elektroenergeetika, Tehnikateaduste bakalaureuse kraad
Tallinna Tehnikagümnaasium	1999	Keskharidus

4. Keelteoskus (alg-, kesk- või kõrgtase)

Keel	Tase
Eesti keel	Emakeel
Inglise keel	Kõrgtase
Soome keel	Kesktase
Saksa keel	Kesktase

5. Täiendusõpe

Õppimise aeg	Täiendusõppe läbiviija nimetus
2012	National and Kapodistrarian University of Athens, Kreeka
2005, 2006	Energy Regulators Regional Association, Ungari
2003, 2004	Högskolan på Gotland, Rootsi
2002-2003	Aalborg University, Taani
2002	Stralsund University, Saksamaa

6. Teenistuskäik

Töötamise aeg	Tööandja nimetus	Ametikoht
2012-	Sihtasutus Säästva Eesti Instituut, Stockholmi Keskkonnainstituudi Tallinna Keskus	Teadur
2005-	Tallinna Tehnikaülikool	Assistent
2005-2006	Energiaturu Inspektsioon	Peaspetsialist
2003-2005	PKC Eesti AS	Toodangu planeerija

7. Teadustegevus

- Leping ETF2008. Elektrienergia hajatootmise struktuuri optimeerimine, põhitäitja.
- Välisleping V293. Dissemination strategy on electricity balancing for large scale integration of renewable energy (DESIRE), põhitäitja.
- Leping 520705. Elektritootmise, soojatootmise ja transpordikütuste kasutamise stsenaariumite väljatöötamine ja mudelite LEAP ja EcoSenseWeb abil mõjude hindamine riikliku energiamajanduse arengukava aastani 2020 jaoks, põhitäitja.
- Välisleping V342. Intelligent energy - Europe. Renewable energy sources in Estonia for year 2020, põhitäitja.
- Leping Lep8056. Eesti kasvuhoonegaaside heitkoguste riiklike prognooside aruanne, põhitäitja.
- Leping Lep697. Uuring energiatoodete maksustamise kohta, põhitäitja.
- Leping SF2008. Säästev ja jätkusuutlik elektroenergeetika, täitja.
- Leping SF2003. Töökindel ja säästlik energeetika, täitja.

8. Kaitstud lõputööd

Magistritöö: Biogaasil põhineva elektri ja soojuse koostootmise tasuvusuuring, 2005, juhendaja professor Juhan Valtin.
Bakalaureusetöö: Biogaasikütusel koostootmisjaama majanduslik analüüs, 2003, juhendaja professor Juhan Valtin.

9. Teadustöö põhisuunad

Energeetika arengu planeerimise mudelid, energeetika arengu planeerimine, taastuvenergia, elektri ja soojuse koostootmine, õhuemissioonide prognoosimine.

CURRICULUM VITAE

1. Personal data

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2. Contact information

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3. Education

Educational institution	Graduation year	Education (field of study/degree)
Tallinn Universtity of Technology	2005	Master of Science in Electrical Power Engineering
Tallinn Universtity of Technology	2003	Bachelor of Science in Electrical Power Engineering
Tallinn Technical Gymnasium	1999	Secondary education

4. Language competence/skills (fluent; average, basic skills)

Language	Level
Estonian	Mother tongue
English	Fluent
Finnish	Fluent
German	Average

5. Special Courses

Period	Educational or other organisation
2012	National and Kapodistrarian University of Athens, Greece
2005, 2006	Energy Regulators Regional Association, Hungary
2003, 2004	Högskolan på Gotland, Sweden
2002-2003	Aalborg University, Denmark
2002	Stralsund University, Germany

6. Professional Employment

Period	Organisation	Position
2012-	Stockholm Environment Institute Tallinn Centre	Research fellow
2005-	Tallinn University of Technology	Teaching assistant
2005-2006	Estonian Energy Market Inspectorate	Chief Specialist
2003-2005	PKC Eesti AS	Production planner

7. Scientific work

- Contract ETF2008. Optimisationof the structure of distributed electricity production, 2008-2011.
- International contract V293. Dissemination strategy on electricity balancing for large scale integration of renewable energy (DESIRE), 2005-2007.
- Contract 520705. Development of scenarios for the electricity production, heat production and use of transport fuels and assessing the impact of these scenarios with the models of LEAP and EcoSenseWeb for the National Energy Development Plan 2020, 2007-2009.
- International contract V342. Intelligent energy - Europe. Renewable energy sources in Estonia for year 2020, 2006-2008.
- Contract Lep8056. The prognosis of the emissions of greenhouse gases in Estonia, 2008.
- Contract Lep697. Research on taxation of energy products, 2006.
- Contract SF2008. Energy saving and sustainable electrical power engineering, 2008.
- Contract SF2003. Reliable and sustainable power engineering , 2006-2007.

8. Defended theses

Master Thesis: Economic analysis of a biogas-fueled cogeneration power plant, 2005, supervisor prof. Juhan Valtin.
Bachelor Thesis: Cost-efficient analysis of a biogas-fueled cogeneration plant, 2003, supervisor prof. Juhan Valtin.

9. Main areas of scientific work/Current research topics

Energy planning models, energy planning, renewable energy, combined heat and power production, prognosis of air emissions.

APPENDIX A – Appended Tables and Figures

Table 7. *Electricity gross consumption by county in GWh*

County	Households	Other sectors	Total consumption	Distribution losses	Gross consumption
Harju	808	3254	4063	573	4635
Hiiu	15	24	40	6	45
Ida-Viru	256	418	675	95	770
Jõgeva	56	64	119	17	136
Järva	55	85	140	20	159
Lääne	42	67	109	15	124
Lääne-Viru	102	179	281	40	321
Põlva	47	62	109	15	124
Pärnu	135	254	389	55	444
Rapla	56	77	133	19	151
Saare	53	96	148	21	169
Tartu	230	549	779	110	889
Valga	52	68	120	17	137
Viljandi	85	122	207	29	236
Võru	57	82	140	20	159
Total	**2 050**	**5 400**	**7450**	**1 050**	**8 500**

Table 8. *Heat gross consumption by county in GWh*

County	Households	Other sectors	Total Consumption	Distribution losses	Gross consumption
Harju	1 656	2 893	4 549	505	5 054
Hiiu	31	22	53	6	59
Ida-Viru	525	372	897	100	997
Jõgeva	115	57	171	19	190
Järva	113	75	188	21	209
Lääne	86	59	145	16	161
Lääne-Viru	210	159	368	41	409
Põlva	96	55	151	17	168
Pärnu	277	226	503	56	558
Rapla	115	68	183	20	203
Saare	108	85	193	21	215
Tartu	472	488	960	107	1 066
Valga	106	60	167	19	185
Viljandi	173	108	282	31	313
Võru	118	73	191	21	212
Total	**4 200**	**4 800**	**9 000**	**1 000**	**10 000**

Table 9. *Alternative 1 - electricity generation from local renewable resources in GWh*

	Wood	Straw	Biogas	Wind	Solar	Hydro	Total
Harju	208	54	149	561	355	29	1 356*
Hiiu	60	6	22	333	7	0	428
Ida-Viru	192	22	56	500	113	124	1 007
Jõgeva	175	104	66	46	25	3	418
Järva	138	93	50	43	24	1	352
Lääne	133	59	41	870	18	1	1 122
Lääne-Viru	207	137	100	1 001	45	7	1 497
Põlva	146	62	45	38	21	7	319
Pärnu	303	62	59	949	59	21	1 453
Rapla	182	44	53	52	25	0	356
Saare	171	34	73	1 887	23	0	2 188
Tartu	154	151	104	67	101	0	577*
Valga	138	50	41	36	23	1	289
Viljandi	238	115	62	77	37	3	532
Võru	155	41	66	40	25	2	329
Total	**2 599**	**1 035**	**988**	**6 500**	**900**	**200**	**12 222**

Table 10. *Alternative 2 - electricity generation from local renewable resources in GWh needed to meet the local demand*

	Wood	Straw	Biogas	Wind	Solar	Hydro	Total
Harju	208	54	149	561	355	29	1 356*
Hiiu	18	0	10	17	0	0	45
Ida-Viru	192	22	56	376	0	124	770
Jõgeva	57	0	33	43	0	3	136
Järva	66	0	25	41	26	1	159
Lääne	52	0	21	51	0	1	124
Lääne-Viru	100	0	100	114	0	7	321
Põlva	53	0	22	38	4	7	124
Pärnu	200	0	30	193	0	21	444
Rapla	65	0	27	52	8	0	151
Saare	64	0	36	69	0	0	169
Tartu	154	145	104	67	101	0	572*
Valga	62	0	21	36	18	1	137
Viljandi	106	0	31	77	19	3	236
Võru	64	0	33	40	20	2	159
Total	**1 458**	**221**	**699**	**1 776**	**551**	**200**	**4 904**

* - the electricity demand is not covered because of not enough of local resources.

Table 11. *Alternative 3 - electricity generation from renewable fuels in GWh needed to meet the local demand if wood is also transported to neighboring counties*

	Wood	Straw	Biogas	Wind	Solar	Hydro	Total
Harju	1 872	54	149	561	355	29	3 021*
Hiiu	3	6	22	15	0	0	45
Ida-Viru	330	22	56	238	0	124	770
Jõgeva	0	26	66	43	0	3	136
Järva	0	41	50	43	24	1	159
Lääne	0	28	41	54	0	1	124
Lääne-Viru	51	34	100	129	0	7	321
Põlva	0	28	45	38	7	7	124
Pärnu	94	62	59	208	0	21	444
Rapla	0	33	53	52	13	0	151
Saare	0	29	73	67	0	0	169
Tartu	146	151	104	67	101	0	569*
Valga	2	34	41	36	23	1	137
Viljandi	0	60	62	77	34	3	236
Võru	0	31	66	40	20	2	159
Total	**2 497**	**635**	**988**	**1 669**	**578**	**200**	**6 567**

Table 12. *Alternative 4 - electricity generation from renewable fuels in GWh if wind power is produced only in coastal areas*

	Wood	Straw	Biogas	Wind	Solar	Hydro	Total
Harju	1 872	54	149	561	355	29	3 021*
Hiiu	3	6	22	200	0	0	230
Ida-Viru	330	22	56	500	0	124	1 032
Jõgeva	15	52	66	0	0	3	136
Järva	20	70	50	0	0	1	141
Lääne	0	27	41	500	0	1	569
Lääne-Viru	51	34	100	600	0	7	792
Põlva	21	28	45	0	0	7	100
Pärnu	94	62	59	600	0	21	836
Rapla	15	34	53	0	0	0	102
Saare	0	29	73	539	0	0	641
Tartu	146	151	104	0	101	0	502*
Valga	25	33	41	0	13	1	113
Viljandi	24	67	62	0	18	3	174
Võru	0	31	66	0	13	2	111
Total	**2 615**	**697**	**988**	**3 500**	**500**	**200**	**8 500**

* - the electricity demand is not covered because of not enough of local resources.

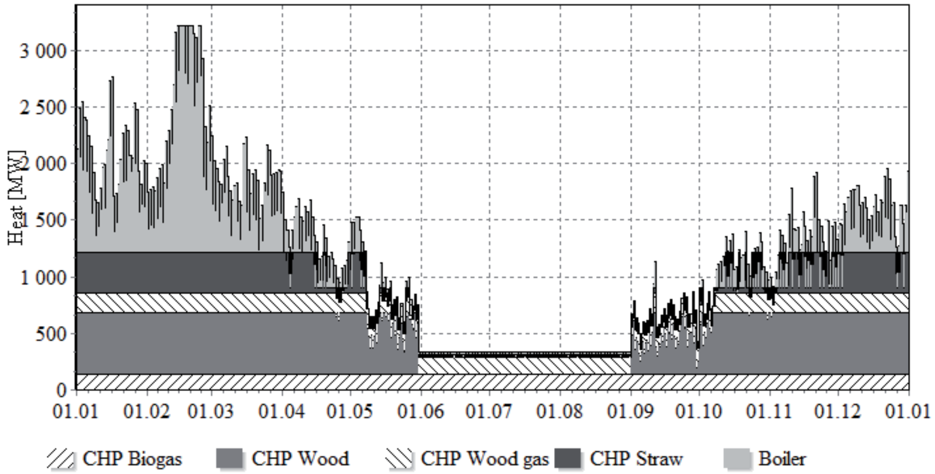

Figure 10. *Simulated annual heat production of CHP plants and boilers*

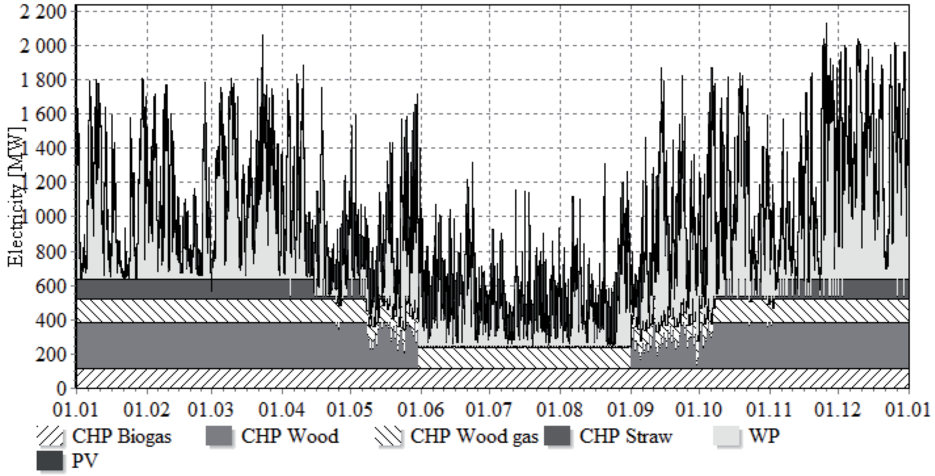

Figure 11. *Simulated annual electricity production of CHP plants, wind and solar power*

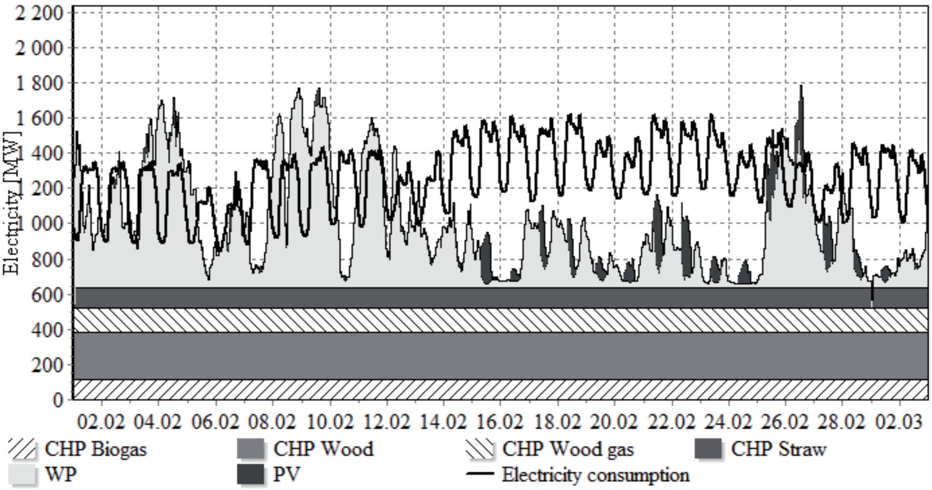

Figure 12. *Simulated electricity generation and consumption in February*

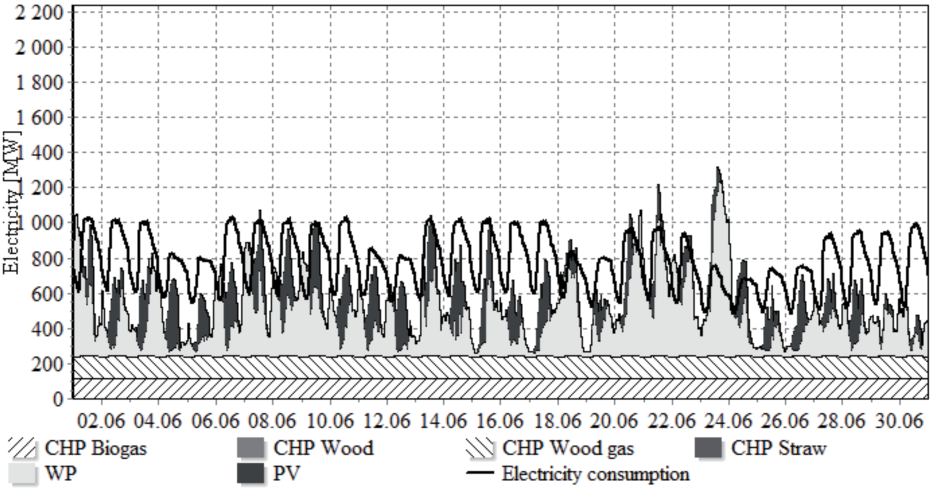

Figure 13. *Simulated electricity generation and consumption in June*

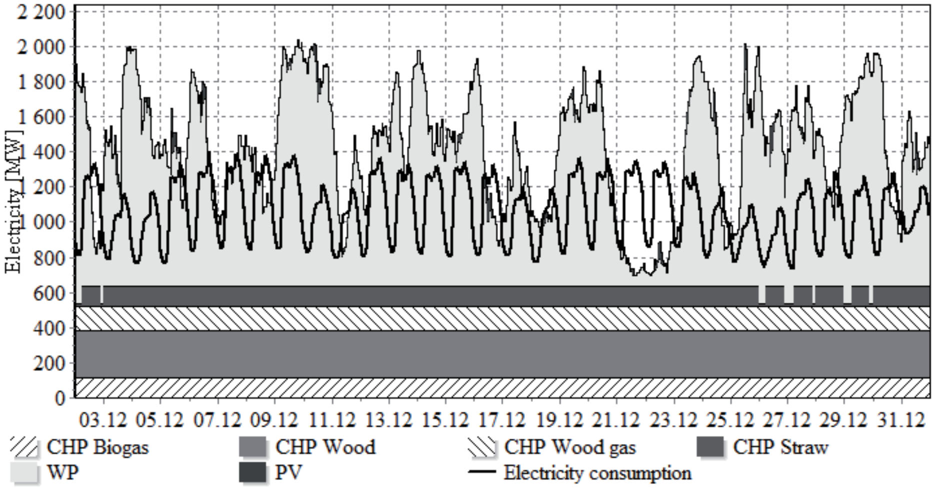

Figure 14. *Simulated electricity generation and consumption in December*

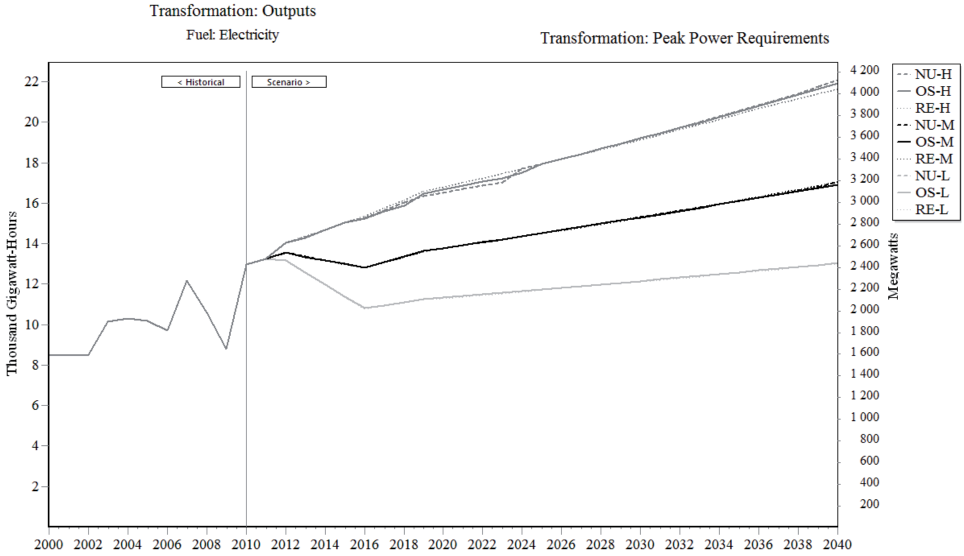

Figure 15. *Electricity demand and peak power requirements of different electricity consumption growth and export scenarios*

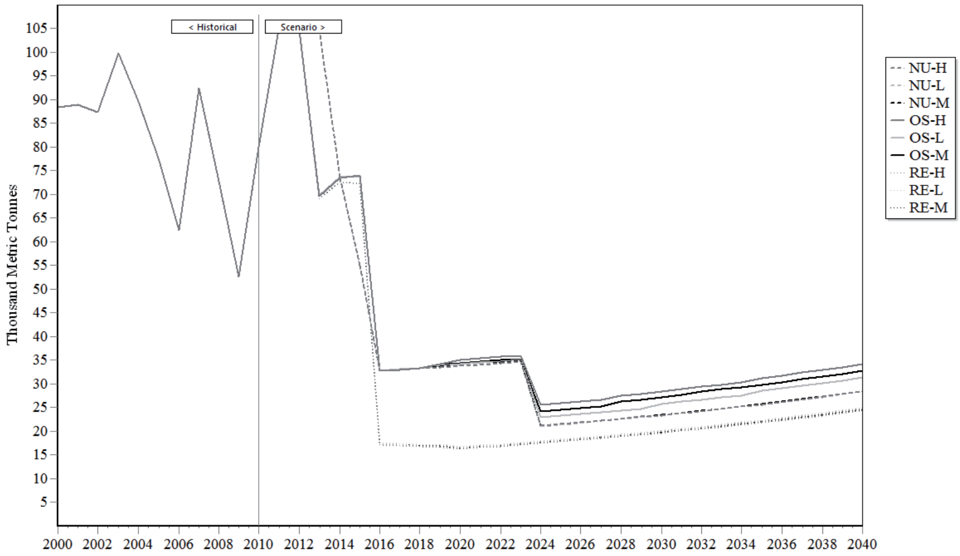

Figure 16. *The total SO_2 emissions of different electricity generation scenarios in thousand tons*

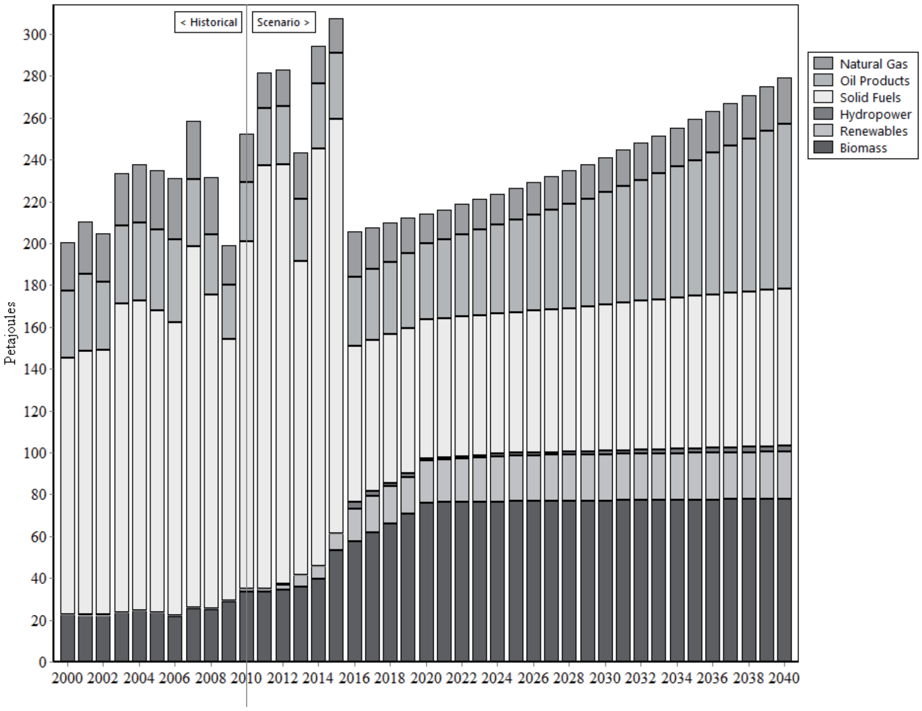

Figure 17. *Primary energy consumption of renewable electricity generation scenario with a medium demand growth in PJ.*

APPENDIX B – Appended author’s publications

Paper I

Kuhi-Thalfeldt, **R**., Valtin, J. The potential and optimal operation of distributed power generation in Estonia. Oil Shale, Vol. 28, No. 1S, 2011, Estonia, pp. 240-252.

Oil Shale, 2011, Vol. 28, No. 1S, pp. 240–252
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ISSN 0208-189X

THE POTENTIAL AND OPTIMAL OPERATION OF DISTRIBUTED POWER GENERATION IN ESTONIA

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Estonian electricity generation requires new investments due to limitations for emissions, deterioration of old power plants and growing electricity consumption. This could be the turning point for distributed generation (DG) in Estonia. DG would allow saving energy and reducing emissions due to more efficient fuel usage. Also the supply reliability and energy security would be increased through availability of local power generation. In this paper the definition and potential of DG in Estonia is estimated and the optimal operation criteria are examined. The possible effect of DG development on electricity price and emissions is assessed using LEAP software.

Introduction

The Estonian energy sector is one of the most CO_2-intensive sectors in European countries. As the CO_2 quotas and limits for emissions are becoming more and more tighten, there is a need for production capacities with low emissions. The old oil shale based production units will be closed after the year 2015 as their sulfur dioxide emissions do not comply with the EU directive requirements. This means that significant investments are required for building of new production capacities, which will probably result in higher electricity prices. Also energy saving issue is important aiming that electricity and heat should be produced using technology of higher efficiency and thereby saving primary energy. In quest for new production capacities DG could provide several advantages compared to classical, central power production.

In this paper the definition of DG is analyzed and its main features are brought up. As DG is defined differently depending on specifics of a country, it is necessary to introduce the definition of DG in Estonia. In order to assess the importance of DG in Estonia, the current production capacities are evaluated and divided to central and decentralized producers. When

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analyzing the possible consequences of DG development, it is essential to estimate the potential of DG until the year 2020. Modeling tool LEAP is used to appraise the effect of DG on Estonian electricity and heat generation. Also the influence of DG development on electricity price and CO_2 emissions is analyzed with this software.

It is essential that the possible outcomes of DG depend on different aims of optimal operation. Therefore three different optimal operation criteria are presented and described.

Definition of distributed generation

DG is often used in relation to the term smart grid, which is a modernized electricity network mainly allowing consumers to direct their consumption depending on electricity market price. These networks are also designed integrating local generation, like DG is. The term of DG, which is also called dispersed generation, embedded generation or decentralized generation is defined differently depending on specifics of a country. Some countries define it as production units connected to the distribution network. Others have limits for the production capacities or start from the principle that DG is power production using renewables [1].

Regardless of precise definition, the fundamental principle of DG is to produce electricity close to the point of consumption. The main features of DG are brought up in Table 1.

In the case of DG, the produced energy is supposed to be consumed within the distribution network. However, DG-s can feed back some of their generated electricity to the transmission network, if it exceeds the networks demand [1].

The size of DG units can be very different, which could be in some cases even up to 300 MW. By the production capacities the producers are classified as micro (<5 kW), small (5 kW-5 MW), medium (5 MW-50 MW) and large ones (50 MW-300 MW) [3].

DG comprises all kind of production technologies, and the assortment depends rather on availability of technology in required size. Possible equipments are gas and steam turbines, internal combustion engines, micro turbines, biomass gasification devices, wind turbines, small hydro power plants, photovoltaic panels, fuel cells and storage units. The choice of fuel

Table 1. **Main features of distributed generation [2]**

Purpose	Provide a source of active electric power
Location	Connected to the distribution network or on the customers site of the meter
Delivery area	Energy is mostly consumed within the distribution network
Size	From 1 W up to 300 MW
Technology	Wide variety
Fuels	Renewable as well as fossil

depends on what is locally available, like biomass, biogas, peat, household waste, natural gas wind, water, solar energy, etc. [2].

The advantages of DG are emission reductions and energy savings due to the use of high-efficient production units, such as those of cogeneration of heat and power (CHP), and the use of renewable fuels. DG allows using locally available fuels like biogas, landfill gas and biomass, which improves the independence from imported fuels (energy security). Also the network losses are reduced, power quality and supply reliability are improved. In addition DG could serve as a substitute for investments in transmission and distribution capacity [3].

Distributed generation in Estonia

Fixed electricity prices and investment supports for renewable electricity producers and small CHP plants have provided the essential assurance for investors to renovate the old hydro power plants and to build new wind parks and CHP plants. Also the opening of electricity market has provided producers a possibility to sell their electricity to the market and in addition to receive a subsidy. The short construction time and automated operation are great advantages compared to big power plants as well.

In Estonia DG could be defined as production units generating electricity close to the point of consumption. The connection point of producer is not relevant as long as the size is suitable to cover the local demand. In the case of cogeneration the production should take place at efficient cogeneration regime. All other producers are named as central producers.

In order to assess the importance of DG in Estonia it is necessary to define what kind of existing producers are central and which decentralized producers. Overview of one possible classification is presented in Table 2.

According to the transmission network operator Elering [4], the total installed capacity of all power producers in Estonia is currently about 2400 MW, of which over 2200 MW are central power plants. The generation capacity of DG in 2009 is 213 MW and it consists of small CHP plants, hydro power and wind power (WP) plants. The distributed CHP plants are

Table 2. **Electricity production capacity in Estonia in the year 2009**

	Installed capacity, MW
Oil shale power plants	2 068
Natural gas power plants	156
Total central producers	**2 224**
Distributed CHP plants	78
Hydro power plants	4
Wind power plants	131
Total distributed generation	**213**
Total installed capacity	**2 437**

using wood, peat, natural gas or biogas as a fuel. The electrical capacity of the biggest DG producers is 25 MW, which is the output of CHP plant using wood and peat. Smallest producers are probably small hydro and wind turbines with a capacity below 10 kW.

The potential of distributed generation in Estonia

The capacity of DG in Estonia has doubled during the last year, as in 2009 new CHP-s and wind turbines started operating. The importance of DG is expected to grow also in the nearest future as more plants will be built and some are already under construction. During the research the possible development of DG until the year 2020 was estimated taking into account the potential of cogeneration and availability of local fuels.

Lately interest for building wind parks and CHP plants has grown noticeably. It is expected that soon all the biggest towns and energy intensive industries will have their own CHP plant, which will all be DG sources. Also WP will have an important role in Estonian power generation.

In the next years many industrial consumers could set up their own CHP plant. With opening of electricity market the electricity price for industrial consumers has risen considerably. Also the expenditures on heating and hot water are increased. The required heat is currently often produced using electricity or from fossil fuels like shale oil, which is becoming more and more expensive. Thus by constructing a CHP plant the consumers could benefit from reduced expenditures on electricity as well as heat.

The potential of DG until the year 2020 is estimated to be 900 MW of electricity and 1060 MW of heat, which is specified in Table 3.

Most of DG electricity in 2020 would be produced from wood, natural gas and wind. The growth in the production capacities results from WP and CHP plants running on wood, natural gas, biogas or household waste. The biggest potential of DG is based on building CHP plants instead of boilers. The capacity of these plants could reach 300 MW of electricity and 600 MW of heat.

Table 3. **The available and potential capacity of distributed generation in Estonia**

Production capacity, MW	in 2009		in 2020	
	Electricity	Heat	Electricity	Heat
Wind	117	0	400	0
Wood and peat	68	178	225	685
Natural gas	20	22	196	258
Hydro	5	0	10	0
Biogas	3	3	45	45
Household waste	0	0	24	72
Total	**213**	**203**	**900**	**1060**

WP plants with a capacity of 400 MW are considered to be DG producers as it is assumed that their production is consumed in the same area. By the year 2020 the capacity of WP plants in Estonia will probably be more than that as there have been connection agreements settled for about 750 MW [4]. But only 400 MW of WP is counted DG as at a certain capacity the produced electricity cannot be consumed locally. All offshore WP plants are considered central production.

The availability of 900 MW of DG electricity generation capacities will clearly have an effect on the environmental emissions and on electricity price. The analysis is carried out using the LEAP software, which is a scenario-based energy-environment modeling tool, developed by Stockholm Environment Institute [5]. The model for Estonia's energy system was created in LEAP, and two electricity generation scenarios were designed (central and distributed scenario) based on predicted electricity production capacities until the year 2020.

For creating the Estonian energy system model, statistical data for the years 2000–2008 was inserted in LEAP. The production units for electricity and heat were created and their production was optimized to represent the real situation. Load curve for electricity and heat consumption was designed. A reference model was built, where the production from generating units is at the same level as the actual numbers in 2000–2008. Thereafter the development of energy consumption in 2009–2030 was predicted and for both scenarios changes in the production capacities (closing of plants and building of new ones) were made. The production capacities of DG were inserted based on data presented in Table 3. The software thereafter simulates the generation of these production units based on defined availability factors, type of production (base load, medium load or peak load producer) and other dispatch rules. The desirable outcomes like electricity and heat generation from different production units, CO_2 and SO_2 emissions etc. can be observed in LEAP' graphical as well as numerical results. In this paper some of the findings are presented, detailed information regarding the software, modeling assumptions and possible outcomes can be found in the article [6].

As DG in Estonia comprises electricity generation from renewable energy, therefore the national emission levels will be reduced. The overview of DG electricity generation and saved CO_2 emissions is presented in Fig. 1.

Based on analyzes in LEAP it is evident that the development of DG will reduce notably the CO_2 emissions from electricity and heat sector. As the CHP plants are replacing conventional power production as well as heat production from boilers, less primary energy is used to produce same amount of electricity and heat and less emissions are emitted. Thus DG will have an important role fulfilling the national target of reducing CO_2 emissions from energy sector by 5 million tons. As currently the energy sector emissions are 15.7 million tons [7], the development of DG would reduce the emissions by one third.

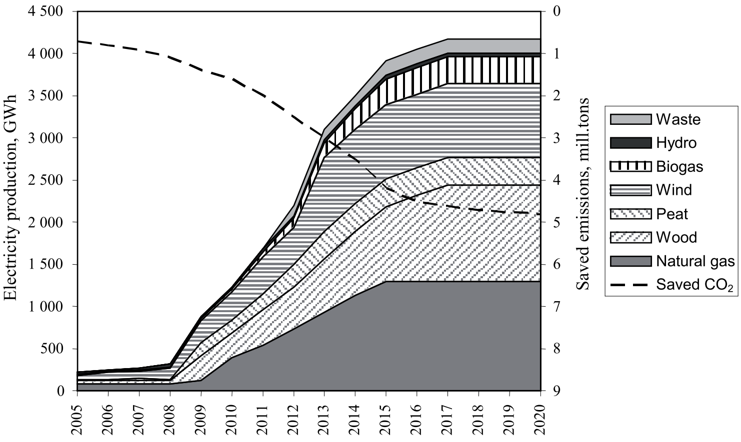

Fig. 1. Electricity generation of DG and saved CO_2 emissions.

In order to evaluate the role of DG in Estonian electricity and heat generation it is essential to examine the DG share in the total production. This can be carried out with LEAP model, as there is no statistical data available about DG in Estonia. In Fig. 2 the share of DG, CHP and renewable energy in gross electricity consumption (consumption + network losses) and the share of DG in gross heat consumption are visible. The figure represents generation only from DG producers. In addition there could be central power plants producing at cogeneration regime or using renewables.

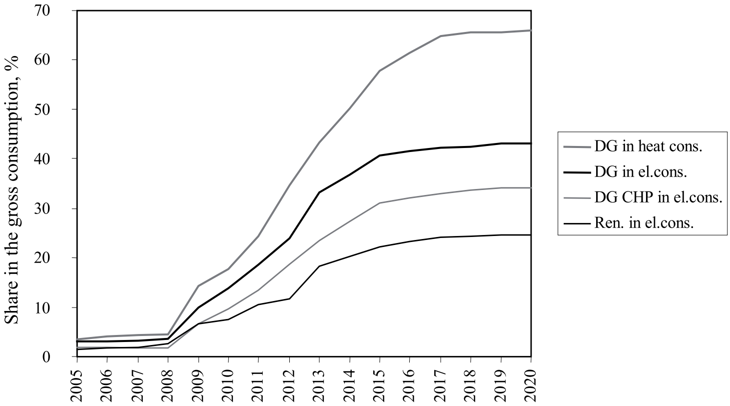

Fig. 2. The importance of distributed generation on the gross consumption.

In the year 2009 DG production was about 10% of the gross electricity and 15% of the heat consumption. In 2020 these shares could be correspondingly 40% and 65%. The goal of Estonian Long-term Electricity Sector Development Plan until 2018 is that 15% of the electricity gross consumption in 2015 be produced from renewable energy sources. Also in 2020 cogeneration should form 20% of the gross electricity consumption [7]. Currently these shares are about 6% and 10%, respectively [8]. The effect of DG is that in 2020 renewable energy sources would form 25% and cogeneration 35% of the gross electricity consumption. This means that DG is one important executor for meeting the goals of electricity sector development. Also it is seen in Fig. 2 that most of the heat will be produced in small distributed CHP plants. Therefore production from boiler houses will be reduced significantly as currently about one third of heat is produced using cogeneration.

Usually the capital costs per kW and also the production price of DG are relatively high compared to central power plants. Therefore Estonian government has introduced subsidies to guarantee the development of renewable electricity production. The subsidy depends on fuel and production technology. Producers generating electricity from renewable energy sources will receive a subsidy 54 €/MWh (84 s/kWh) [9]. In addition the producers get incomes from sale to the electricity market. For the WP plants there is a limit regarding the annual production, each year the subsidy is paid only until the national WP production reaches 600 GWh. Thereafter wind turbine owners get incomes only from electricity sale to the market. CHP plants using waste or peat as fuel receive a subsidy 32 €/MWh (50 s/kWh) [9]. The same subsidy is also paid to small CHP plants with an electrical capacity up to 10 MW using fossil fuels like natural gas.

The subsidy paid to DG is charged from the end-consumers as a fee for renewable energy. Therefore it is clear that the development of DG will affect the electricity price. This fee is calculated by the transmission network operator, and in 2010 it is 8 €/MWh (12.64 s/kWh) [10]. In Fig. 3 the

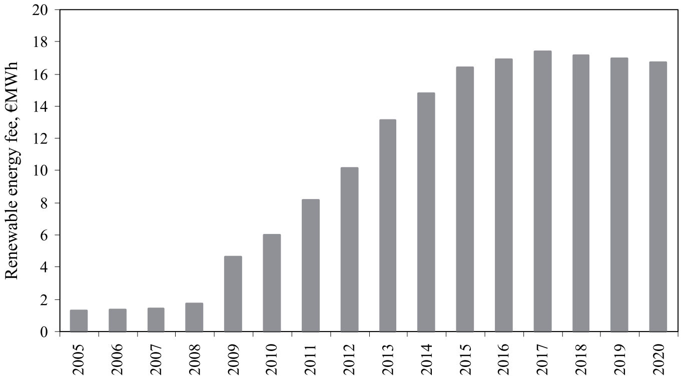

Fig. 3. Renewable energy fee (€/MWh).

renewable energy fee is shown, which is calculated only from DG production. This is only a part of the total fee as also some central producers receive subsidies. Calculations in LEAP showed that availability of 900 MW DG will raise the electricity price in 2020 by 17 €/MWh (26 s/kWh). But as according to Electricity Market Act the subsidies are paid only in the first twelve years of operation, the renewable energy fee will be actually reduced afterwards.

Optimal operation

There are different objectives how the DG plants could be operated. They can be used to cover a part or all of consumer's power demand. DG could be operated as a standby appliance to supply electricity during grid outages or as peak load provider for industrial consumers. In the open electricity market conditions they could be producing only when the market price is high.

It is assumed that DG is connected to a certain part of the energy system, which has a grid connection to the central production network. In this part of distribution network there is a demand for electricity and heat. The objectives of DG in this network are as follows:

- To maximize the profit of electricity and heat producers;
- To maximize the supply reliability and energy security;
- To minimize the environmental emissions.

The first criteria is an economical, a so called classical approach to energy planning. Usually the optimal dispatch problem is determination of power unit loads so that the cogeneration system production cost is minimized [11]. In the deregulated market there is usually a big public power company who owns all production units of a country. In this energy system the production between different power units can be optimized according to lowest production costs.

At the present day the electricity price is formed in open electricity market conditions. The market price is set up as supply and demand equilibrium through matching the offers from many generators to bids from consumers. All producers are now independent market participants and their production cannot be optimized according to lowest costs. Each individual producer is now aiming to maximize its profit.

The goal is to maximize the profit of all producers in the particular part of the energy system:

$$\max E = \sum_{i=1}^{n} E_i \tag{1}$$

It is assumed that all individual producers are maximizing their profits.

DG producers are specific market participants, as in addition to market price, the producer using renewable energy or efficient cogeneration will receive additional incomes from subsidies. Therefore, the aim of DG producers is to maximize the profit of electricity production taking into account the production costs, subsidies and electricity market price.

The electricity production profit of one DG producer i can be represented as follows:

$$E_i = \Sigma P_{gen,t} \cdot (H_t - C_t) \cdot \Delta t + \Sigma P_{gen,\,t} \cdot L_{\,t} \cdot \Delta t, \tag{2}$$

where $P_{gen,t}$ – net capacity at the time t,
H_t – electricity market price at the time t,
C_t – total production costs at the time t,
L_t – subsidies for a specific production type and fuel defined by government,
Δt – time period, where above mentioned variables are constant, usually one hour.

In certain cases, if the DG producer generates only for self-consumption, no electricity is sold to the market and only subsidy is received. Then the production profit can be calculated as follows:

$$E_i = \Sigma P_{gen,\,t} \cdot L_t \cdot \Delta t. \tag{3}$$

In this type of operation optimization it is possible to take into account the technical, supply reliability and environmental conditions as restrictions. For example the generation of wind turbines depends on wind speed. Also the electricity generation of CHP is restricted to heat demand. But if heat storage is available at the CHP plant, then it is also possible to produce electricity when the electricity price is high and not to produce when it is low [12].

Also the conditions when the DG producer is willing to produce are different. The typical central producer is willing to produce electricity whenever the market price is higher than its production cost.

$$C_t < H_t. \tag{4}$$

As the DG producers receive additional subsidy from its electricity generation, the producer is willing to sell electricity also in case the market price is lower than its production cost.

$$C_t - L_t < H_t. \tag{5}$$

For example if the producer generates electricity with wind turbines, he receives a subsidy 54 €/MWh [9]. If the production cost of this wind turbine is for example 53 €/MWh [13], the producer is willing to sell whenever the market pricis higher than 1 €/MWh. If the distributed CHP using wood has a production cost of 74 €/MWh [13] and receives the same subsidy, then the lowest favorable market price is 20 €/MWh. In Estonia electricity has been traded on spot market at NordPool Estonia area since 1 of April 2010. During the first six months of trading, the market price has been changing between 1.94 to 2000 €/MWh, with a daily average changing between 30 to 50 €/MWh [14]. This means that market price will be profitable for DG producers and they are interested producing most of the time.

The second objective of DG optimal operation is maximizing supply reliability, which means maximizing DG in the observed energy system. We can also speak about energy security if there are enough potential fuels in proximity to produce the required amount of energy.

Thus the optimization criterion at the specific area

$$\max P = \sum\nolimits_{i=1}^{n} P_{gen,i} \tag{6}$$

is subject to the boundary condition:

$$\sum\nolimits_{i=1}^{n} P_{gen,i} = \sum\nolimits_{j=1}^{m} P_{D,j} + \Delta P\,, \tag{7}$$

where $P_{gen,i}$ – electricity generation capacity,
P_D – electricity demand,
ΔP – network losses.

This means that DG should be optimized so that the production should meet the local demand at any given time. Therefore the aim is to locally minimize the shortfall and surplus of electricity.

In the network containing DG, it is possible to calculate the share of DG as follows:

$$k_{DG} = \frac{\sum\nolimits_{i=1}^{n} P_{gen,max}}{\sum\nolimits_{j=1}^{m} P_{D,jmax}}\,, \tag{8}$$

where k_{DG} – share of DG in the observed energy system,
$P_{gen,max}$ – available generation capacity of DG at the moment of maximum electricity demand,
$P_{D,j\,max}$ – maximum electricity demand.

Here the WP generation is not included in the DG, as the generation of wind turbines is unsteady and could not be available on the moment of the maximum demand. If considering also WP, the share of DG is:

$$k_{DG}^{*} = \frac{\sum\nolimits_{i=1}^{n} P_{gen,max} + \sum\nolimits_{k=1}^{l} P_{gen,WT}}{\sum\nolimits_{j=1}^{m} P_{D,jmax}}\,, \tag{9}$$

where k^{*}_{DG} – share of DG in the observed energy system considering also wind power,
$P_{gen,WT}$ – available generation capacity of wind power.

In the energy system without DG the value of k_{DG} equals 0. In certain cases the factor can also be greater than 1, which means that at this moment the DG production exceeds the consumption and the surplus will be exported. It is also possible to use distributed CHP for balancing the supply and demand in a system with fluctuating WP generation [14]. In that case the aim would be that the value of k_{DG} equals 1. CHP plants would then adjust their production taking into account the local electricity demand, network losses and WP generation. At hours when WP covers the whole electricity demand, the CHP plants avoid producing. Alternatively storage appliances could be used to store the surplus electricity.

The third aim of defining the optimal operation of DG is to minimize environmental emissions. Producers are interested in reducing emissions only if they could thereby save money. Therefore, the aim is to minimize the emission costs, which can be presented as follows:

$$\min B = \sum\nolimits_{l=1}^{p} B_l \cdot H_l , \tag{10}$$

where B_l – amount of emission,
H_l – price of emission.

This means, that energy should be produced by power units with lower emissions resulting in lower expenditures. These emissions could be CO_2, SO_2, NO_x, water, ashes, etc. Some emissions have a price, for example CO_2, which has a market price. Alternatively, the environmental taxes or charges can be used for emissions without a price. Also it is necessary to take into account that although some modes of operation have emissions, they are nevertheless counted as 0. This is the case of renewable energy, whose CO_2 emissions are not taken into consideration. As the most significant expenditures are made for CO_2 emissions, therefore according to this optimization principle, power units using renewable energy or fuels with low CO_2 emissions should be favored. Already now the expenditures for CO_2 form a considerable part of the production price of fossil power plants. DG has usually low or no CO_2 emissions, therefore their competitiveness will improve in the future, as the CO_2 price is expected to rise.

Conclusions

Distributed generation has currently a small importance in the Estonian electricity production, but opening of the electricity market, favorable feed-in tariffs, investment supports and rising prices of fossil fuels will favor further development of this kind of generation. It does not comprise only small production units generating for consumers own demand, but also wind turbines on land and CHP plants of a size up to 25 MW. In some countries the DG unit capacity could even reach 300 MW. The total electrical capacity of DG in Estonia is currently about 200 MW and their production could form about 10% of electricity consumption. This electricity is mainly produced from wood and wind power. By the year 2020 the capacity of DG in Estonia could reach 900 MW and it could cover 40% of consumption. The availability of DG will be one important means for meeting the targets of the electricity sector development. It will raise noticeably the share of renewable electricity and cogeneration in the electricity and heat production. The 900 MW of DG producers will reduce the CO_2 emissions from electricity sector by one third.

There are different objectives how the DG plants could be operated. In the open electricity market conditions, the DG plants are aiming to maximize their profit as in addition to market price, the producers will receive additional incomes from subsidies. These subsidies are proven to be so favorable that DG producers are interested in maximizing their production and generating most of the time. The subsidy is charged from the end-consumers as a fee for renewable electricity, which would be then doubled. The second optimization aims that the production from DG should meet the local demand at any given time. The objective is to locally minimize the shortfall and surplus of electricity. The third optimization targets minimizing environmental emissions, thus power units using renewable energy or fuels with low emissions should be favored.

The presented optimization conditions could be adapted in LEAP as dispatch rules. Further investigation should include additional simulations of these three particular cases in LEAP. Also sensitivity analysis regarding the effect of different optimal operation criteria on electricity price and emissions could be carried out.

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Influence of distributed generation development on national targets and electricity price in Estonia

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Abstract

Distributed generation has currently a small importance in the electricity generation, but opening of the electricity market, favorable feed-in tariffs, investment supports and rising prices of fossil fuels will favor further development of this kind of generation. In this paper the definition and potential of distributed generation is estimated and the influence on national targets and electricity price is evaluated. The analysis is carried out using the Long range Energy Alternatives Planning System (LEAP) software, which is suitable for elaborating different production scenarios and their impact on power balance and to the environment.

Keywords

Distributed generation, cogeneration, wind power, renewable energy, development plan, CO_2 emissions, LEAP.

Introduction

The term of distributed generation (DG), which is also called dispersed generation, embedded generation or decentralized generation is defined in several ways. Some countries define it as production units connected to the distribution network. Others have limits for the production capacities, which could be from 1 W to 30 MW, in some cases even up to 300 MW. Whereas others start from the principle that DG is production using renewables or production which is not centrally dispatched. [1]

The main aim of DG is to produce electricity close to the point of consumption. DG units could produce electricity for one house, commercial building, village, small city or industrial area. DG includes not only electricity generated from renewable energy sources (biomass, wind, water, solar, geothermal), but also cogeneration technologies such as gas turbines or reciprocating engines, and fuel cells. [2]

The advantages of DG are emission reductions and energy savings due to use of production units with high efficiency and use of local fuels. Thereby also the losses in the distribution network are reduced and power quality, supply reliability and independence from imported fuels are improved. [3]

In this paper, the DG is defined as production units generating electricity close to the point of consumption, which are not centrally dispatched. In case of cogeneration of heat and power (CHP) the production should be at efficient cogeneration regime. All other producers are named as central producers. The fuels considered as potential recourses for DG in Estonia are biomass (wood and wood processing residues), biogas (produced from animal manure, in landfills or sewage treatment plants), peat, household waste, natural gas, hydro power and wind power. The possible technologies are gas engines (running either on natural gas or biogas), steam turbines (for biomass), wind turbines and hydro turbines.

The total installed capacity of all power producers in Estonia is currently about 2400 MW and overview of generation units in 2008 an 2009 is presented on Table 1. The production capacities are divided into two parts – central and distributed producers.

Table 1. Electricity production capacity in 2008 and 2009 [4, 5]

Installed capacity, MW	**2008**	**2009**
Eesti and Balti PP	2 000	2 000
Other oil-shale based PP	96	96
Iru PP	94	94
Total central producers	**2 190**	**2 190**
Distributed CHP plants	38	90
Hydro power	5	5
Wind power	65	117
Total distributed generation	**108**	**212**
Total installed capacity	**2 298**	**2 402**

Table 1 shows that the capacity of central producers in 2009 is 2190 MW and distributed producers 212 MW.

Eesti power plant (PP) is considered as central producer, as it is a condensing power plant located near to the oil shale mining and is producing 75% of the total electricity production in Estonia. In spite of the fact that Balti and Iru PP produce at the cogeneration regime to meet the local demand (like DG units) they are considered as central producers, because of being centrally dispatched. Also other power plants using oil shale, shale oil or oil shale gas with a total capacity of 96 MW are not DG units though they are not centrally dispatched and their production is locally consumed. They are excluded due to use of generation with a low efficiency.

The generation capacity of DG consists of distributed CHP plants, hydro power and wind power. The capacity of DG has doubled during the last year from 108 MW to 212 MW, as in 2009 new CHP-s and wind turbines started operating. As there is no statistical data available in the level of each producer, therefore it is possible only to estimate the share of DG in the Estonia's electricity production. In 2008 it was about 3% of the total production and in 2009 it will be about 7%.

The new CHP-is in Väo (25 MW) and in Tartu (25 MW) are using biomass (wood and peat) and Viljandi CHP (2 MW) is using natural gas.

The existing wind turbines are considered as DG producers as it is assumed that the electricity is consumed in the same area, as the wind turbines are located in the coastline where no other production units are currently available. Also the production of wind turbines is not centrally dispatched.

1 Development of electricity sector

The Estonian electricity sector will face great changes regarding the production capacities. The old oil shale based production units will be closed after the year 2015 as their sulfur dioxide emissions don't comply with the EU directive requirements. This means that 70% of generation capacity will be out of operation. In addition to DG units, only Iru PP and two new oil shale fuelled power units with a capacity of 430 MW will remain in operation. [4]

In February 2009 Estonian government adopted a new Long-term Electricity Sector Development Plan until 2018, which sets several targets and indicators regarding the production, transmission and consumption of electricity.

The most important indicators of the development plan are that [6]:

1. 5,1% of the electricity gross consumption (consumption + network losses) in 2010 and 15% in 2015 should be produced from renewable energy sources.
2. 20% of the electricity gross consumption in 2020 should be produced using cogeneration.
3. The share of oil shale in the gross electricity generation (including own consumption by PP) in 2018 should be lower than 70%.
4. CO_2 emissions from electricity sector in 2020 should be lower than 5 million tons annually.

In 2008 2,3% of electricity gross consumption was produced from renewables, 10,7% using cogeneration and oil shale had a share of 94% in the electricity gross generation [7]. The CO_2 emissions from combustion of fuels in 2007 were 18,4 million tons [7], of which 15,7 million tons [6] are originating from the electricity sector.

The development plan brings out great changes regarding the production capacity in Estonia and foresees several investments in the next 10-15 years. The development plan presents in detail one scenario of development of electricity production in Estonia. This scenario was chosen out from several alternatives and is also the basis of central production scenario of this paper. The scenario presented in the development plan recommends building of following production capacities [6]:

1. Renovation of two energy units in Narva PP with a total capacity of 600 MW by the year 2015.
2. Fitting 4 old energy units in Eesti PP with sulfur and nitrogen capture appliances by the year 2012 (with a total capacity 658 MW), which will be in operation until the year 2017.
3. Capacity of wind turbines should reach 900 MW in 2018, of which 400 MW is on land and 500 MW offshore.
4. For regulating purpose of wind production there should be equal capacities of gas turbines operating and in 2018 it would reach 900 MW.
5. The capacity of reserve units should be 900 MW, which are also gas turbines.
6. 600 MW nuclear power plant could start operating in 2023.

This means that significant investments are required for building of new production capacities. The aim is that the total capacity of production units would rise from current 2400 MW to 3600 MW in 2025 (excluding the capacity of wind power). This will have a great influence on the electricity price, which could turn some of currently economically not feasible DG projects into beneficial ones.

2 The potential of distributed generation

The development plan also foresees that the capacity of CHP plants should reach 300 MW and the new cogeneration plants should use mainly biomass as a fuel. But it does not specify the location or the size of these possible plants. Different studies have estimated the potential capacity of new cogeneration plants from 100 to 397 MW [5] of electricity. In this study the possible development of DG cogeneration plants until the year 2030 is estimated according to following assumptions:

1. Capacity of existing CHP plants
2. Capacity of CHP plants replacing the old oil-shale fired plants.
3. Capacity of CHP plants built instead of a boiler.

Based on analyzed data the total potential of DG using cogeneration is estimated to be 490 MW of electricity and 1060 MW of heat, which is specified in Table 2.

The capacity of existing DG CHP-s is 90 MW of electricity and 203 MW of heat. The total capacity of DG replacing the old CHP-s is 100 MW of electricity and 258 MW of heat. The plants that are already in construction or which building is decided are Ahtme CHP on wood and peat and Iru waste burning CHP [4].

Table 2. The potential of distributed generation using cogeneration

Electrical capacity, MW	Existing in 2009	Replacing old CHP-s		Instead boilers		Total
		Planned	New	Planned	New	
Natural gas	20	0	33	2	141	196
Biogas	3	0	0	7	36	45
Wood/peat	68	25	25	25	82	225
Waste	0	17	0	0	7	24
Total electrical capacity	**90**	**42**	**58**	**34**	**266**	**490**
Thermal capacity, MW						
Natural gas	22	0	93	2	141	258
Biogas	3	0	0	7	36	46
Wood/peat	178	50	65	65	328	686
Waste	0	50	0	0	22	72
Total thermal capacity	**203**	**100**	**158**	**74**	**527**	**1060**

The biggest growth in the production capacities are based on new CHP-s instead of boilers. In the year 2008 there were 4053 boilers installed in Estonia with a total capacity of 5565 MW. These boilers generated 5851 GWh of heat, of which 53% was produced from natural gas, 25% from wood, 9% from shale oil, 7% from peat and 5% from light fuel oil. [7]

All other fuels like heavy fuel oil, coal, oil shale gas, biogas, vegetable biomass and electricity have a share below 1% in total. 37% of heat was produced in boilers with a capacity from 5 to 20 MW, 29% in boilers from 1 to 5 MW and 21% below 1 MW. The boilers with a capacity above 20 MW produced 13% of heat. [7]

The potential capacity of DG CHP-s instead of boilers is 300 MW of electricity and 600 MW of heat. These plants are fuelled mainly with natural gas or biomass (wood or peat), but also biogas and waste have role there. The potential production from these plants is about 1900 GWh of electricity and 3900 GWh of heat, which corresponds to 6500 full load working hours annually. The estimation of capacity of CHP-s is based on meeting the base load heat consumption. In summer the CHP would run on minimum load, but during the heating period it would allow them to run on full load. In the peak load hours of coldest days the additional heat demand would be produced in the boilers. This will guarantee the efficient operation of the CHP plant. [8]

The plants that are already in construction or which building is decided are Tabasalu CHP [9] on natural gas, Tallinn Landfill CHP [10] and Aravete, Ilmatsalu, Oisu, Vinni CHP-s [11] on biogas and Pärnu CHP [4] on wood and peat.

All the 400 MW wind turbines located on land foreseen in the development plan are considered as DG. Offshore wind parks are considered as central producers. No changes regarding the capacity of hydro power plants and no other types of additional electricity production are foreseen in this study.

When including also the wind power and hydro power, then the total potential of DG in Estonia is 895 MW of electricity.

3 LEAP model

The aim of the study is to evaluate the share of renewable energy sources and the use of cogeneration in case of two electricity generation scenarios – central and distributed generation. As the emissions have an importance in the development of this sector, also CO_2 emissions are observed. The electricity generation from DG producers is bought according to the electricity market act with feed-in tariffs. These costs are paid by the end-consumers and therefore it is also very essential to analyze how much the development of DG will affect the electricity price. The analysis is carried out using the LEAP model and a model of Estonian energy sector is created.

LEAP is a scenario-based energy-environment modeling tool, which is suitable for analyzing energy consumption, production and emissions in all sectors of economy. It can be used to account for both energy sector and non-energy sector greenhouse gas emissions. It can be used to create models of different energy systems, where each requires its own unique data structures. LEAP supports a wide range of different modeling methodologies: on the demand side these range from bottom-up, end-use accounting techniques to top-down macroeconomic modeling. On the supply side, LEAP provides a range of accounting and simulation methodologies for modeling electricity generation and capacity expansion planning. [12]

For creating the Estonian energy system model, statistical data for the years 2000-2008 was inserted in LEAP [7]. The production units for electricity and heat were created and their production was optimized to represent the real situation. This means that a reference model was built, where the production from generating units would be at the same level as the actual numbers in 2000-2008. Thereafter the development of energy consumption in 2009 – 2030 was predicted and for both scenarios changes in the production capacities (closing of plants and building of new ones) were made.

The main assumptions of the work:

1. The planning period is from 2000-2030, where 2000-2008 is based on historical data and from 2009 the data is either predicted by LEAP based on historical numbers or is user-defined as changes in the production capacities, building of new plants, etc.
2. The electricity consumption is growing based on gross domestic product (GDP) and elasticity coefficient 0,3. This means that electricity consumption increases annually between 0,9 to 1,5%.
3. The heat consumption is assumed to be at the same level as it was in 2008.
4. The evaluation is given only on emissions from electricity and heat production sectors.
5. The emission coefficients are taken from LEAP-s database.
6. Electricity export is assumed to be at the same level as it is been in years 2000 to 2008.
7. Distribution and transmission losses are assumed to be in the same level as in 2008.

The two electricity production scenarios were constructed in LEAP based on above described data and building of new plants and closing of old ones was simulated. The first scenario, called as Scenario DG, represents the central electricity production. Second scenario, named Scenario DG, visualizing the effect of distributed generation. The overview of production capacities in 2030 of both scenarios is presented in Table 3.

Table 3. Electricity production capacity in 2030

Electrical capacity, MW	**CG**	**DG**
Gas turbine	1800	1800
Oil Shale CFB	1030	1030
Nuclear	600	600
Wind offshore	500	500
Natural Gas	94	94
Wood CFB	43	43
Total central producers	**4067**	**4067**
DG Wind	400	400
DG Natural Gas	20	196
DG Wood	44	175
DG Peat	24	50
DG Biogas	3	45
DG Waste	0	24
DG Hydro	5	5
Total distrib. producers	**495**	**895**
Total	**4562**	**4959**

In the Scenario CG it is assumed that building of new production capacity will be as described in Long-term Electricity Sector Development Plan until 2018, which was presented in the section 1. In addition it was included that starting from 2010 in two renovated energy units in Narva PP 10% of wood is burned together with oil shale [9]. In 2030 the total electricity production capacity of Scenario CG is 4562 MW, of which 4067 MW are central producers and 495 MW distributed producers.

In the Scenario DG it is assumed that new CHP plants would be built based on assumptions given in Table 2. This means addition of CHP plants with 400 MW electrical capacities. The total electricity production capacity of Scenario DG is 4959 MW, of which 4067 MW are central producers and 895 MW distributed producers.

4 Results of the study

The electricity generation of Scenario CG is presented in Figure 1 and for Scenario DG on Figure 2.

From Figure 1 it is seen, that in case of Scenario CG the future fuel mix of electricity generation is rather different from the current one. Today about 94% of electricity is produced from oil shale, shale oil and oil shale gas, 4% from natural gas and 2% from renewables. Whereas in 2030 only 45% of electricity is produced from oil shale, 28% is nuclear power, 15% is wind power, 10% of natural gas and 2% of other renewable sources (excluding wind power). When comparing the Figure 1 with Figure 2 it is visible, that the further development of distributed generation will reduce the share of oil shale even more. In case of Scenario DG the share of oil shale in 2030 is reduced to 24% of the power generation, nuclear power forms still 28% and wind power 15%. But the share of natural gas is increased to 18% of the total production, peat forms 2% and other renewable sources (mainly wood, but also biogas and waste) have a share of 12%.

Another important issue is the heat production from CHP plants, of which a short summary is visible on Table 4.

Table 4. Heat production in 2008 and 2030

Heat production, GWh	2008	2030	
		CG	DG
CHP	3391	911	6448
Boiler	5849	8329	2792
Share of CHP	37%	10%	70%
Total	9240	9240	9240

From the Table 4 it is seen, that in 2008 total heat production was 9240 GWh, of which 37% was produced using cogeneration and the rest was produced by boilers [7]. In case of Scenario CG the heat production from CHP will decrease annually until in 2030 it forms only 10% of the total heat production. The reason for reduction is that currently 50% of the heat generation in CHP plants is produced from oil shale, shale oil or oil shale gas. As all these plants are old and don’t comply with emission requirements, they will be closed in 2015.

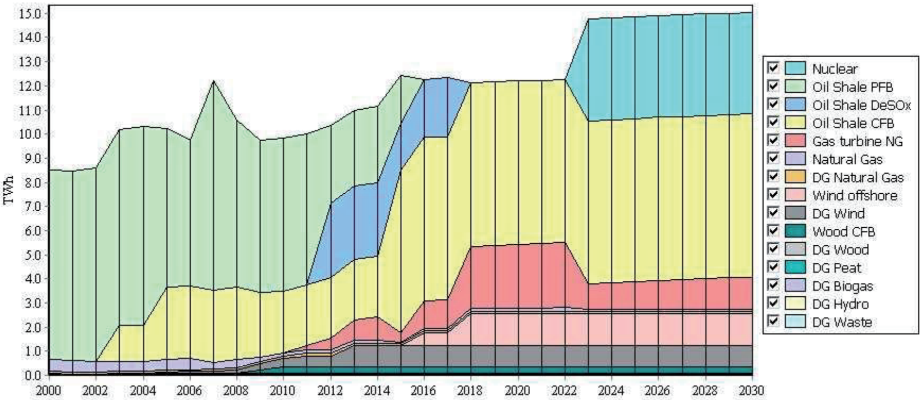

Fig. 1. Electricity generation in TWh of central generation scenario

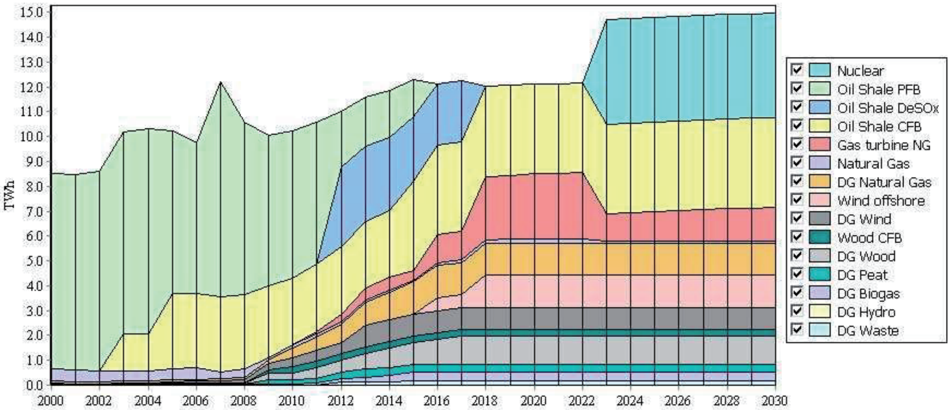

Fig. 2. Electricity generation in TWh of distributed generation scenario

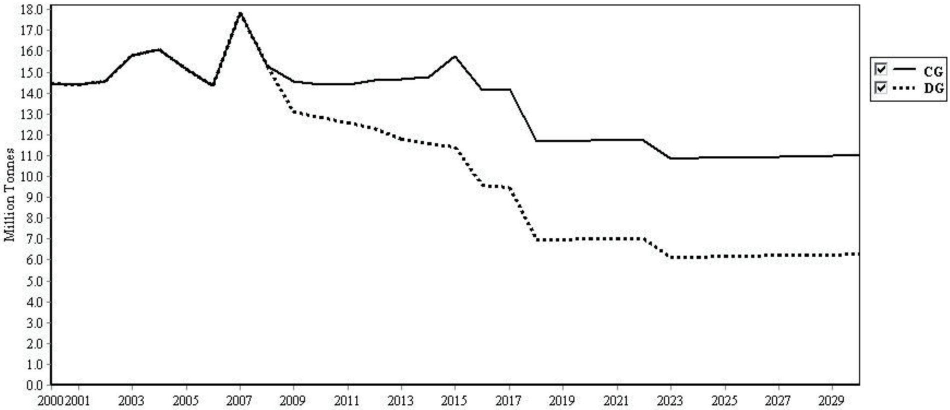

Fig. 3. CO_2 emissions from electricity and heat generation in million tons

But no new cogeneration units will be built in this scenario. Also the production from natural gas fired CHP-s will be reduced. Meanwhile the heat consumption is assumed to stay at the same level during the whole period.

The heat production of Scenario DG is rather different as the share of cogeneration in the total heat production will reach 70% in 2030. About 90% of heat produced by CHP will be generated by DG plants. This will mean that 50% of the boilers heat production is now replaced with CHP plants.

As the development of DG will affect also the heat production, therefore the reduction of CO_2 emissions should be assessed from total emissions from electricity and heat production. From Figure 3 it is seen that the total emissions from electricity and heat production have recently increased to 18 million tons. Due to closing down of production units with low efficiency and high pollution level the total emissions of Scenario CG will be reduced to 11 million tons in 2023. The development of DG will reduce the CO_2 emissions even more, so that in 2023 they will be only 6 million tons, which means a reduction about 3 times.

The task of this paper was to assess the effect of DG development on national targets, which can be evaluated based on Table 5.

Table 5. Fulfillment of national targets

	Target	CG	DG
Renewables in electricity gross consumption			
in 2010	>5.1%	7%	10%
in 2015	>10%	13%	25%
Cogeneration in electricity gross consumption			
in 2020	>20%	9%	40%
Oil shale in the electricity generation			
in 2018	<70%	56%	30%
CO_2 emissions from electricity sector			
in 2020	<5 million tons	9 million tons	5 million tons

Table 5 justifies, that both scenarios meet the targets for share of renewables in electricity gross consumption and share of oil shale in the electricity production. Actually the Scenario DG meets all the presented targets. But in the Scenario CG the share of cogeneration in electricity consumption will be lower and CO_2 emissions from electricity sector higher than the requested level.

Second important task was to appraise the influence of DG on electricity price.

The producers of renewable electricity and CHP-s using efficient cogeneration are receiving a feed-in tariff for their produced electricity, which according to the Electricity Market Act is currently:

- 115 s/kWh (74 €/MWh) for electricity produced from renewable energy sources. This price is received when the electricity is sold to the transmission network operator. Alternatively they could receive a subsidy of 84 s/kWh (54 €/MWh) and to receive additional incomes from sale to the electricity market. For the wind mills there is a limitation regarding the annual production – the fixed price is paid only until the national wind power production is 200 GWh, where after the producer could receive a subsidy until 400 GWh is reached.
- 81 s/kWh (52 €/MWh) for electricity produced by efficient CHP plants using waste, peat or oil shale gas as a fuel or CHP plants built instead of a boiler house with a maximum electrical capacity of 10 MW. Also these producers can choose an alternative receiving a subsidy 50 s/kWh (32 €/MWh).

The price difference between the fixed tariff and subsidy is 31 s/kWh (20 €t/MWh), which is lower than the production price of oil shale fired power plants (46,01 s/kWh = 29 €/MWh). Therefore producers prefer receiving the subsidy and selling their electricity to the eligible consumers.

The costs of these feed in tariffs are paid by the electricity consumers, which are represented as a separate fee for renewable electricity on the electricity bill. Based on simulated electricity production of two scenarios in LEAP it is possible to calculate the renewable electricity fee until the year 2030, which is visualized on Figure 4.

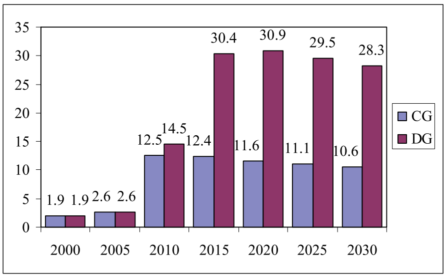

Fig. 4. Renewable electricity fee in s/kWh

Figure 4 demonstrates the effect of DG development on electricity price. In case of Scenario CG the calculated renewable electricity fee in 2010 is 12,5 s/kWh (8 €/MWh), which will be reduced to 10,6 s/kWh (6 €/MWh)in 2030. The reduction of the fee is seen, because no new CHP-s are built and in spite that the wind power is increased to 900 MW, the producers will receive the subsidy until national production reaches 400 GWh. This corresponds to wind power generation capacity of 160 MW.

The renewable electricity fee of Scenario DG is 14,5 s/kWh (0,9 € cent/kWh) in 2010, 30,9 s/kWh (20 €/MWh) in 2020 and 28,3 s/kWh (18 €/MWh) in 2030. The renewable electricity fee is in reality calculated by the transmission network operator and it will actually be 12,64 s/kWh (18 €/MWh) in 2010, which is quite close to the CG scenario. This means, that adding of 400 MW DG CHP plants will guarantee the fulfillment of national targets, but the electricity price will raise about 18 s/kWh (11€/MWh).

5 Conclusions

Model for Estonia's energy system was created in LEAP software and two electricity generation scenarios were designed based on predicted electricity production capacities until the year 2030. The potential of distributed generation was estimated based on new CHP plants built instead of old power plants or boilers. The electricity and heat generation, share of renewable energy and cogeneration in electricity consumption, CO_2 emissions of these scenarios were presented and analyzed in this study. Also the calculated addition to electricity prices due to use of distributed generation was given.

Currently the capacity of distributed generation is about 200 MW of electricity and its share in the total power generation is 7%. The capacity has doubled during the last year and is expected to grow also in the nearest future as more plants will be built and some are already under construction. The total potential of distributed generation is estimated to reach 895 MW, of which 490 MW are cogeneration plants, 400 MW wind turbines and 5 MW hydro power. Annual electricity production of these plants would be 5500 GWh and heat production 7000 GWh, which would form about 35% of the electricity generation and 70% of the heat production. The share of renewable energy sources in the gross electricity consumption would rise from today's 2,3% to 25% in 2015 and share of cogeneration from 10,7% to 40% in 2020.

Based on analyzed CO_2 emissions from electricity and heat sector, it is evident that the development of distributed generation will reduce the emissions three times. Distributed generation will have an important role fulfilling the national target of reducing CO_2 emissions from electricity sector from current 15,7 million tons to 5 million tons in 2020. Whereas the central generation scenario showed that not all national targets will be met.

The distributed producers will receive a feed-in tariff for their produced electricity, which will be paid by the electricity consumers as a fee for renewable electricity. Calculations showed that the electricity price will raise about 18 s/kWh (11€/MWh) when 400 MW CHP plants will be installed. Distributed generation will add variety into the power generation capacities, diversify the fuel mix of electricity generation and reduce dependence on oil shale.

Acknowledgements

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Paper III

Kuhi-Thalfeldt, R., Valtin, J. Combined heat and power plants balancing wind power. Oil Shale, Vol. 26, No. 3 Special, 2009, Estonia, pp. 294-308.

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COMBINED HEAT AND POWER PLANTS BALANCING WIND POWER

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Wind power (WP) is the most developing area in the Estonian renewable energy sector, but there are technical limitations on its integration. At a certain capacity some balancing measures are required to handle large amounts of WP. This could be achieved by introducing combined heat and power plants (CHP) at regional level. The use of gas engine allows quick response to load changes and therefore is suitable for regulating activities. As for principles of distributed power generation, the aim is to locally minimise the shortfall and surplus of electricity. By this additional costs of rebuilding power lines and building new balancing generation units can be avoided. In this paper possibility of balancing WP with CHP is analysed. The investigation is carried out with the help of energyPRO software, which allows simulating the cooperation of WP and CHP. Also the essence of building heat storage is analysed, to add flexibility into the plant operation.

Introduction

The wind resources in Estonia are excellent, but there are different technical limitations on their utilization, such as transmission capacity bounds of electrical network and lack of regulating reserves to compensate the fluctuations in wind power [1]. WP has currently only a small share in Estonian electricity production. In the year 2007, 91 GWh electricity was generated by wind turbines corresponding to 0.7% of electricity production [2]. WP will have a bigger importance in the future as there are several hundred MW projects under development. The total capacity of planned wind power projects in Estonia reaches 4000 MW, which is more than two times higher than the maximum consumption of the whole country. Most probably all these projects will not be implemented, but at least 200 MW by 2010 and 400 MW by 2012 will be in operation. As there are no fast start-up

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production capacities in Estonia, some balancing measures are necessary if the capacity of WP exceeds 200 MW. [3]

Currently the Estonian electricity network is not suitable for large-scale integration of WP. The best wind resources can be found along the coastline and on islands, but the electric grids in these areas are very weak and cannot transmit large amounts of electricity. Another problem related to WP is its unpredictability. Wind energy is a fluctuating weather-dependent energy source where wind speed varies rapidly and frequently within wide range. This will have an influence to production as power output from WP is a function of the wind speed in the third power [1]. A wind power plant must foresee its power generation. The accuracy of wind power generation forecast models currently available allows predicting the WP production up to 72 hours ahead with preciseness between 10 and 20% [4]. There are many options for balancing the WP, like using hydro power plants, gas turbines, gas engines, condensation power plants, connections to neighbouring countries etc. In this paper the focus is on small-scale CHP plant operation for balancing the supply and demand in a system with fluctuating WP generation.

Cogeneration plants are commonly found in Estonian district-heating systems of bigger towns, department stores, paper mills, wastewater treatment plants and industrial plants with large heating needs. In the year 2007, 869 GWh of electricity and 2777 GWh of heat was produced using cogeneration, corresponding to 7.1% of electricity and 27.4% of heat production [2]. The whole potential for cogeneration is not utilized in Estonia. According to the long-term development plans 20% of electricity production would come from CHP-s by the end of 2020. Currently many new CHP plants are planned and some of them are already under construction. By the year 2011 three new CHP-s will start operating with capacity of 75 MW of electricity and 150 MW of heat [3].

The use of CHP plants balancing the WP production supports the principles of distributed generation. Distributed generation (also decentralised generation) comprises all generation installations that are connected to the distribution network and are based on the use of renewable energy sources or technologies for CHP with a maximum size of approximately 10 MW of electricity. This means that electricity is generated close to the point of use to match the load requirement of the customer reducing the necessity to build power lines and improving the reliability of the power supply [5].

The operation of CHP according to the availability of WP is complicated, as it is necessary to take into account the heat consumption. A normal operation of a CHP plant is determined by thermal load. In the case of balancing activities, CHP plants would produce within these hours when electricity is needed *i.e.* at low WP production. At hours when WP covers the electricity demand, the CHP plant avoids producing, and heat demand could be covered through the use of boilers. Additionally, if heat storage is applied, heat produced by CHP could either be used to cover the demand directly or be stored and used later on [6].

Modeling the operation of wind turbines and CHP plant

The aim of the study is to investigate at which level a CHP plant could compensate the fluctuating WP and how it would affect the operation of the CHP plant. Also the essence of building heat storage is analysed, to add flexibility into the plant operation.

The key assumptions are summarized in Table 1.

Table 1. **Key assumptions**

Temperature	Daily temperature data of Estonia
Heat demand	Annual demand 27.5 GWh 70% temperature-dependent from September to May Reference temperature 15 °C Daytime demand/night-time demand 10/6
Electricity demand	Annual demand 25.0 GWh 50% temperature-dependent Reference temperature 25 °C Daytime demand/peak/night-time demand 11/12/9
Production units:	
Wind park	Annual production 42.8 GWh , different shares are used
Gas engine	Electrical capacity 3.0 MW Thermal capacity 3.0 MW Minimum load 30%
Boiler	Thermal capacity 10.0 MW
Fuel	Natural gas Heat value 9.35 kWh/Nm3
Thermal store	Capacity 50 m^3 – 500 m^3, different capacities are used Temperature difference 30 °C Utilization 90%
Planning period	1 year

The investigation is based on the example of Pakri wind park. The park consists of 8 Nordex N-90 wind turbines with a capacity of 2.3 MW each. The total capacity of the park is 18.4 MW and is currently the second largest in Estonia. Eight wind turbines situated in the coastline, 52 km west of Tallinn, began to operate in spring 2005 [7]. Pakri wind park was chosen as an example, as hourly production data for the year 2006 was available for this site. The production during the year 2006 was 42.8 GWh.

The aim of local CHP-s compensating WP production is to avoid additional costs of rebuilding power lines and building new generation units performing balancing. Typically a weak electricity grid in areas with best wind resources would require extensive investments, which could be thereby avoided or reduced. For the investigation purpose it is therefore assumed that, due to limited capacity of power lines, the system operator requires balancing activities to reduce the need for transmitting large quantities of wind power to the transmission network.

The balance in Estonia's electricity system is currently regulated by oil-shale power plants, which are not designed for that purpose [4]. Therefore the system operator is planning to build a new gas turbine for balancing activities [3]. This investment could be avoided or postponed if these duties would be carried out by local CHP-s. Therefore, second assumption is that the balancing activities will be carried out by an existing small-scale CHP plant, situated in the same distribution network as the wind park.

As there is currently no CHP-s near Pakri wind park, it was taken as an example that the balancing CHP could be placed in Paldiski as it is the nearest town to Pakri wind park. In Paldiski, there are approximately 4200 inhabitants who live mainly in apartment houses and consume district heating. Additionally there are some industrial consumers nearby like harbour, saw mill, etc, of which some are not connected to the district heating network, but could be possible electricity consumers [8]. The annual heat demand is approximately 27.5 GWh, and electricity consumption is estimated to be 25.0 GWh. It is assumed that Paldiski would have an existing cogeneration unit, which would be used to balance locally the WP. Based on estimated electricity and heat demand, the optimal size of CHP would be a Jenbacher gas engine with a capacity of 3.0 MW electricity and 3.0 MW of heat. For heat production, there is a boiler with a thermal output of 10.0 MW. It is assumed that the plant uses natural gas as a fuel, which used in gas engines allows quick response to load changes and therefore is suitable for regulating activities.

The principle idea of balancing WP locally by a CHP is visualised in Fig. 1.

Figure 1 shows that wind park and CHP generate electricity to the network to satisfy the local demand of domestic and industrial consumers. The aim is to minimise the need for additional electricity import from outside this area and also to minimise electricity production which could not be consumed locally and therefore would be considered as export. This means that the following power balance equation will be guaranteed for every hour of the whole year:

$$P_{cons} + P_{eks} = P_{WT} + P_{CHP}(Q_{CHP}) + P_{imp}. \tag{1}$$

The goal is to minimize the following objective function:

$$\min(P_{eks}, P_{imp}) \tag{2}$$

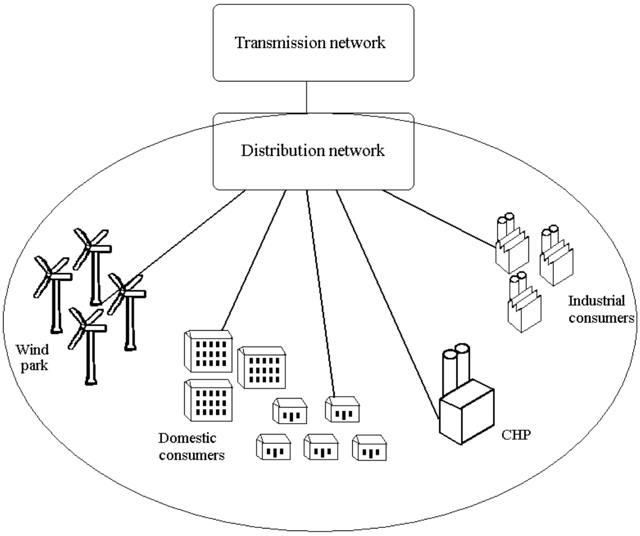

Fig. 1. Distributed generation network.

Also the heat balance equation must be fulfilled:

$$Q_{cons} = Q_{CHP} + Q_B \,, \tag{3}$$

where P_{cons} – electric power demand
P_{eks} – electricity export
P_{WT} – power output from wind turbines
$P_{CHP}(Q_{CHP})$ – power output from CHP; produces simultaneously heat
P_{imp} – electricity import
Q_{cons} – heat demand
Q_{CHP} – thermal output of CHP
Q_B – thermal output of boiler

WP is renewable energy source and its production is nonpredictable, therefore the whole balancing is made by CHP. In case the power balance is carried out perfectly, there would not be any electricity directed into and no electricity needed from the transmission network. In the system operator's point of view, this would be a positive effect, as the WP fluctuations would not reach the transmission network and therefore no WP regulation would be necessary. Also the investment into raising the transmission capacity of electricity network would not be needed.

For the simulation and optimisation a software package energyPRO is used, which is a Windows-based software package for design, optimisation, and analysis of energy projects developed by Danish company Energi- and

Miljødata. The user is able to input a wide range of data on different energy plant types, external conditions such as demands, operating strategies, tariff structures, revenues and operating costs, investments and finance arrangements. Based on the inputs, the energyPRO optimises the operation of the plant against technical and financial parameters and provides a graphical overview. Software also provides the user with the operating results and a detailed financial plan in a standard format accepted by the World Bank [9].

EnergyPRO is an input/output model for calculating annual production in steps of one hour. In the current project the inputs are capacities, efficiencies, fuel data, hourly outdoor temperature and hourly WP production. For the optimisation it is necessary to define hourly demand for electricity and second curve for heat. For this purpose annual demand, its dependency on outdoor temperatures, hourly variation of demand during a day and period of heating were modeled.

The optimisation in energyPRO is based on calculation periods and is dependent on operational strategy. Based on user-defined data, the model constructs for the whole planning period (in this case for one year) hourly time series for electricity demand and similar curves for heat. The production units (wind park, CHP and boiler) are given priorities, and additionally it is defined whether the partial load, production to heat storage and restrictions to electricity demand are allowed or not.

As for principles of distributed power generation, it was assumed that a CHP plant would be operated to balance the WP production and to meet the electricity and heat demand of the area. For this purpose demand profile for electricity and heat were modeled. The WP production is prioritized, which means that electricity demand, which is not covered by WP, will be covered by CHP plant. In balancing activities the CHP plant is not allowed to produce more electricity than needed locally, but for wind turbines it is assumed that the surplus is transmitted to consumers outside the given area. Based on these criteria's energyPRO models the annual production of wind park, CHP and boiler. The operation is based on priorities of production units, which are defined by the modeller. Firstly, as WP is prioritized, the hourly time caps for electricity demand are filled with wind energy production. The remaining electricity demand is covered with CHP. As simultaneously CHP produces heat, the time series for heat consumption is covered. If the CHP produces more heat than the actual heat consumption, the excess heat is stored in the accumulator (if available). In case the storage is full, the unit can only produce as much as needed to cover the heat demand. If after these two steps there will be caps under the electricity demand not filled, this demand will be covered with electricity import.

After filling the electricity demand, the model continues with heat demand. The remaining caps, which have not been covered by CHP, will be now covered with heat from accumulator (if available). The remaining heat demand will be covered with boiler. The graphical overview of electricity and heat production during one week in winter is presented in Fig. 2, where

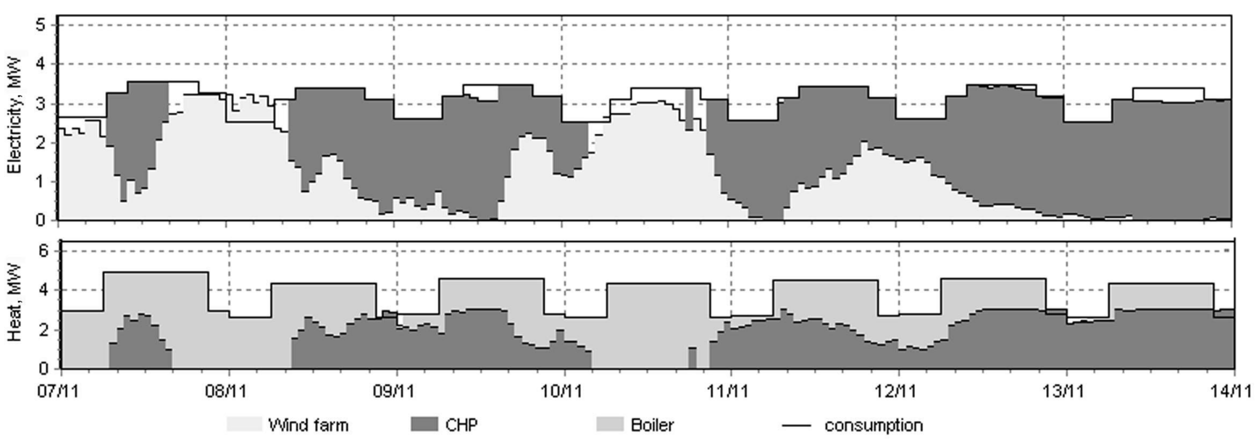

Fig. 2. Production of electricity and heat.

the operation of CHP is restricted taking into account the wind power production and the demand for electricity and heat.

As seen from Fig. 2, energyPRO manages to operate WP, CHP and boiler to meet the local electricity and heat demand. There are different operational cases, which are shown in Fig. 2:

1. During some hours on the 7th, 8th and 10th November the WP production covers the whole electricity demand and as there is enough of WP to meet the whole demand, operation of CHP plant is restricted. Hence it is necessary to cover the heat demand and as the CHP is restricted to operate, the heat demand will be covered by boiler. During some hours the WP production is even greater than the demand, therefore electricity surplus is directed to the transmission network.
2. On the 9th, 11th and 12th November wind turbines produce electricity, but their production is not sufficient to meet the whole demand. Therefore additional electricity demand is covered by CHP. As the production of CHP is limited due to WP, the additional heat demand is covered with the boiler.
3. On the 13th and some hours on 9th and 11th November there is no WP production, and therefore the whole electricity demand is covered by CHP. As thermal capacity of CHP is 3 MW, but the heat demand exceeds 4 MW, the remaining heat demand is covered by the boiler.

Balancing activities

The energyPRO models were constructed to investigate the balancing ability of CHP. As a basic model, a model of conventional operation of CHP plant was constructed, in which case the production of CHP is dependent only on heat demand. Secondly the operation of CHP was restricted, taking into account wind power production, electricity consumption and heat consumption. To estimate the optimal size of WP, which CHP would be able to balance, different shares of actual electricity generation of Pakri wind park were considered in the model (from 5%, 10%, 15%... to 100%). Finally availability of heat storage was included in the model and different accumulator capacities were simulated.

Based on simulation of all these models in energyPRO, the results of annual electricity and heat production, import and export are presented in Table 2. Only some examples of WP capacities (percentages of actual production of Pakri wind park) were chosen to be presented in this table. The results of a model with heat storage will be analyzed later, and the results presented in Fig. 4.

From Table 2 it is seen that in the basic model, there is no need to balance WP production, *e.g.* CHP is producing regardless the electricity demand and availability of WP, the total annual electricity production is 61.4 GWh, of which production of CHP is 18.7 GWh and the rest is WP. As

Table 2. **Annual production of electricity and heat**

Windpower, MW	18.4	1.8	3.7	9.2	18.4
% of actual Pakri WP generation	100	10	20	50	100
CHP restrictions	no	yes	yes	yes	yes
Electricity production, GWh					
Wind	42.8	4.3	8.6	21.4	42.8
CHP	18.7	16.4	12.8	7.8	5.3
Total production	**61.4**	**20.6**	**21.4**	**29.2**	**48.1**
Import	1.7	4.4	3.8	2.7	2.0
Total balance	**63.1**	**25.0**	**25.2**	**31.8**	**50.1**
Export	38.1	0.0	0.2	6.8	25.1
Consumption	25.0	25.0	25.0	25.0	25.0
Heat production, GWh					
CHP	18.5	16.2	12.7	7.7	5.3
Boiler	9.0	11.3	14.8	19.8	22.2
Total production	**27.5**	**27.5**	**27.5**	**27.5**	**27.5**

the electricity consumption is 25.0 GWh, this means that 60% of produced electricity will not be consumed by locally. Hence of large amounts of excess electricity, there is also a small need for import, which is 3% of the total power balance. Import is necessary mainly in the summer period, where there is no WP production and the heat consumption and therefore also the electricity production from CHP are very low. Therefore, in a conventional operation of WP and CHP, large amounts of export will not satisfy the aim of distributed generation.

If it is necessary to balance 10% of the production from Pakri wind park (equals WP capacity of 1.8 MW and production 4.3 GWh) with CHP, the annual total electricity production is reduced to 20.6 GWh. Electricity production from CHP is 16 4 GWh, meaning that CHP will have to reduce its production by 12% in case it is necessary to take part in balancing. There is practically no export required and import is 4.4 GWh, which is 17% of the total balance. The increased import quantities are due to the fact that the maximum local electricity demand is 5.0 MW, but the maximum output of CHP is only 3.0 MW, and therefore there is a considerable need for import on hours with high electricity demand and low WP production.

Higher share of WP will reduce the need for import and introduce some amounts of export. If it is necessary to balance 20% of the production from Pakri wind park (equals WP capacity of 3.7 MW and production 8.6 GWh), the annual total electricity production is increased by 4% to 21.4 GWh. The production from CHP has decreased by 32% (compared to no balancing operation) to 12.8 GWh, export is 0.2 GWh (1%) and import 3.8 GWh (15%).

Balancing of 50% of the production from wind park (WP capacity 9.2 MW and production 21.4 GWh) will mean that the annual total electricity production is increased to 29.2 GWh. The production from CHP is only 7.8 GWh, export has sharply increased to 6.8 GWh (21%) and import reduced to 2.7 GWh (8%).

The inclusion of the total Pakri wind park (capacity 18.4 MW and production 42.8 GWh) will result in a situation where the CHP produces only 29% (5.3 GWh) of what it should normally produce when no balancing is necessary. Export will be 25.1 GWh (50%) and import 2.0 GWh (4%).

As the main idea of distributed generation is to limit the export into and import from outside the given area, the best indicators for evaluation are the quantities of exported and imported electricity. Figure 3 presents the export and import quantities in case it is necessary to balance the WP production at different shares from 0% (0 MW) to 100% (18.4 MW). Also the calculated regulating price from CHP is visualised on the same graph, which will be analysed later on.

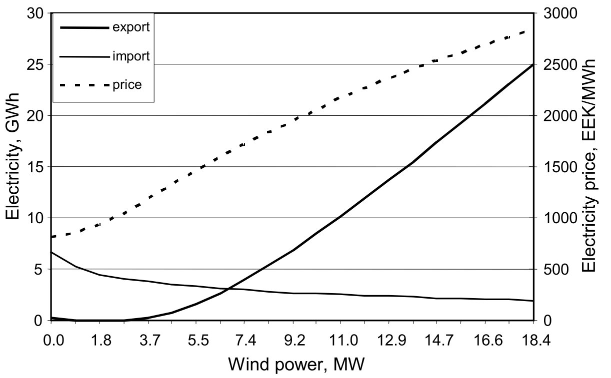

Fig. 3. Export and import quantities and balancing price.

As seen from Fig. 3, the need for import is decreasing from 6.6 GWh, when there is no wind power to be balanced, to 2.0 GWh, when it is required balancing the whole Pakri wind park. Regarding export quantities remarkable changes are observable. At first, there is no electricity surplus, meaning that the total produced electricity will be consumed near the point of generation. Export quantities will start to increase if it is necessary to balance more than 20% (3.7 MW) of the total wind park production and will sharply rise to 25.1 GWh. If the electricity consumption is 25.0 GWh and it is needed to balance the whole wind park, the export quantities equal the consumption. It results in a situation where CHP and wind turbines produce so much electricity that it covers nearly twice as large area as the current example. This means that most of the WP will not be consumed locally and is therefore sent to the transmission grid. So, looking from the point of view of distributed generation, it is reasonable to balance up to 20% of the total WP generation or a wind park with a capacity of 3.7 MW. Therefore the CHP, with an electrical output of 3 MW, is suitable to balance the maximum 20% forecasting faults from 18.4 MW Pakri wind park or production from any wind park which is about the same size as the CHP.

Also the heat production of CHP will be affected in balancing activities, as electricity and heat are produced simultaneously. In non-balancing activities CHP produces 18.5 GWh and boiler 9.0 GWh of heat. In balancing activities the production from CHP decreases and uncovered heat demand will be fulfilled by boiler. As already seen in the electricity production analysis, the CHP has to reduce its production dramatically. In case it is needed to balance the whole Pakri wind park, the heat production will be only 5.3 GWh, and 81% (22.2 GWh) of heat will be produced in boiler.

Economical aspect

In order to motivate CHP plants to balance the fluctuating WP production, some incentives are necessary. From Table 2 it was seen, that in case the operation of CHP plant is dependent on WP generation, the total CHP electricity production will be reduced, in this case even to only one third of what it would normally be. This will result in lower incomes from electricity sale and leads us to a state where it is not economically feasible to operate the CHP plants in conjunction with WP. Therefore electricity price must provide an incentive in order to regulate power at certain hours. Possible measures could be electricity sale in competitive electricity market or introducing tariffs with a hourly variation.

Normally, if no balancing is required, the total electricity production from CHP is 18.7 GWh. For the sold electricity a small CHP plant in Estonia would receive, according to the Energy Market Act, a fixed tariff 810 EEK per sold MWh of electricity (52 €/MWh) [10]. This price will be received independent from the time when electricity is generated. Thus, the incomes from electricity sale would be approximately 15 million EEK. In balancing duties the plant would receive less, in the worst case only 4.3 million EEK, if paid the current fixed price. Therefore the CHP would not be interested to regulate WP production to meet the whole electricity demand. They would be interested only in case their operation is financially sufficient. Considering that incomes from electricity sale should be at the same level (15 million EEK) as in non-balancing activities, the calculated fixed price for balancing energy units is shown in Fig. 3. From this figure it is seen that this calculated balancing price increases from 810 EEK/MWh to 2800 EEK/MWh, which is extremely high.

As a comparison, the spot-market price in Nordpool market has been changing during the year 2008 between 30 and 70 €/MWh. If taken into account that the balancing price should be at highest 70 €/MWh (1100 EEK/MWh), then it is possible to balance up to 20% of the total WP generation or a wind park which is about the same size as the CHP. This means that, if it is needed to balance more than 3.7 MW of WP, it would be economically reasonable to use the connection to Nordpool to balance the fluctuating WP production and not to force the local CHP to reduce its production.

The essence of heat storage

One task of the paper is to analyse the essence of heat accumulator. Currently CHP-s and boiler houses in Estonia do not have any heat accumulators, but Danish examples [6] have shown that they could be very useful for concentrating the production of CHP-s on certain hours.

From the graphical results from energyPRO, like the one presented in Fig. 2, it was seen that in certain hours some part of electricity demand is not covered (white area between demand and production from wind turbines and CHP). One reason for this is restrictions on CHP production. In this time the CHP is not allowed to produce more, because this would result in excess heat, as the heat demand is already met. This is due to the fact that CHP is not allowed to produce more heat than necessary. In this case, the availability of heat storage could improve the operation, as CHP could then produce as much as needed to cover the electricity demand, and the heat surplus would be stored in the accumulator. Therefore, the availability of heat storage was simulated in energyPRO.

As it was found out above, it is reasonable to balance up to 20% of total production from Pakri wind park without any export quantities, and also at this level the electricity sale price for CHP would be kept at a reasonable level. Therefore it was assumed that it is necessary to balance 20% of the WP production building a heat accumulator at the CHP plant, and capacity from 50 to 500 m^3 was considered. The resulting export and import quantities and electricity price can be seen in Fig. 4, as they are best indicators for evaluation.

Figure 4 shows that if the CHP plant balances 20% of WP production and has no heat storage (capacity 0 m^3), the import is 3.8 GWh, export 0.2 GWh, and the previously calculated electricity price is 1180 EEK/MWh. Regarding different sizes of heat accumulator, the export will stay at the same level, as it is necessary to balance the same amount of WP and CHP is not allowed to produce more electricity than locally needed. Changes are seen in regarding import quantities, which will decrease by 30% from 3.8 GWh to 2.7 GWh. The biggest effects of having a heat storage will be accomplished with the smallest storages. A storage with a size of 50 m^3 will reduce the import by 17%, and 100 m^3 – an additional 5% to 3.0 GWh. Beyond that capacity, larger storages will reduce the need for import only in smaller amounts and therefore could not be very feasible. Also the balancing price will be affected as the CHP is now allowed to produce more. Figure 4 shows that the price will be reduced by 8% to 1088 EEK/MWh.

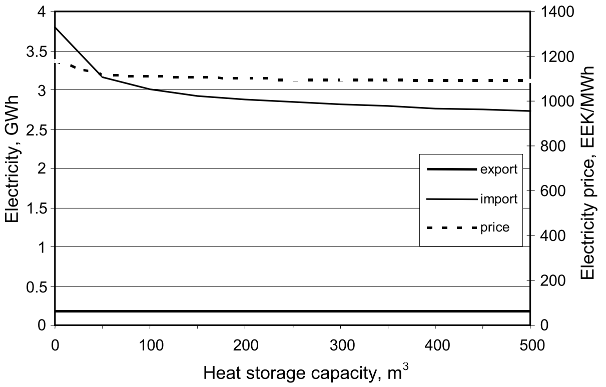

Fig. 4. Export and import quantities and electricity price.

At analyzing heat storages it was discovered that, during a certain period (from November to March) accumulator is used rarely and only at a very low level. The rare use of heat storage is due to the fact that there is no excess heat during the period of high heat demand, as it is consumed simultaneously. This is also caused due to the fact that, for this specific CHP technology, the gas engine produces equal amounts of electricity and heat (power ratio 1 to 1). In the case of different production technology with a heat and power ratios for example, 1 to 2 or 1 to 3, more heat is produced for the same amount of electricity, and this will result in a wider use of storage. However, for this certain technology the effects of heat storage can be mainly seen in the period from April to October when the heat demand is lower. In this case CHP will run on a maximum load or as high as the electricity demand allows storing surplus heat in the accumulator to be used later when CHP is restricted to operate (e.g. at high WP production).

To calculate the economic benefits of building an accumulator, it is necessary to estimate the cost of heat storage, which, based on Danish examples, can be taken as 200 €/m^3 [11]. This means that the cost of 100 m^3 storage is 310 000 EEK (20 000 €). By comparing the CHP electricity production between energyPRO models with storage and without, it is possible to calculate how much the CHP plant could benefit through having heat storage. If CHP has no heat accumulator, the electricity production is 12.8 GWh and the availability of storage will increase the production to 13.6 GWh. So CHP plant could gain additional incomes from the sale of

0.8 GWh electricity. Calculations show that the costs of storage is paid back in 4 years, and the balancing price would be 6% lower.

Conclusions

The data presented in figures and tables demonstrate that it is possible to balance the WP production locally with a small-scale cogeneration plant. CHP with electricity output of 3 MW is suitable to balance the maximum 20% forecasting fault of 18.4 MW Pakri wind park or production of a wind park which is about the same size as the CHP. In this case there would be no electricity surplus, also import quantities and balancing price are kept at a reasonable level. However, as a result CHP will have to reduce its production by one third of the normal operation level. In order to motivate CHP to regulate its production at certain hours, the electricity sale price must provide an incentive for CHP. To guarantee the same income for the enterprise, the current fixed price has to be higher, in this case 1180 EEK/MWh.

Based on calculations it was seen that if it is required to balance larger amounts of WP than the electrical output of the CHP, it would be economically feasible to use the connection to Nordpool to balance the WP production and not to force the local CHP-s to reduce its production. Larger amounts of WP will reduce the need for import, but export quantities will sharply rise up to double of the local consumption, and the calculated balancing price would be even 3.5 times higher. Also boiler will gain a greater importance in the heat production as less electricity and heat will be produced by CHP.

In spite of the fact that CHP plant can manage the production optimization according to the WP without using the accumulator, the building of heat storage will improve the CHP operation and reduce the need for electricity import. The biggest effect of having heat storage will be accomplished with the smallest storages. Calculations show that the cost of a 100-m^3 storage is paid back in four years, and the balancing price would be 6% lower.

Heat storage is rarely used during the period of high heat demand, as there is no excess heat from CHP. One reason for that is the use of specific gas engine. Technology with a different heat and power ratio could result in different usefulness of storage. Currently the benefit of using the heat storage is seen mainly in summer, but also in situations in which the heat demand is only slightly higher than the heat production.

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Paper IV

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Estonian electricity production scenarios and their CO_2 and SO_2 emissions until 2030

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Abstract - Closing of old oil-shale based power plants and fast development of wind power has raised several issues regarding possible future electricity production capacities in Estonia and their environmental performance. In February 2009 Estonian government adopted a new Development Plan of Energy Sector until 2020. This study was performed in conjunction to the strategic environmental assessment of the plan highlighting especially the CO_2 and SO_2 emissions of electricity production scenarios. The analysis is carried out using the Long range Energy Alternatives Planning System (LEAP) software, which is suitable for elaborating the scenarios and their impact on power balance and to the environment.

Key-Word s – Estonia, development plan, CO_2 emissions, SO_2 emissions, oil shale, wind power

1 Introduction

Estonian energy system is unique for its oil shale based electricity production, which has been an important energy source for many years. For more than 40 years, the two worlds' largest oil-shale fired power plants situated in the north-east Estonia have been producing over 90% of Estonia's electricity.

As it is visible from Figure 1, the electricity production has been reducing from 19 TWh in 1980 to 8,5 TWh in 2000 and thereafter has been increasing reaching 12 TWh in 2007. The export of electricity has been reducing considerably, as in 1970's and 1980's it formed 60% of the generation and has in recent years been approximately 20% of produced electricity. Currently electricity is exported mainly to Latvia and Finland, but by closing down of Ignalina nuclear power plant in Lithuania in the end of 2009, the export is expected to grow even more. [1]

The electricity consumption has been growing since 1990's and is currently about 7 TWh with an increase of 4% in a year.

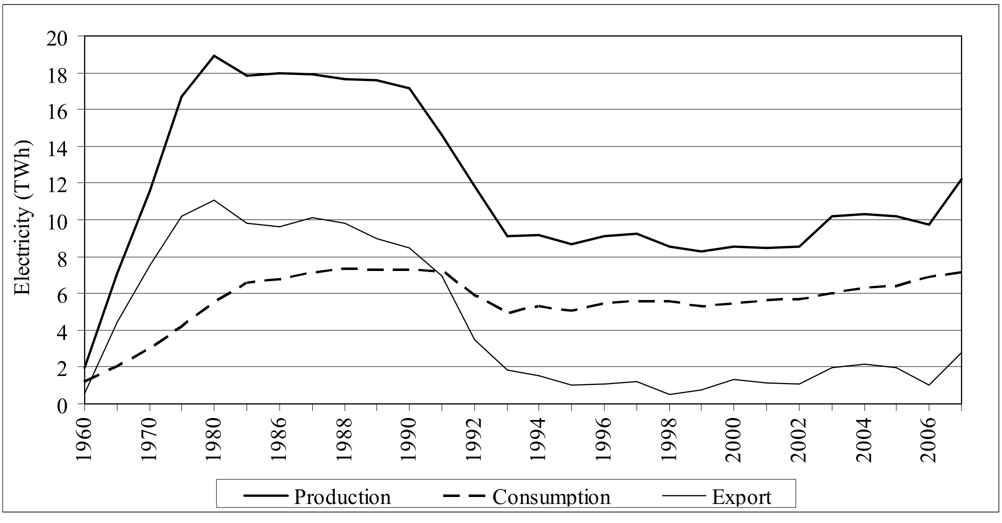

Fig. 1. Production, consumption and export of electricity in TWh

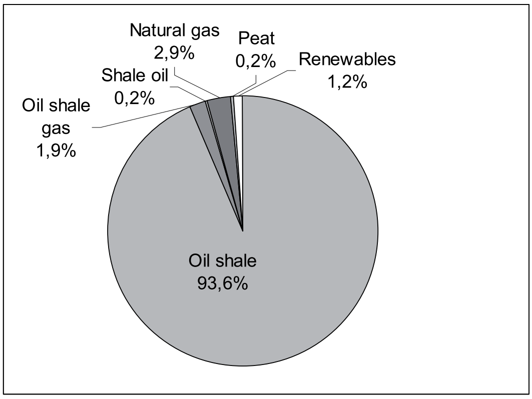

Fig. 2.Electricity generation in 2007

As it is presented on Figure 2 electricity generation in 2007 was 12,2 TWh, of which 93,6% was produced from oil shale, 2,9% from natural gas, 1,9% from oil shale gas and 1,2% from renewable sources. [1]

Oil shale is a local fossil fuel, but there are several environmental issues with regards to its usage. Emissions from oil shale power plants are responsible for most of the CO_2 and SO_2 emissions in Estonia.
The mining quantities of oil shale have been increasing from 11,7 mill. t in 2000 to 16,5 mill. t in 2007 of which 80% is used in electricity and heat production and the rest for producing shale oil (oil product, which can be used alternatively instead of conventional oil) [1].

The total capacity of power producers is currently about 2400 MW, of which 2000 MW is the capacity of before mentioned two biggest oil shale fired power plants. These old pressurized fluidized bed combustion (PFBC) power units were built in 1963-1973. Two new power units with a capacity of 430 MW, started operating in 2003 and 2005, which are using circulating fluidized bed combustion (CFBC) technology. The comparison of unit capacity, efficiency and their emissions are presented in Table 1.
From the table 1 it is seen that the new CFBC power units have bigger unit capacity and higher efficiency, but remarkable changes are seen with regards to their emissions compared to the old PFBC units. Especially the SO_2 emissions, which are over 100 times lower. These PFBC units will be closed after the year 2015 as their sulphur dioxide emissions don't comply with the EU directive requirements. Alternatively it is considered to invest into sulphur capture technologies to keep some of old PFBC units operating [2].

Table 1. Comparison of old and new oil shale combustion technologies. [3, 4]

	PFBC	CFBC
Unit capacity, MW	180	215
Building year	1963-1973	2003, 2005
Net efficiency, %	30	36
SO_2, mg/Nm^3	1900-3000	20
CO_2, t/TJ	102,1	98,8
NO_x, mg/Nm^3	240-320	90-175
Fly ash, mg/Nm^3	2100-2800	30

Closing down of PFBC units will mean that 1600 MW of generation capacity will be out of operation, which is 67% of the total production capacity. [2] Therefore Estonia will face a great production capacity shortage unless there would be new power plants built. New production units are therefore needed to be in operation already in 6 years. As the planning and building of power plants takes several years, definite decisions regarding new production capacities are needed to be made within nearest future.

On the other hand big changes are seen with regards to wind power. It has currently only a small share in Estonian electricity production as the capacity of wind turbines is at the moment 108 MW [2]. In the next years wind power will have a growing role in the electricity generation as it has the biggest contribution to meet the target to produce 5,1% of electricity in 2010 from renewable energy sources [5].

The total capacity of planned wind power projects in Estonia reaches already 4000 MW, which is more than two times higher than the peak consumption of the whole country. Most probably all these projects will not be implemented, but at least 200 MW by 2010 and 400 MW by 2012 will be in operation. [2] The wind resources in Estonia are very good, but there are different technical limitations on its utilization, like lack of regulating reserves to compensate the fluctuations in wind power production [6]. As there are no fast start-up production capacities in Estonia, some balancing measures are necessary if the capacity of wind power exceeds 200 MW. According to the plans the balancing would be performed through exporting the electricity to neighbouring countries and building a 120 MW gas turbine by 2013 and a second submarine cable to Finland. [2]

The study was performed in conjunction to the strategic environmental assessment of the Development Plan of Energy Sector until 2020. This development plan replaces the National Long-Term Development Plan for Fuel and Energy Sector until 2015 that is now divided into specific development plans like development plan for electricity sector, for heating sector, for the use of oil shale, for promoting the use of biomass and bio-energy, energy conservation program and action plan of renewable energy. The development plan of energy sector directs the development related to production, consumption, imports and exports of energy resources, including electricity, heat and liquid fuels. It states the strategic objectives until the year 2020 and aggregates the aims and limitations of specific development plans in this sector. [7]

The Strategic Environmental Assessment of the Development Plan of Energy Sector until 2020 was carried out by Stockholmi Environment Institute's Tallinn centre. The aim of strategic environmental assessment is to define and evaluate the consequences of the plan, their correspondence to national and international environmental targets and to propose suggestions for avoiding and mitigating the environmental damage [8]. The strategic environmental assessment analyses the emissions from electricity and heat sector as well as the use of bio fuels in the transport sector. In this paper only the emissions of different scenarios in the electricity sector are analyzed.

2 LEAP model

The aim of the study is to evaluate CO_2 and SO_2 emissions in case of different electricity production scenarios in the period 2000-2030. The analysis is carried out using the LEAP model and a model of Estonian energy sector is created.

LEAP is a scenario-based energy-environment modelling tool, which is suitable for analysing energy consumption, production and emissions in all sectors of economy [9]. It can be used to account for both energy sector and non-energy sector greenhouse gas emissions. It can be used to create models of different energy systems, where each requires its own unique data structures. LEAP supports a wide range of different modelling methodologies: on the demand side these range from bottom-up, end-use accounting techniques to top-down macroeconomic modelling. On the supply side, LEAP provides a range of accounting and simulation methodologies for modelling electricity generation and capacity expansion planning. [10]

For creating the Estonian energy system model, statistical data for the years 2000-2006 was inserted, which is available in Estonia's statistical database [1] and annual results. Final energy consumption data (all primary fuels, electricity and heat) by different sectors (industry, agriculture, transport, commercial and households) were used. The production units for electricity, heat, oil shale mining and shale oil production were created in LEAP and their production was optimized to represent the real situation. This means that a reference model was built, where the production from generating units would be at the same level as the actual numbers in 2000-2006. Thereafter the development of final energy consumption in 2007 – 2030 was predicted and for the each scenario changes in the production capacities (closing of plants and building of new ones) were made.

The main assumptions of the work:

1. The planning period is from 2000-2030, where 2000-2006 is based on historical data and from 2007 the data is either predicted by LEAP based on historical numbers or is user-defined as changes in the production capacities, building of new plants, etc.
2. The electricity consumption is growing based on gross domestic product (GDP) and elasticity coefficient 0,3. This means that electricity consumption increases annually between 0,9 to 1,5%.
3. The evaluation is given only on emissions from electricity sector.
4. The emission coefficients are taken from LEAP-s database.
5. As the development plans do not concern any changes in the production capacities of cogeneration based on natural gas, wood, peat, biogas and also hydropower, therefore it is assumed that electricity production from these production units will remain at the same level as it is been in years 2000 to 2006.
6. Electricity export is assumed to be at the same level as it is been in years 2000 to 2006.
7. Distribution and transmission losses are assumed to be in the same level as in 2006.

The electricity production scenarios were constructed based on scenarios from Estonia's Long-term Electricity Sector Development Plan until 2018 [11] and National Oil Shale Development Plan for 2008-2015 [12]. Additionally one scenario was added by authors of strategic environmental assessment of the development plan.

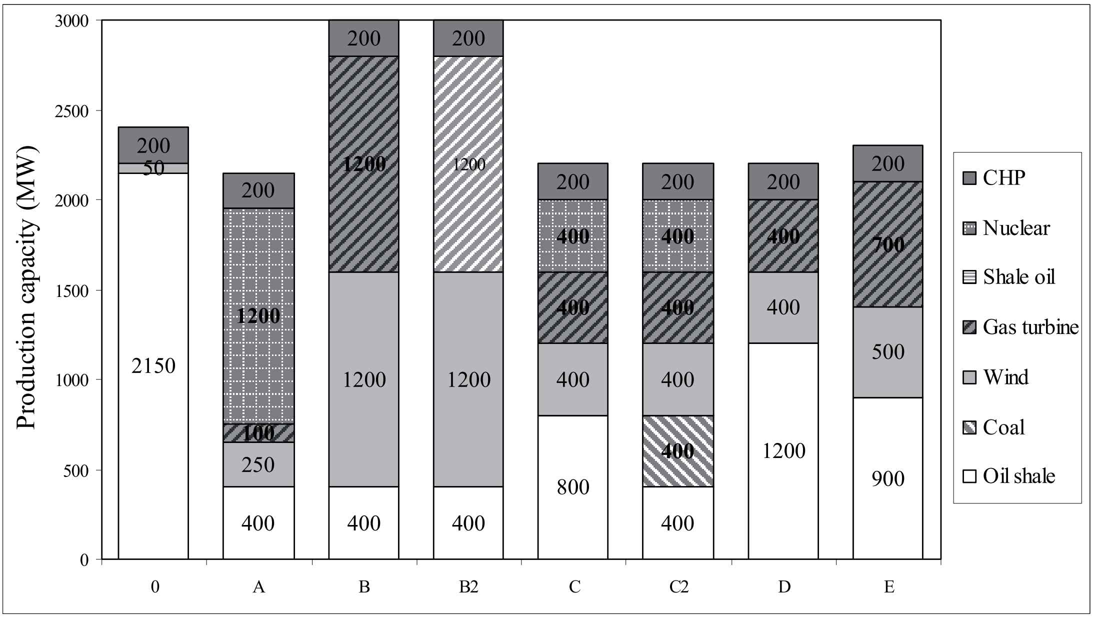

Fig. 3. Production capacities in 2030 of all scenarios

The overview of electricity production capacities in 2030 are presented in the Figure 3. Below each of the scenarios 3 is described separately.

Scenario 0 is the base model, where it is assumed that the current situation will be continuing - there will be no power plants built or closed. There will be 2150 MW of power plants in operation using oil shale (including shale oil, oil shale gas, also CHP), 200 MW of CHP-s (including natural gas, wood, peat, biogas) and 50 MW wind power.

For the all other scenarios it is assumed that the old PFBC units will be closed in 2015. Two CFBC units with a total capacity of 400 MW, 200 MW CHP-s and 50 MW of wind power will remain in operation. In addition the mining capacity is limited. The National Oil Shale Development Plan for 2008-2015 sets the annual mining quantities to 20 mill. t and reducing it to 15 mill. t after 2015 [12].

Scenario A is a nuclear power scenario, where a 1200 MW nuclear power plant will be available in 2025. New wind parks are built and by 2010 the wind power capacity reaches 250 MW. To balance the fluctuating production of wind power, a 100 MW gas turbine will start operating in 2013.

Scenario B foresees a major wind power development, reaching 1200 MW in 2013 and a 1200 MW gas turbine (using natural gas) is built on the same year to balance the production.

As a one sub-scenario B2, a case was studied, when shale oil is used in gas turbine instead of natural gas. This case is derived from discussions in media where it is proposed that in case the old oil shale power plants will be closed; there will be large amounts of oil shale available for shale oil production, which could then be used in gas turbine.

Scenario C is a mix of oil shale, wind, gas turbine and nuclear power, where 400 MW of new oil shale units will be built in addition to existing 400 MW. The capacity of wind turbines reaches 400 MW in 2012 and a 400 MW gas turbine starts operating in 2013. Also 400 MW of nuclear power will be available in 2025.

Scenario C2 is a modification of Scenario C, with the only difference that instead of 400 MW new oil shale units there will be a 400 MW coal based production unit built.

Scenario D is an oil shale scenario, where it is assumed that in addition to existing CFBC units there will be new capacities built for 800 MW. The capacity of wind turbines reaches 400 MW in 2012 and a 400 MW gas turbine starts operating in 2013.

Scenario E is a development of oil shale power plants and wind turbines together with balancing gas turbine. It is foreseen that in addition to existing CFBC units there will be new capacities built for 500 MW. The capacity of wind turbines reaches 500 MW by 2012 and a 700 MW gas turbine starts operating in 2013.

The electricity generation of Scenarios O, A, B, C, D and E are presented in Figures 4 to 9.

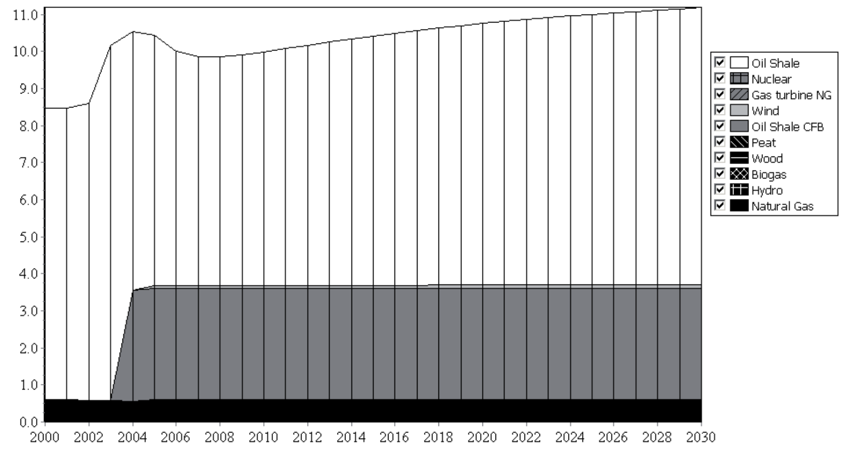

Fig. 4. Electricity generation in TWh of Scenario 0

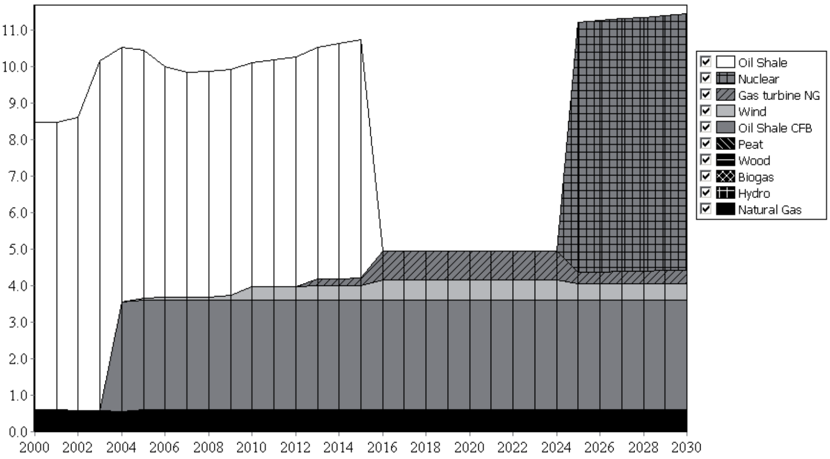

Fig. 5. Electricity generation in TWh of Scenario A

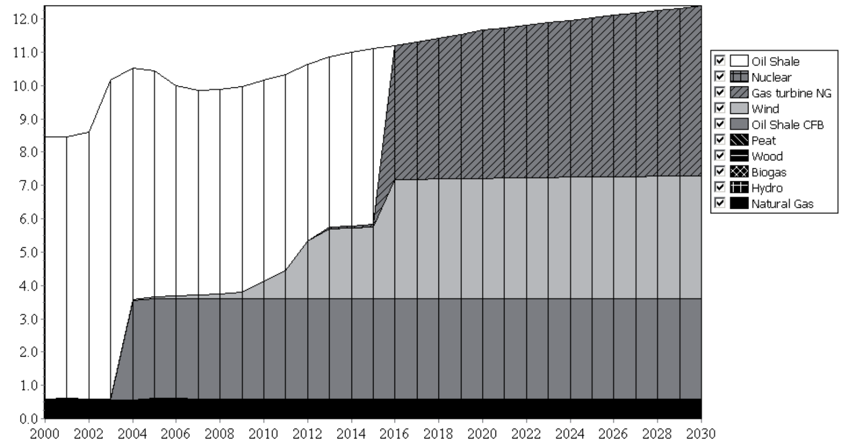

Fig. 6. Electricity generation in TWh of Scenario B

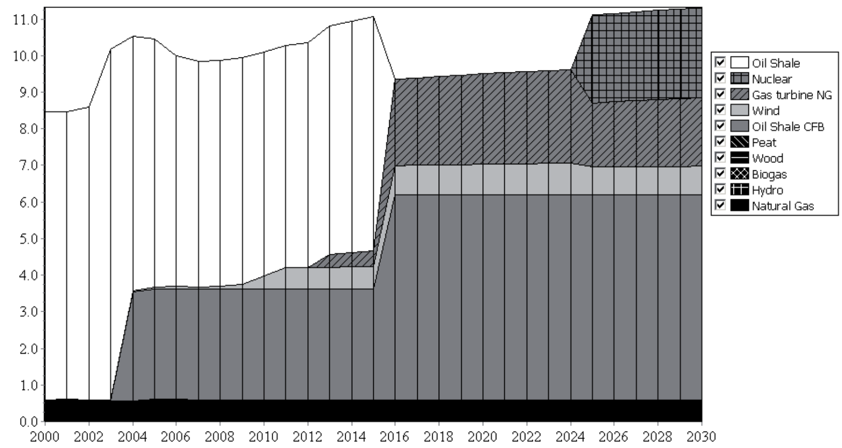

Fig. 7. Electricity generation in TWh of Scenario C

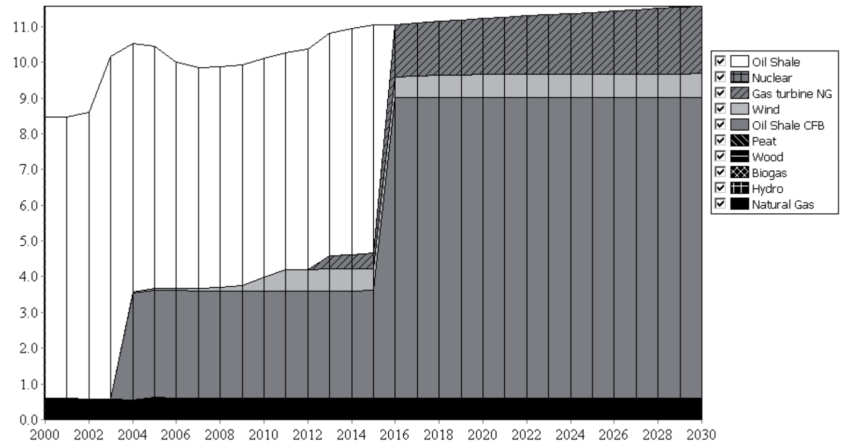

Fig. 8. Electricity generation in TWh of Scenario D

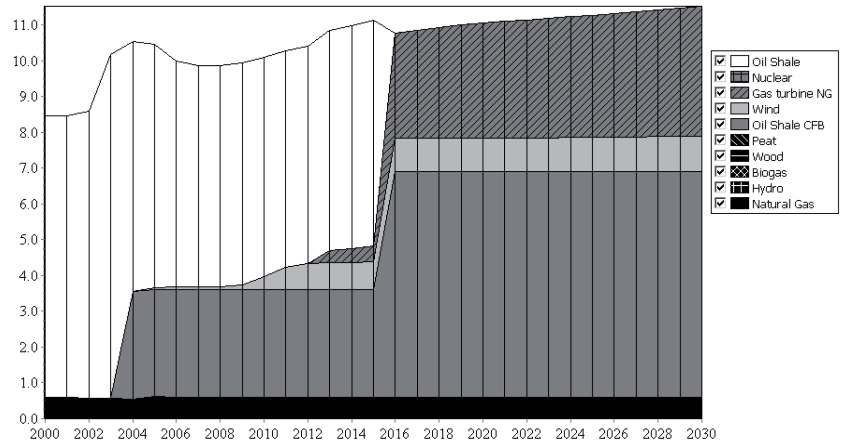

Fig. 9. Electricity generation in TWh of Scenario E

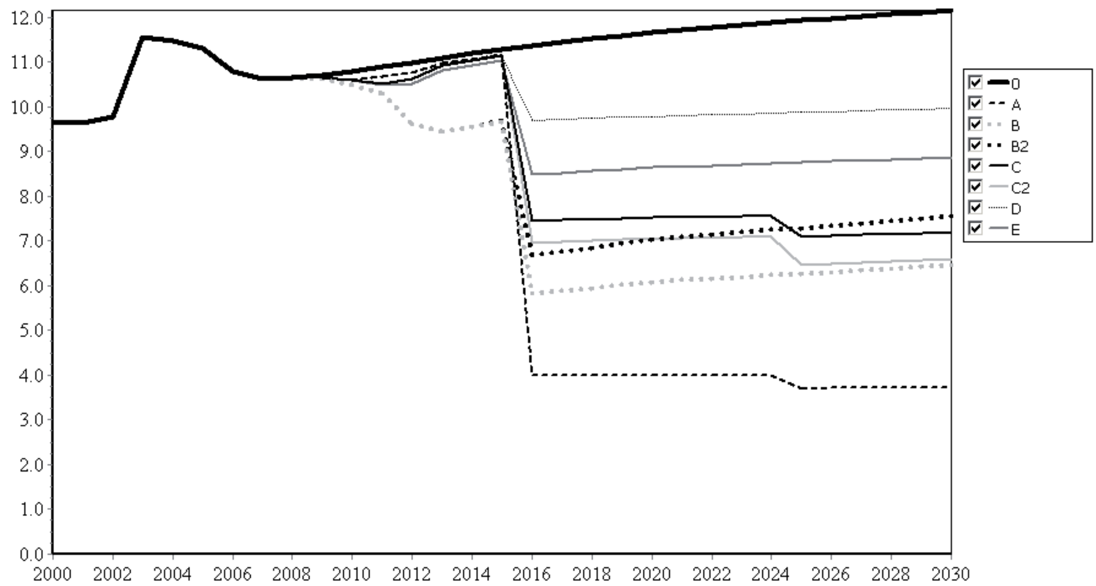

Fig. 10. CO_2 emissions from electricity sector of all scenarios in million tonnes

3 Comparison of emissions

3.1 Comparison of CO_2 emissions

The comparison of CO_2 emissions from electricity sector of above described scenarios is visualized on Figure 10.

From Figure 10 can be seen, that the CO_2 emissions from the electricity generation have been increasing from 9,6 mill. t to 11,6 mill. t in 2003 and the starting point for all scenarios in 2006 is 10,8 mill. t. The emissions are decreasing after 2003 when the new CFCB production units have been replacing the old ones, which have 3% lower [13] CO_2 emissions. But after 2006, the predicted emissions have a slight increasing trend, as the production from conventional power plants is growing due to electricity consumption growth.

It is also clear from Figure 10 that all scenarios will have a lower emission level than the base-scenario 0.This means that closing down of old oil shale power units will have a positive effect on CO_2 emissions.

The highest emissions of scenario 0 are caused by greater oil shale production capacities. Scenarios D (oil shale) and E (oil shale with wind and gas turbine) have also high CO_2 emissions, which is verifying that highest emissions have the scenarios with high oil shale based production capacities This is due to a fact that most of CO_2 emissions are originating from oil shale. Therefore, in this matter the extensive shale oil production should be avoided.

Figure 10 is also showing that the scenario with the lowest emissions is A. The emissions of Scenario A (nuclear power) are remarkably lower than from other ones, as no new oil shale units either wind power plants are constructed, and also due to reason that nuclear power plants are not emitting any CO_2.

It can also be observed from Figure 10, that in spite that the Scenario B (wind power) is the greenest scenario; the CO_2 emissions will be not as low as Scenario A. This is due significant increase in natural gas usage for balancing the wind power production.

The emissions of scenarios B2 (wind with shale oil), C (mixed) and C2 (mixed with coal) are in the medium level.

The level of CO_2 emissions will have a growing importance in Estonia, as already now it is necessary for the power producers to buy some amounts of CO_2 allowances from the market. The national development plan foresees that also in the future Estonia should have production capacity sufficient to supply the domestic consumption. Also it is highly probable that Estonia will continue exporting electricity, as other two Baltic countries are facing shortage of production capacity. Therefore it is very important to make right decisions with regards to building new production capacities when taking into consideration different emission levels from all scenarios. This is a topical question also in other countries [14] of European Union, as the emission allowances will be even more reduced in the future.

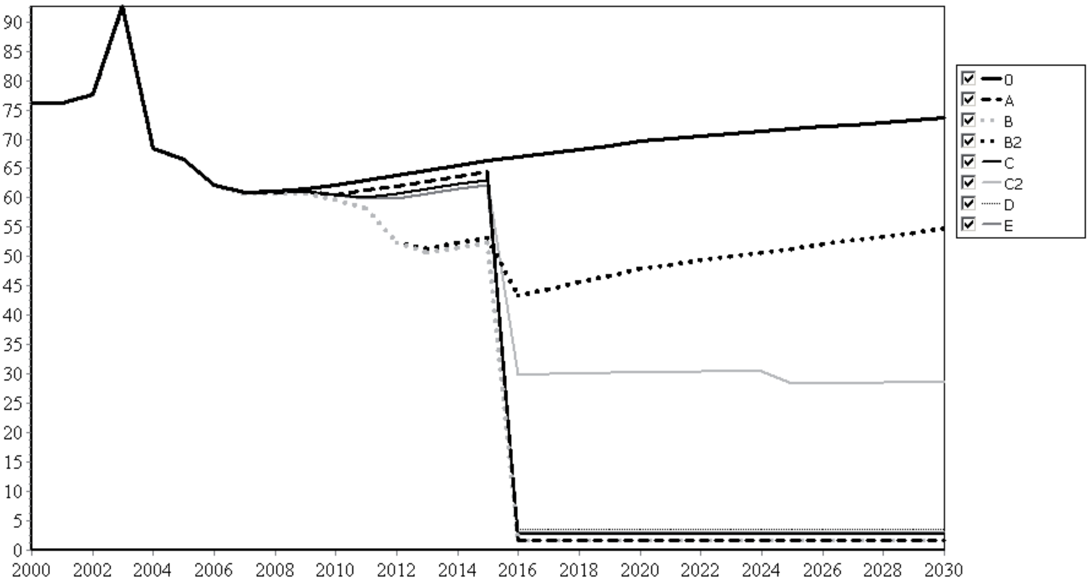

Fig. 11. SO_2 emissions from electricity sector of all scenarios in thousand tonnes

3.2 Comparison of SO_2 emissions

The comparison of SO_2 emissions of eight electricity production scenarios is presented on Figure 11.

From Figure 11 it is evident, that emissions of SO_2 have been decreasing from 93 th. t in 2003 to 62 th. t in 2006, as about one third of electricity is now produced using more efficient CFBC production units, which have remarkable low SO_2 emissions. From 2007 there is again a slight increase in emissions as the production from oil shale power plants is growing.

But from 2016 emissions of most of the scenarios are in the same, low level, which is the point when old oil shale units are closed. Only in Scenarios B2 (using shale oil in the gas turbine instead of natural gas) and C2 (building a 400 MW coal power plant instead of oil shale power plant) the emissions are higher than for the rest of scenarios.

From the Figure 11 can be also seen, that the scenario with highest SO_2 emissions is base-scenario 0. This is due to being the only scenario with so high share of oil shale in the electricity production.

What is interesting is that the scenarios with the lowest SO_2 emissions (A, B, C, D, E) are in the same pollutant level after the year 2015 in spite of fact, that the capacity of oil shale power units are different, which is between 400-1200 MW. The reason for this is that most of the SO_2 emissions are caused by burning oil shale in the old PFBC units, which will be closed in 2015. Whereas the new CFBC units emit over 100 times less SO_2 [3] and therefore the level of emissions will be so low, that the difference in oil shale based generation will not affect the results in a significant way.

The SO_2 emissions are proving that sub-scenarios B2 and C2 have higher emissions as their main models. In the Scenario B2, where shale oil is used in gas turbine instead of natural gas, also the CO_2 emissions will be higher than in B Scenario, but remarkable difference is seen in relation to SO_2 emissions. If in the Scenario B the SO_2 emissions in 2030 are 2 th. t, then in Scenario B2 they are 55 th. t. Therefore, looking in point of view of SO_2 emissions, the use of shale oil in gas turbine instead of natural gas should be avoided.

As for other sub-scenario C2 (400 MW coal instead of oil shale), the emissions will be higher than of Scenario C. Therefore in sense of environmental impact, it is advisable to invest into 400 MW oil shale generation units and not to use coal. As the emissions are dependent on combustion technology used, which in this case was selected from LEAP-s database, the selection of different combustion technology for coal power plant could result in a different outcome.

3.2 Import of electricity

During the analyzing process it was noticed, that in some scenarios the available production units cannot meet the whole electricity demand and therefore import is needed. This means that emissions from imported electricity will be not represented in the emission numbers. Therefore, a question arises whether the results would be different if there is needed to cover the whole demand with local production units. It conflicts also with the national development plan, which foresees to have production capacity sufficient to supply the domestic consumption. The overview of imported electricity in TWh is presented on Figure 12.

From the Figure 11 it is seen, that in the period from 2000-2006 the import has been below 0,5 TWh, which corresponds to real situation, as only small amounts of electricity is needed to balance differences between consumption and production, as the regulating ability of current power producers is not sufficient. After the year 2009 model foresees a growing need for import for some of the scenarios, especially for Scenarios A, C and C2.

As seen from Figure 12, the highest imported electricity quantity has Scenario A, where import reaches 7 TWh in 2024. This is the nuclear power scenario, where in the period 2015-2024 annually about 53-60% of electricity demand will be covered with import. This is caused by situation where the old oil shale power units are closed and no power units are built until the year 2025, when nuclear power plant is starting its operation.

Also in case of Scenario C (mixed version) and C2 (mixed with coal) 20% of electricity comes from imports due to lack of production capacity before the nuclear plant starts operating. Therefore it should be considered to invest into sulphur capture technologies to keep old PFBC units operating until 2025 and thereby reducing the need for import. This of course means that the CO_2 and SO_2 emissions for these scenarios would be higher in the period 2015-2024.

Also Scenario 0 has growing import requirements during the whole planning period, as there is lack of regulating power units in the Estonian power system. Additionally, the limitations of the oil shale mining quantities start to limit the production of oil shale power plants as the electricity consumption is growing and no new power plants will be built.

It is also visible on Figure 11, that the lowest import requirements have scenarios B (wind power) and B2 (wind power and shale oil). The import of these two scenarios is exactly at the same level and therefore you can see only a line for Scenario B on the figure. These scenarios have sufficient production capacities as well as regulating power units, as gas turbine is used to balance the fluctuating wind power.

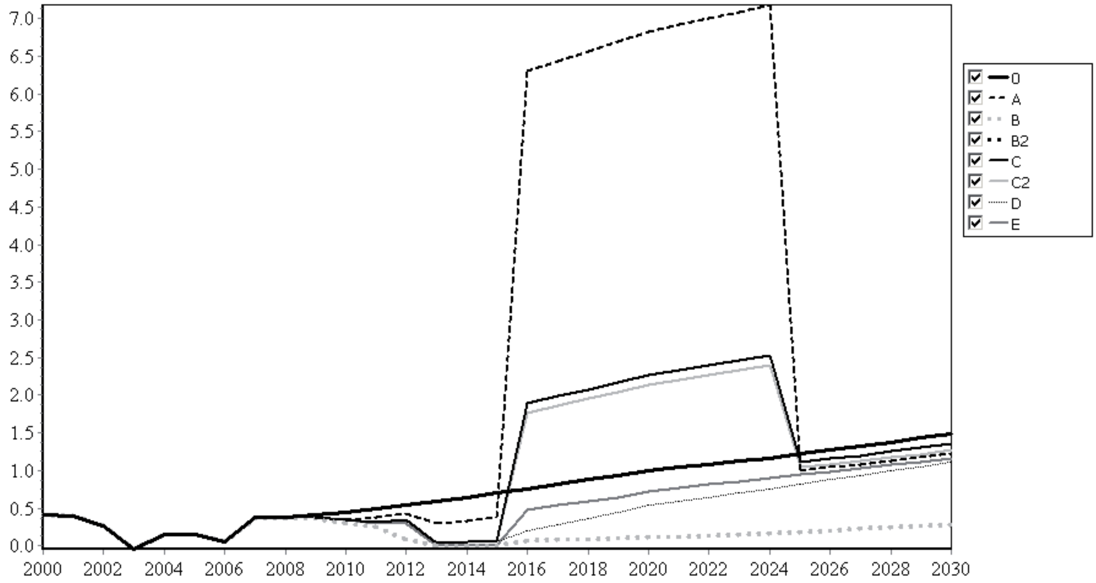

Fig. 11. Import of electricity in TWh of all scenarios

4 Conclusions

Model for Estonia's energy system was created in LEAP software and eight different electricity generation scenarios were designed based on the long term development plans. The CO_2 and SO_2 emissions of these scenarios were presented and analyzed in this study.

Based on analyzed CO_2 and SO_2 emissions it is evident, that all scenarios are showing a reduction of emissions compared to Scenario 0, where continuation of current situation is assumed. Closing down of old oil shale PFBC units will have a significant impact on pollution reduction. The new CFBC units have lower emissions; particularly the SO_2 emissions are over 100 times lower.

The best scenarios regarding the pollution level are A and B. Scenario A foresees use of nuclear power and has the lowest emissions, but during a ten year period more than half of the electricity consumption would be imported. This is due a fact that the old oil shale power units are closed in 2015 and no power units are built until the year 2025, when nuclear power plant stars operating.

As the emissions from imported electricity will be not represented in the emission numbers, a question arises whether the results would be different if there is needed to cover the whole consumption with local production units. One possible way is to invest into sulphur capture technologies to keep some of old PFBC units operating until 2025.

Scenario B is with large wind power development, but its CO_2 emissions will be hence higher than for Scenario A. These additional emissions are coming from gas turbine for balancing wind power. But unlike the Scenario A, in this scenario electricity import is kept on a low level, as there is sufficient production capacity and balancing units available.

Shale oil usage in the gas turbine instead of natural gas was also investigated in Scenario B2, but due to higher emissions it would not be environmentally thoughtful.

Scenarios with high oil shale share, like 0, D and E verified that is very important to limit oil shale mining and extensive oil shale power production, as emissions from these scenarios are higher than for the others. Analysis of Scenario C2 proved that it's also not advisable to invest into coal power plant instead of oil shale. But selection of different combustion technology for coal power plant could result in a different outcome

The level of CO_2 emissions will have a growing importance, as also in the future Estonia should have production capacity sufficient to supply the domestic consumption as well as some export to neighbouring countries. As the emission allowances set by European Union will be reduced even more in the future, therefore it is very important to make right decisions with regards to building new production capacities when taking into consideration different emission levels from scenarios presented in this study.

Acknowledgements

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Paper V

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„Topical Problems in the Field of Electrical and Power Engineering“
Narva-Jõesuu, Estonia, June 15-20, 2009

CO_2 and SO_2 emissions in Estonia in the period 2000-2030

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Abstract

This paper summarizes a study performed as one part of to evaluating the environmental impact of long term development plan of Estonia's energy sector. The main objective is to assess the CO_2 and SO_2 emissions of electricity production scenarios and comparing them with each other. The study was carried out with the Long range Energy Alternatives Planning System (LEAP), which is a widely used software tool for energy policy analysis and climate change mitigation assessment developed at the Stockholm Environment Institute.

Keywords

Development plans, CO_2 emissions, SO_2 emissions, oil shale

Introduction

The Development Plan of Energy Sector until 2020 directs the development related to production, consumption, imports and exports of energy resources, including electricity, heat and liquid fuels. The development plan states the strategic objectives until the year 2020 and aggregates the aims and limitations of specific development plans in this sector, like development plan of electricity sector, national development plan for the use of oil shale, development plan for promoting the use of biomass and bio-energy, energy conservation program. Furthermore it provides guidelines for creating the development plan for heating sector and action plan of renewable energy. The development plan defines the current situation in the sector, presents topical issues, states the strategic development objectives for the energy sector and the development principles. [1]

The study was performed in conjunction to the strategic environmental assessment of the development plan. The aim of strategic environmental assessment is to define and evaluate the consequences of the plan, their correspondence to national and international environmental targets and to propose suggestions for avoiding and mitigating the environmental damage [2]. The strategic environmental assessment analyses the emissions from electricity and heat sector as well as the use of bio fuels in the transport sector, but in this paper only the emissions of different scenarios in the electricity sector are analysed.

LEAP is a scenario-based energy-environment modeling tool, which can be used to track energy consumption, production and resource extraction in all sectors of an economy. It can be used to account for both energy sector and non-energy sector greenhouse gas (GHG) emissions. [3]

LEAP is not a model of a particular energy system, but rather a tool that can be used to create models of different energy systems, where each requires its own unique data structures. LEAP supports a wide range of different modeling methodologies: on the demand side these range from bottom-up, end-use accounting techniques to top-down macroeconomic modeling. LEAP also includes a range of optional specialized methodologies including stock-turnover modeling for areas such as transport planning. On the supply side, LEAP provides a range of accounting and simulation methodologies for modeling electric sector generation and capacity expansion planning, but which are also sufficiently flexible and transparent to allow LEAP to easily incorporate data and results from other models. [3]

In the Estonias energy sector is facing great challenges with regards to closing of old oil-shale based production units and rapid development of wind power. In the year 2007 the electricity generation was 12189 GWh, of which 93,6% was produced from oil shale, which is a local fossil fuel. 2,9% of electricity was produced from natural gas, 1,9% from shale oil gas and 1,2% from renewable sources. The electricity consumption was 7180 GWh, which has grown 24% since year 2000. 22% of the produced electricity was exported and 4,8% consumption was covered with import. [4]

The capacity of power producers in the year 2008 was 2362 MW, but actual possible capacity is lower depending on maintenances, interruptions, availability of hydro and wind power, etc. After the year 2015 the power plants have to fully comply with the EU directive requirements. Therefore the oil shale pressurized fluidized-bed combustion (PFBC) units have to be closed down, as their sulfur dioxide (SO_2) emissions are considerably higher. This means that 1614 MW of power generation capacity will be out of operation. [5] Therefore Estonia will face a great production capacity shortage unless there would be new power plants built.

Wind power has currently only a small share in Estonian electricity production and the capacity of wind turbines is 65 MW. The favorable conditions are boosting the wind power development and currently the total capacity of planned wind power projects reaches 4000 MW, which is more than two times higher than the maximum consumption of the whole country. Most probably all these projects will not be implemented, but at least 200 MW by 2010 and 400 MW by 2012 will be in operation. As there are no fast start-up production capacities in Estonia, some balancing measures are necessary if the capacity of WP exceeds 200 MW. According to the plans the balancing will performed through exporting the electricity to neighbouring countries and building a 120 MW gas turbine. [5]

The mining quantites of oil shale have been increasing from 11,7 mill. t in 2000 to 16,5 mill. t in 2007 of which 80% is used in electricity and heat production and the rest for producing shale oil. [6] To limit the use of oil shale and thereby induced pollution, the National Oil Shale Development Plan for 2008-2015 sets the annual mining quantities to 20 mill. t and reducing it to 15 mill. t after 2015 [7].

As the most important indicators of the study, the CO_2 emissions in 2006 were 16,0 mill. t and SO_2 emissions 71 th. t [6] In 2007 CO_2 emissions from energy sector were 15,7 mill. t and the target is to reduce them 2 times by the year 2020. This would mean that the CO_2 emissions in 2020 would be 7,9 mill. t. [1]

Basic considerations

The aim of the study is to evaluate CO_2 and SO_2 emissions in case of different electricity production scenarios in the period 2000-2030. The analysis is carried out using the LEAP model and a model of Estonian energy sector is created. To simulate the energy system, statistical data for the years 2000-2006 was inserted in the model, which are available from Estonia's statistical database [6] and annual results. The data used concerns final energy consumption (all primary fuels, electricity and heat) by different sectors (industry, agriculture, transport, commercial and households). The production units for electricity, heat, oil shale mining and shale oil production were created in LEAP and their production was optimized to represent the real situation. This means that a reference model was built, where the production from generating units would be at the same level as the actual numbers in 2000-2006. For the modeling purpose emission coefficients were used, which are available in LEAP's database.

Thereafter the development of final energy consumption in 2007 – 2030 was predicted and for the each scenario changes in the production capacities (closing of plants and building of new ones) were made.

The main assumptions of the work:

1. The planning period is from 2000-2030, where 2000-2006 is based on historical data and from 2007 the data is either predicted by LEAP based on historical numbers or is user-defined as changes in the production capacities, building of new plants, changes in the oil shale mining and shale oil production (produced from oil shale) etc.
2. The final energy consumption in different sectors will grow according to gross domestic product (GDP) taking into account the elasticity coefficient, which is calculated based on historical data.
3. The Electricity consumption is growing based on GDP and elasticity coefficient 0,3. This means that electricity consumption increases annually about 1,1%.
4. The evaluation is given on the total emissions, which means also from other sectors besides electricity production. The variable part of emissions from different scenarios will be from electricity production, emissions from other sectors will remain the same.
5. The emission coefficients are taken from LEAP-s database.
6. As the development plans do not concern any changes in the production capacities of cogeneration based on natural gas, wood and peat, also hydropower, etc, it is assumed that electricity production from these production units will remain at the same level as it is been in years 2000 to 2006.
7. Electricity export and import is assumed to be at the same level as it is historically been.
8. The district heat consumption will remain at the level of year 2006.
9. The amount of oil shale used for electricity production and for shale oil production is calculated during the modeling work and is calculated separately for the each scenario. It is assumed that the first priority is to provide fuel for the electricity sector and the rest will remain for the shale oil production.

The electricity production scenarios presented in the Table 1 were constructed based on scenarios from Estonia's Long-term Electricity Sector Development Plan until 2018 [4] and National Oil Shale Development Plan for 2008-2015 [7]. Additionally three scenarios were added by authors of strategic environmental assessment of the development plan. Below each of the presented scenarios is analyzed separately.

Table 1. Electricity production scenarios.

Scenario	Production capacities (MW)						Oil shale	
	Oil shale	Wind	Gas turbine	Nuclear	CHP	Total	Mining (mill. t)	electricity/oil production
0/0	2150	50	0	0	250	2450	15	80/20
A/6	400	250	100	1200	200	2150	15	30/70
B/4	400	1200	1200	0	200	3000	15	30/70
C/2	800	400	400	400	200	2200	15	50/50
C2/3	400+400	400	400	400	200	2200	15	30/70
D/1	1200	400	400	0	200	2200	15	70/30
-/5 E	900	500	700	0	200	2300	15	60/40
-/7 E	900	500	700	0	200	2300	10	80/20
-/8 E	900	500	700	0	200	2300	25	30/70

Scenario 0/0

The scenario 0/0 is the base model, where it is assumed that the current situation will be continuing. There will be no power plants built or closed. Meanwhile the electricity consumption will be rising according to above mentioned assumptions. In addition the mining capacity is limited from the year 2007 to 20 million t and from 2016 to 15 million t.

The exertion of oil shale is regulated so that 80% is used in power plants and 20% used to produce shale oil. There will be 2150 MW of power plants in operation using oil shale (including shale oil, oil shale gas, also CHP), 250 MW are CHP-s (including natural gas, wood, peat, biogas) and 50 MW wind power. The electricity production of scenario 0/0 by fuels is visible on Figure 1.

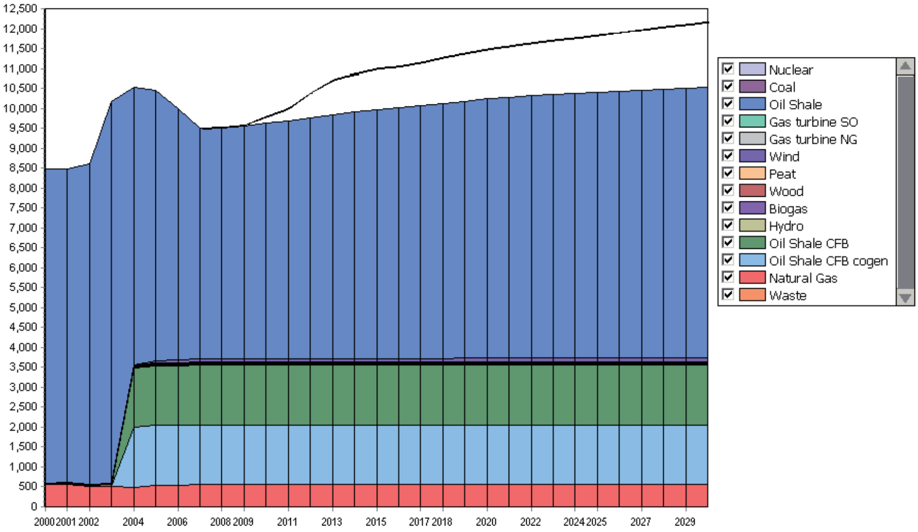

Fig 1. Electricity production in GWh of Scenario 0/0

From the Figure 1 it is seen, that the existing production units can produce the whole demanded electricity until the year 2010, when the limitations for the oil shale mining start to limit the production of oil shale power plants. The remaining electricity demand should be covered with import or through changing the ratio (80/20) of oil shale usage so more fuel would be available for power production.

It is also visible from the Figure 1 that most of the electricity is produced in old power units using oil shale (marked with darker blue color), which in reality would be closed after 2015. The new oil shale production units using circulating fluidized bed combustion technology (CFBC) technology are indicated with two colors, cogeneration unit with green and condensing unit with lighter blue. The production of natural gas fired CHP-s (marked with red color) has also a considerable share in the electricity production, but production from other units is unnoticeable. As the development plans don’t concern any changes in the production capacities of wood, peat, hydropower, etc, these production units will be hereafter visualized on graphics as “all others”.

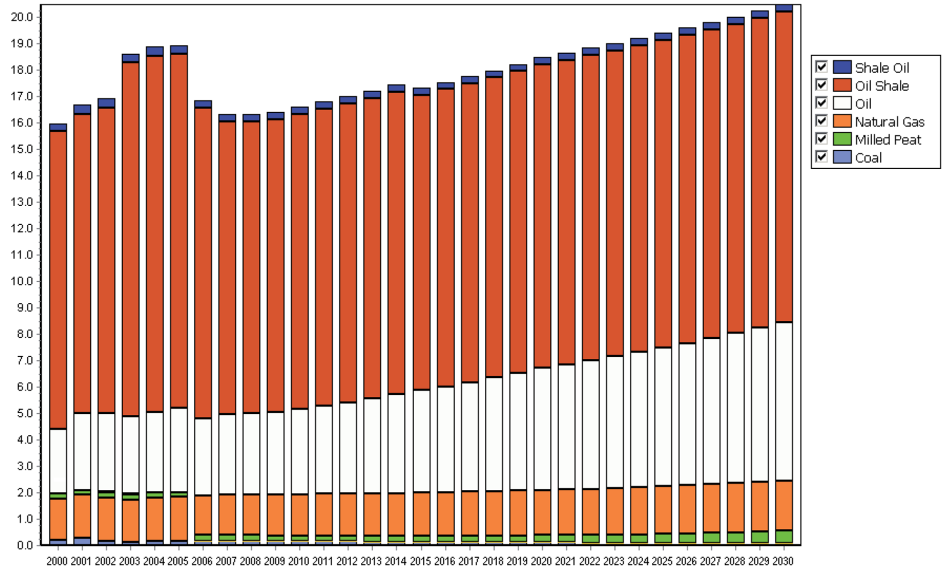

Fig 2. CO_2-emissioons in mill. t of Scenario 0/0

The CO_2-emissions of scenario 0/0 are presented on Figure 2. As it is seen from this figure, the annual emissions of CO_2 are increasing from 16,0 mill. t in 2000 to 18,9 mill. t in 2005 and then dropping to 16,5 mill. t and increasing again to 20,5 mill. t in 2030. This means that the national goals for reducing the CO_2-emissions will not be fulfilled, if the current situation continues.

The emissions of CO_2 descended from oil shale have the biggest share in the total emissions. The emissions from oil shale are decreasing after 2005 when the new CFCB production units have been replacing the old ones, which have 3% lower [8] CO_2 emissions. The emissions originating from oil shale are increasing from the year 2007 as the production from conventional power plants is growing until the limitations for oil shale mining will restrict the further development.

As it is seen from Figure 2, the main cause of emissions is oil shale, but the biggest growth is caused by use of oil products (diesel, benzene, etc). Emissions from oil products are mainly from the transport sector, which has rapidly grown during the last years.

Overview of SO_2 emissions is presented on Figure 3.

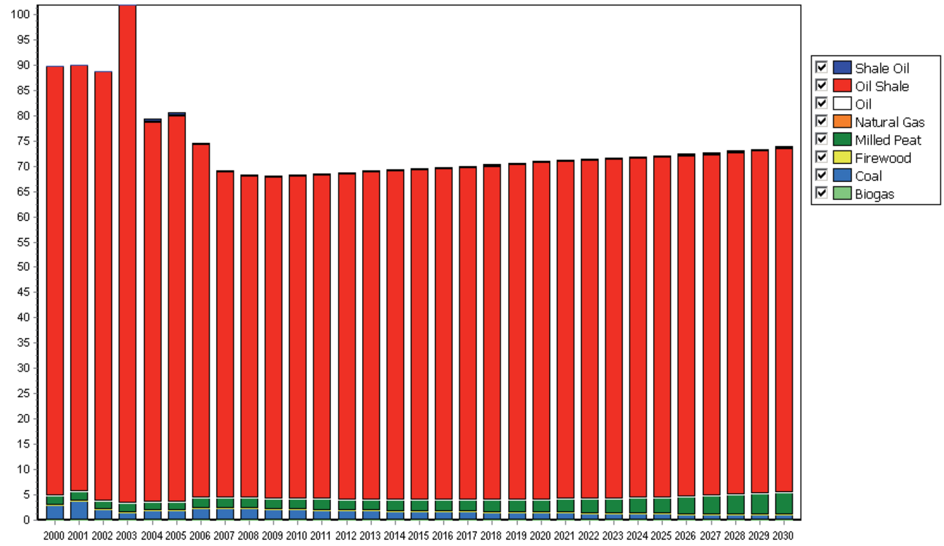

Fig.3. SO_2-emissions in th. t of Scenario 0/0

From Figure 3 it is evident, that emissions of SO_2 have been decreasing from 102,0 th. t in 2003 to 71,2 th. t in 2006, as part of electricity is produced using more efficient CFBC production units, which have remarkable low SO_2 emissions. From 2007 there is a slight increase in emissions as the production from oil shale power plants is increasing and therefore the SO_2 emissions reach 73,8 th. t in 2030. It is also visible, that most of the pollution comes from oil shale fired power plants. Peat and coal have only a small part in the total emissions.

Scenario A/6

Based on Scenario A/6 the old PFBC units will be closed in 2015 and therefore only two new oil shale production units with a total capacity of 400 MW will remain in operation. New wind parks are built and by 2010 the wind power capacity reaches 250 MW. To balance the fluctuating production of wind power, a new 100 MW gas turbine will start operating in 2013. In this scenario 1200 MW of nuclear power will be available in 2025. As substantial part of oil shale based electricity production is closed down and no new oil shale units are built, therefore the usage ratio for oil shale can be reduced, so that 30% of mined tons will be used in power plants and the rest for shale oil production.

The electricity production of Scenario A/6 by fuels is visible on Figure 4.

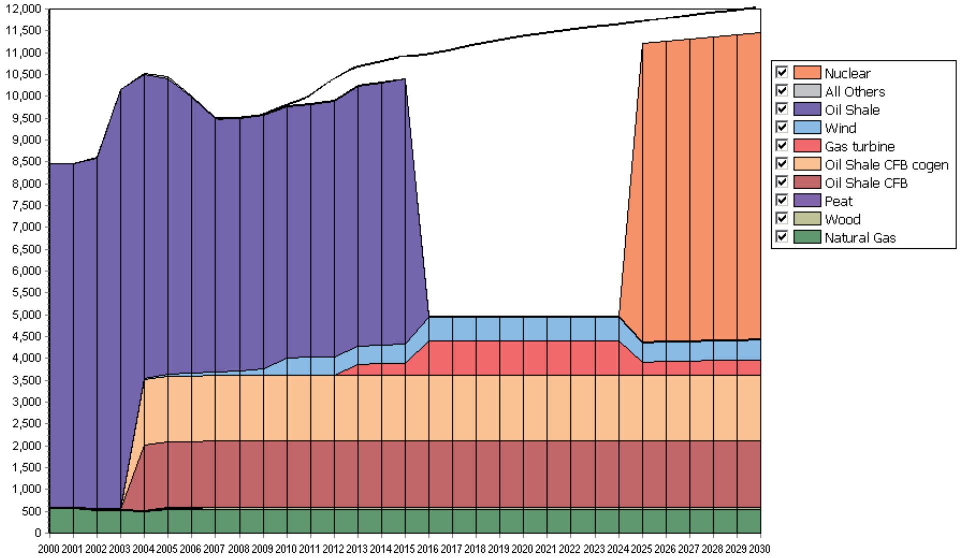

Fig.4. Electricity production in GWh of Scenario A/6

From Figure 4 can be concluded, that the currently existing and new production units can produce almost all the needed electricity until year 2015, when old oil shale power plant units are closed. The remaining generators cannot produce as much electricity as demanded, because the nuclear power plant will start operating not before 2025. Therefore during the period 2015-2024 almost half of electricity demand will be covered with import. Alternatively it would be possible to invest into sulfur catching technologies to keep some of old PFBC units operating until 2025 and thereby reducing the need for import.

As the electricity production from oil shale is reducing rapidly from 2015, this will have a positive effect on the emissions. The CO_2 emissions are decreasing from 16,0 mill. t in 2000 to 15,6 mill. t in 2030 and SO_2 emissions are decreasing substantially from 89,8 th. t to 10,4 th. t.

Scenario B/4

The Scenario B/4 foresees a major wind power development reaching 1200 MW in 2013 and a 1200 MW gas turbine (using natural gas) is built on 2013 to balance their production. The PFBC units will be closed in 2015 and 400 MW CFBC units will remain in operation. Similarly to Scenario A/6, as the electricity production from oil shale is reducing, therefore substantial amount of oil shale is available for the shale oil production.

The electricity production of Scenario B/4 can be observed on Figure 5. As seen from the figure, the existing and new power units can provide all the domestic electricity demand and therefore no import is needed.

The Scenario B/4 is the greenest scenario, but the CO_2 emissions will be higher than for Scenario A/6. This is due significant increase of natural gas usage. The CO_2 emissions are increasing from 16,0 mill. t in 2000 to 17,6 mill. t in 2030 and SO_2 emissions are decreasing substantially from 89,8 th. t to 9,9 th. t.

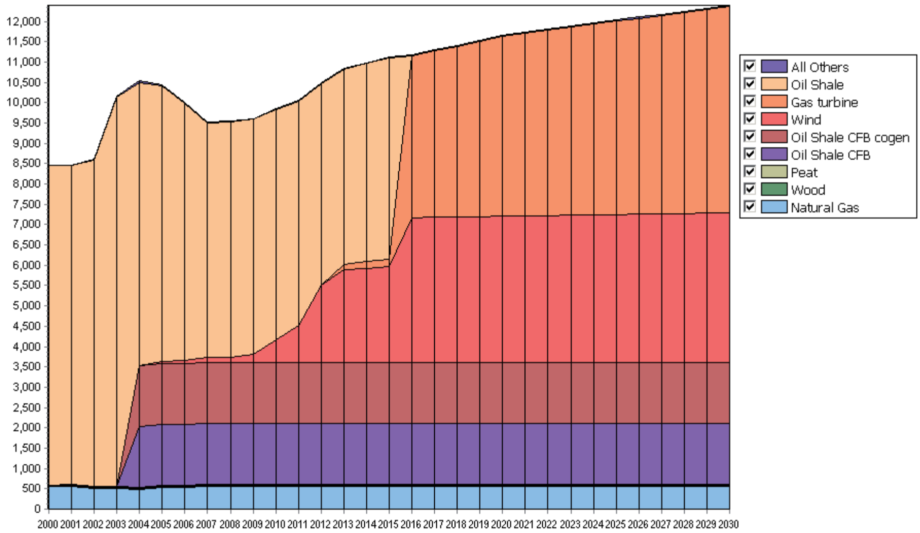

Fig. 5. Electricity production in GWh of Scenario B/4

As a one sub-scenario B2/4, a case was studied, when shale oil is used in gas turbine instead of natural gas. This case is derived from discussions in media where it is proposed that in case the old oil shale power plants will be closed; there will be large amounts of oil shale available for shale oil production, which could then be used in gas turbine. In this case the CO_2 emissions are increasing to 18,7 mill. t in 2030 and SO_2 emissions are decreasing to 62,8 th. t. This means that the CO_2 emissions will be higher than in B/4 Scenario, but the remarkable changes are seen in relation to SO_2 emissions. If in the Scenario B/4 the SO_2 emissions in 2030 were 9,9 th. t, then in Scenario B2/4 they are 62,8 th. t. Therefore, looking in point of view of SO_2 emissions, the use of shale oil in gas turbine instead of natural gas should be avoided.

Scenario C/2

In the Scenario C/2 the old oil shale units are closed in 2015 and 400 MW of new units will be built in addition to remaining 400 MW. The capacity of wind turbines reaches 400 MW in 2011 and a 400 MW gas turbine starts operating in 2013. Also 400 MW of nuclear power will be available in 2025. As there is a higher oil shale capacities than in previous two scenarios, the ratio for oil shale excertion ratio can be reduced to 50/50 after 2015. The electricity production of Scenario A/6 by fuels is visible on Figure 6.

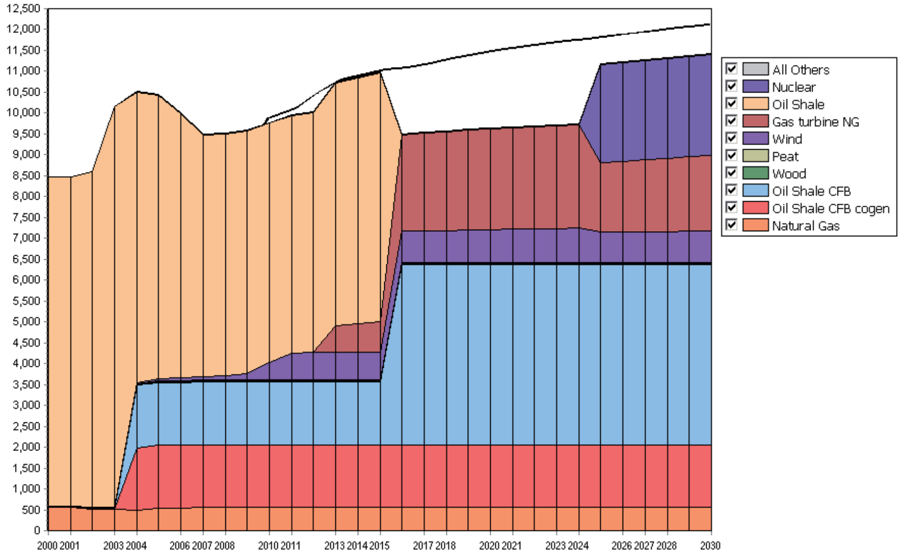

Fig. 6. Electricity production in GWh of Scenario C/2

From Figure 6 it can be concluded, that the existing and new production capacities will cover the electricity demand until 2015, but after that a remarkable amounts of import is needed until the nuclear power plant starts generating. Also in this case it would be possible to use some of old oil shale units operating in case the sulfur catchers are constructed.

The CO_2 emissions in Scenario C/2 will raise from 16,0 mil. t in 2000 to 18,1 mil. t in 2030 and SO_2 emissions are decreasing significantly from 89,8 th. t to 10,6 th. t.

Scenario C2/3

Scenario C2/3 is a modification of Scenario C/2, with the only difference that instead of new oil shale units there will be built 400 MW coal based production units. As there is again a lower oil shale capacities like in A/6 and B/4 scenarios, the ratio for oil shale excertion ratio can be reduced to 30% after 2015 (the rest is used for shale oil production). The CO_2 emissions are increasing to 18,4 mil. t and SO_2 emissions decreasing to 37,3 th. t. This means, that the emissions of Scenario C2/3 will be higher than of Scenario C/2. Therefore in sense of environmental impact, it is advisable to invest into 400 MW oil shale generation units and not to use coal.

Scenario D/1

In the Scenario D/1 it is assumed that the PFBC units will be closed in 2015 and in addition to existing CFBC units there will be new capacities built for 800 MW. The capacity of wind turbines reaches 400 MW in 2011 and a 400 MW gas turbine starts operating in 2013. As this is a scenario with a larger oil shale importance, the usage rate for oil shale must be 70%. The electricity production of Scenario A/6 by fuels is visible on Figure 7.

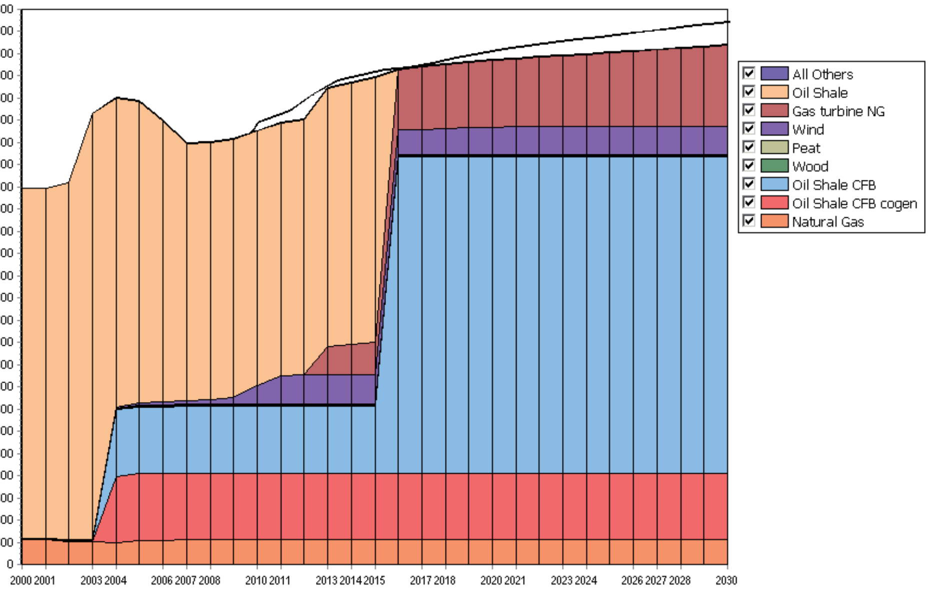

Fig. 7. Electricity production in GWh of Scenario D/1

From Figure 7 it is seen, that the available production units can cover the electricity demand almost completely, small import is required after 2015, which is due lack of production capacity.

The CO_2 emissions are increasing from 16,0 mill. t in 2000 to 19,9 mill. t in 2030 and SO_2 emissions are decreasing from 89,9 th. t in 2000 to 11,0 th. t in 2030.

Scenarios -/5 E, -/7 E, -/8 E

The Scenarios -/5 E, -/7 E, -/8 E are scenarios with the development of oil shale power plants and wind turbines together with balancing gas turbine. For all three scenarios it is foreseen that the old PFBC units are closed in 2015 and in addition to existing CFBC units there will be new capacities built for 500 MW. The capacity of wind turbines reaches 500 MW by 2011 and a 700 MW gas turbine starts operating in 2013. The only difference of these scenarios is related to mining quantities of oil shale. In Scenario -/5 E it is assumed that the mining capacity is limited to 20 mill. t and from 2016 to 15 mill. t (like in all previous scenarios) and 60% will be used in the electricity production and the rest is for shale oil production. In case of Scenario -/7 E the mining quantities are respectively 15 mill. t and 10 mill. t with a ratio 80/20. In the Scenario -/8 E the mined oil shale amounts will be raised to 30 mill. t to 25 mill. t with ratio 30/70.

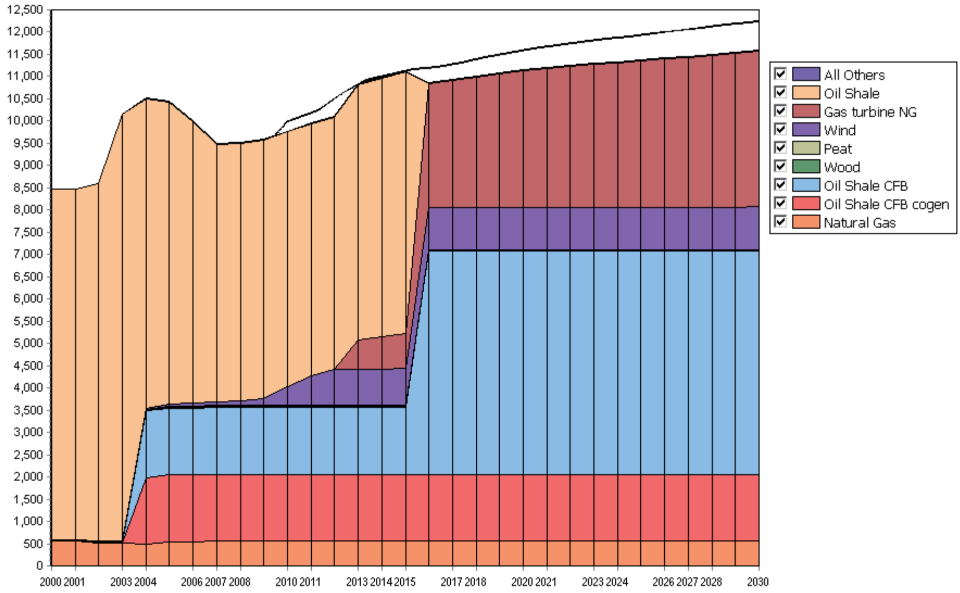

Fig. 8. Electricity production in GWh of Scenarios -/5 E, -/7 E, -/8 E

Figure 8 represents the electricity production of Scenarios -/5 E, -/7 E, -/8 E. As they have same production capacities, the electricity production graphics are alike because ratios have been set to guarantee oil shale for the electricity generation. Figure 8 shows that the available production units can cover the electricity demand almost completely; small import is required after 2015. This is due lack of particular production capacity.

In spite of similar electricity production graphics, the emissions are on the different level. The CO_2 emissions in 2030 for Scenario -5/ E will be 19,3 mill. t, for -/7 E 18,0 mill. t and for -/8 E 22,8 mill. t. The SO_2 emission in 2030 will be respectively 10,6 th. t, 9,8 th. t and 12,9 th. t. This means that the greater the oil shale mining quantities, the higher are emissions, which is due to a fact that mining and shale oil production are also emitting air pollutants.

Comparison of emissions

The comparison of CO_2 emissions of above described scenarios is visualized on Figure 9.

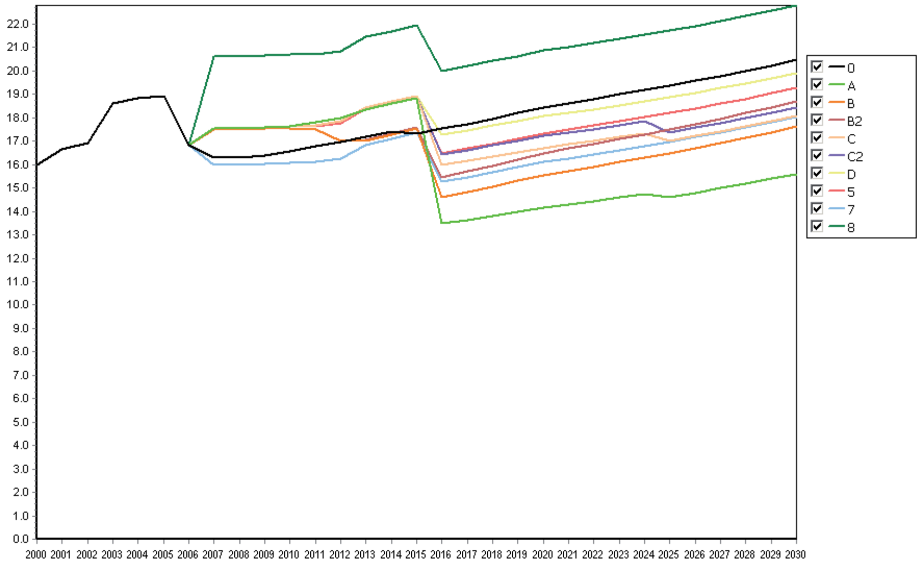

Fig. 9. CO_2 emissions in mill. t of all scenario

From Figure 9 can be concluded, that the scenario with highest CO_2 emissions is -/8 E, and the lowest A/6. The highest emissions of scenario -/8 E are caused by greater oil shale mining amounts and big shale oil industry. The lowest emissions of the scenario A/6 are due use of nuclear power. Other scenarios with lower pollution level are scenarios B/4, -/7 E and C/2. From Figure 9 it is obvious, that none of the scenarios fulfills the emission target of The Development Plan of Energy Sector until 2020 to reduce CO_2 emission 2 times compared to 2007.

The comparison of SO_2 emissions of above described scenarios is presented on Figure 10.From this figure can be seen, that the scenario with highest SO_2 emissions is base-scenario 0/0. This is due to being the only scenario with so high oil shale share in the electricity production. Emissions of most of the scenarios are in the same, low level from the year 2016, when the old oil shale units are closed. Only in Scenarios B2/4 (using shale oil in the gas turbine instead of natural gas) and C2/3 (building a 400 MW coal power plant instead of oil shale power plant) the emissions are higher than for the rest of scenarios.

The scenarios with the lowest SO_2 emissions are in the same pollutant level in spite of fact, that the capacity of oil shale power units are different, which is after 2015 between 400-1200 MW. The reason for this is that most of the SO_2 emissions are caused by burning oil shale in the old PFBC units, which will be closed in 2015. Whereas the new CFBC units emit over 10 times less SO_2 [9] and therefore the level of emissions will be so low, that the difference in oil shale based generation will not affect the results in a significant way.

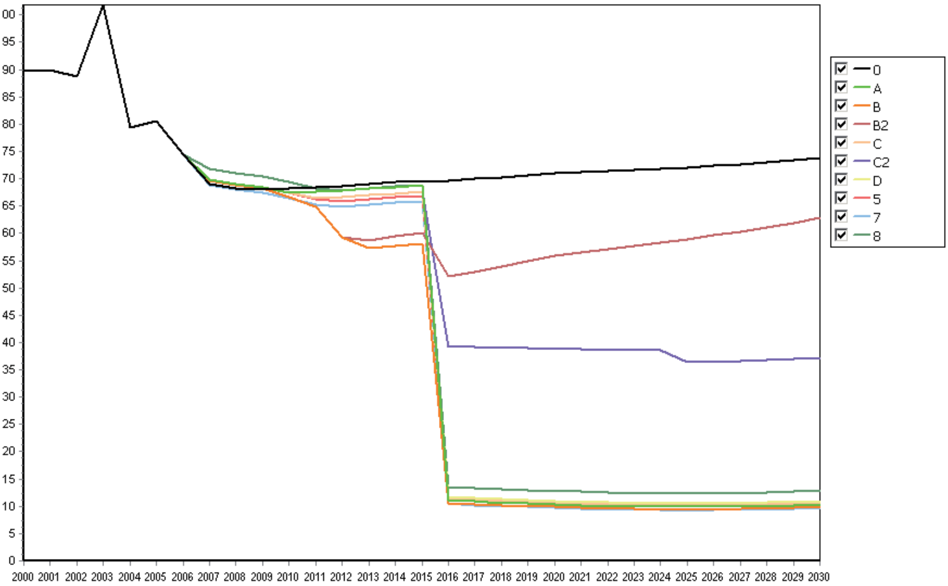

Fig. 10. SO_2 emissions in th. t of all scenarios

Conclusions

From the presented graphics it is clear, that most of CO2 and SO2 emissions are coming from oil shale fired power plants. Unfortunately none of the scenarios fulfills the emission target of The Development Plan of Energy Sector until 2020 to reduce CO2 emissions 2 times. One reason for this is the constant increase of consumption, which is depending on GDP growth. As the study was carried out in september 2008, the GDP prognoses were optimistic and were between 3-5% depending on the year. Probably the results would be a little different, if the LEAP model would include current GDP prognoses. Another reason is that the particular study investigated the scenarios of electricity production and emission reductions in other areas like district heating and transport are not indluded.

Based on analyzed graphics it is seen, that closing down of old PFBC units has a significant impact on the SO_2 emissions as the new CFBC units emit over 10 times less SO_2. Most of the scenarios are in the same pollutant level in spite of fact, that the total capacity of oil shale power units is different. This is due to a fact that the level of SO_2 emissions will be so low, that the difference in oil shale based generation will not affect the results in a significant way. With regards to CO_2 emissions, it was discovered that there is a growing trend of emissions, which is coming from the use of oil products (diesel, benzene, etc) in the transport and district heating sector. .

Based on analyzed CO_2 and SO_2 emissions of 10 electricity production scenarios it is evident, that the best scenarios regarding the pollution level are A/6 and B/4. A/6 is a scenario with nuclear power plant, but before the power plant starts operating, almost half of the electricity consumption would be imported. In this case it should be considered whether it would be beneficial to invest into sulfur catching technologies to keep some of old PFBC units operating until 2025. B/4 is a scenario of wind power development, but the CO_2 emissions will be higher than for Scenario A/6. This is due significant increase of natural gas consumption, which is used in gas turbine to balance fluctuating wind power production. It was also evaluated that it would not be environmentally thoughtful to use shale oil in the gas turbine instead of natural gas.

The scenarios with highest emissions are 0/0 and -/8. The scenario 0/0 is a base model, where it is assumed that the current situation continues. Scenario -/8 E has the highest CO_2 emissions, which is caused by greater oil shale mining amounts and extensive shale oil industry. The scenarios -/5 E, -/7 E, -/8 E have indicated that the greater the oil shale mining quantities, the higher are emissions, despite of the fact that equal amounts of electricity is produced. This is due to a fact that also mining and shale oil production are also emitting air pollutants. Therefore, looking in point of view of emissions, it is very important, that the oil shale mining is limited and the extensive shale oil production avoided. It was also found, that is not advisable to invest into coal power plant instead of oil shale generation units.

Acknowledgements

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