RIGA TECHNICAL UNIVERSITY
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RESEARCH ON DEVELOPMENT OF LATVIAN ENERGY SECTOR. IMPACT ASSESSMENT OF CARBON DIOXIDE CAPTURE AND STORAGE PROCESSES

Dissertation Summary

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The presentation of the dissertation with the purpose of obtaining the Doctoral Degree in Engineering (Dr.sc.ing) will take place on September 16, 2011 at 14:00, in the Assembly Hall of the Faculty of Power and Electrical Engineering of the Riga Technical University, Kronvalda bulvaris 1.

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CONFIRMATION

I, the undersigned, hereby confirm that I have developed this PhD thesis, which is submitted for consideration at the Riga Technical University, for obtaining the degree of Dr.sc.ing. and that this study has not been submitted to any other university or institution for the same purpose.

Julija Gusca ……………………………. (Signature)

Date: ………………………

This dissertation is written in Latvian and contains: introduction, 4 chapters, conclusions, bibliography, 31 figures, 10 tables and 117 pages. The bibliography contains 126 references.

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The topicality of the thesis

Currently there is a degree of discrepancy in the Latvian energy supply system – the potential for wood energy is high but the use of fossil fuels, especially natural gas, dominates the heating and electric energy supply. Moreover, the energy sector development strategies for Latvia call for continued use of fossil fuels for energy supply despite national commitments to reduce climate change and increase the use of renewable energy sources. Although the country does not have difficulties to fulfill its commitments in accordance with the 2012 year goal for the Kyoto protocol (since the year 1990, due to the decrease in industrial activities, the level of greenhouse gas emissions has reduced by two times), Latvia has great technical potential to increase its energy efficiency and reduce its greenhouse gas emissions in the energy sector.

One of the ways to stabilise and reduce greenhouse gas emissions in the atmosphere is the use of carbon capture and storage technologies (CCS) in the energy transformation sector. The CCS system includes the capture of CO_2 emissions from the flue gases emitted as a result of the energy transformation process, the processing, transportation and injection of the emissions in geological reservoirs. Contrary to Lithuania and Estonia, Latvia has geological structures within its territory that are suitable for CO_2 geological storage which makes CCS technologies not only technically possible on the national level, but also provides an opportunity to secure CO_2 emission "import" since Latvia could potentially provide its neighbors with a place to store their CO_2 emission in these reservoirs.

Most of the projects implemented on CCS worldwide are geared towards CO_2 emission capture from large-scale fossil fuel power stations, which are founded on the high CO_2 emissions factors from fossil fuels and on economic considerations. Nonetheless, technically it is also possible to accomplish CCS also for small scale and bio-fuelled power stations.

In order to accomplish the integration of CCS technologies into Latvia's energy supply system successfully, research is necessary to establish the technical, economic, climate and environmental factors which determine the introduction of such technology in Latvia.

The goal of the work

The goal of this thesis is to develop a multi-criteria evaluation methodology for the transfer of Latvia's energy supply system to low CO_2 emissions technologies.

The following objectives are set to be accomplished within this research:

1. To develop scenarios for introducing a carbon capture and storage system in Latvia's energy supply system from the years 2012 to 2020 and evaluate it from engineer-technical, economic, environmental and climate aspects.
2. To develop economic, environmental and climate indicators for introducing a carbon capture and storage system and determine its value in the case of Latvia's energy supply system.

Methodology of the research

A dynamic modelling method is applied for the modelling of the development of energy transformation and the valuation of the technical, economic and climate parameters related to it. Based on the data collected from energy transformation companies during the thesis work, a mathematical analysis was conducted using the mathematical statistics method – regression analysis. The values of CO_2 emission factors are analysed, as well as the electrical and heating energy produced and the energy efficiency indicators. Tests have been conducted on the regression analysis: the correct application of conditions has been tested, correlation test, adequacy test and autocorrelation. An empirical equation has been established whereby CO_2 emission optimisation is dependent on the efficiency ratio of the equipment, the amount of energy produced and the CO_2 emission factor of the energy source without CCS.

Life cycle analysis has been applied for valuation of the environmental factors and impacts resulting from the transportation of CO_2 through pipelines have been established.

Scientific significance

A methodology for implementing CO_2 capture and storage in Latvia's energy supply sector is developed as a result of this research. In order to choose the most optimal solution for the CO_2 capture and storage system from the engineer-technical, economic, climate and environmental aspects, a multi-criteria, dynamic valuation model is developed. During the process of conducting the mathematical analysis of the data of energy transformation companies, an empirical equation was developed and its adequacy was tested. The equation can be applied for the optimization of CO_2 emissions in energy sources without CCS. Indicators and coherences are established for the valuation of the operation of CCS technologies.

Practical significance

The methodologies developed and described within the scope of this research are important to specialists of various sectors:

1. European Union: the first results were acquired that explain the process of introduction of CCS in the energy transformation sector in relation to the requirements of the European Union Climate Package on the integration of carbon capture and storage in the energy transformation and industrial sectors.
2. Civil servants:
   a. The development scenarios for the implementation of CCS processes in Latvia's energy sector developed in this research provide first results of Latvia' s Government in connection with the commitments under the European Union's Climate package on carbon capture and storage process integration in the energy and industrial sectors.
   b. The national-level institutions which are responsible for energy planning in Latvia can apply the methodology on energy sector development for energy sector planning and the establishment of CCS technology. The results in changes of fuel balances provide information on estimations of energy supply security and self-supply through the use of renewable energy resources and CCS technologies and this information can be used for energy policy and strategy development.
   c. The national-level institution responsible for the implementation of the CO_2 capture and storage directive (for example Ministry of Environment and Regional Development) can use the methodology developed and the results produced for the development of a national programme on CO_2 capture and storage. The efficiency indicators set on CCS within the research (the specific expenses and the reduced or captured CO_2 tonnes) can be used to define the country's position on the implementation of the CCS directive.
   d. The national-level institutions responsible for greenhouse gas inventory, emission quota trading and foreseeing climate change processes (for example Ministry of Environment and Regional Development and Latvia's Environmental, Geological and Meteorological Centre) can use the CO_2 emission volumes from the valuation methodology of the CCS system to estimate GHG emission amounts, set goals for achievement of Kyoto protocol goals and develop emission quota distribution plans. The coherencies documented and conclusions made on the opportunity

to reduce CO_2 emissions should be taken into account by the ministry to develop or amend legislation on climate change and GHGs trading.

e. The national-level institution responsible for determining and monitoring environmental pollution and processes (for example Environmental State Bureau) can use the valuation methodology of engineer-technical and environmental factors to prepare conclusions during the process of evaluating the determination of environmental pollution from the impact of CCS processes, and to release pollution permits to those planning activities in CO_2 capture, transportation and storage processes.

3. Businesses:
   a. The engineer-technological valuation provides solutions on the integration of CO_2 capture technologies with various types of fuel, technologies and energy supply volumes, as well as provides a review of the economic, climate and environment indicators for the implementation of such technologies.
   b. The module on CO_2 transportation through pipelines provides information on potential pipeline producers and operators on the preconditions and costs associated with the production, maintenance and operation of CO_2 pipeline infrastructures.
   c. The empirical equation created on CO_2 emissions makes is possible to evaluate and estimate the dynamic dependence of changes in CO_2 emissions on changes in fuel consumption, efficiency ratio, and the emission factors of the fuel.
4. Banks un investors:
   a. The methodology on the valuation of economic factors and the determined correlation makes it possible for investors to evaluation CCS energy project and chose the most profitable technological solutions. The impact of defined CO_2 emission quotas on the payback time of CCS technologies permit the creation of appropriate strategies for the CO_2 emission trading scheme.
   b. The energy-technological indicators acquired (specific costs and the reduced or captured CO_2 emission tonnes and national CO_2 emission factors) allow for climate change and energy financial support funds to define quantitative indicative goals for project applicants on the implementation of CCS technologies.
5. Scientists and researchers: the analysis conducted of CCS technology implementation in Latvia's energy supply development outlines future

research to be conducted in the fields of energy, the environment and the economy.

6. Public: the analysis conducted of CCS technology implementation in Latvia's energy supply development informs the public about the impact of CCS systems on changes in the electricity tariffs and on aspects of the environment and climate.

Approbation

The results of the research has been discussed and presented:

1. Regional seminar "CO_2 Capture and Storage – Response to Climate Change" with the presentation "Introduction of CCS - Effects on Latvian Energy Sector", 13-14 April 2011, Vilnius, Lithuania.
2. 6th International Conference "WSEAS International Conference on Energy, Environment, Ecosystems and Sustainable development" with the presentation "Modelling of a Carbon Capture and Storage System for the Latvian Electricity Sector", 21-23 October 2010, Timisoara, Romania.
3. 10th International Conference „International Conference on Greenhouse Gas Control Technologies" with the presentation "Simplified Dynamic Life Cycle Assessment Model of CO_2 Compression, Transportation and Injection Phase within Carbon Capture and Storage", 19-23 September 2010, Amsterdam, the Netherlands.
4. 2nd International Conference "Environmental Best Practices Conference" with the presentation „The Analysis of Resources within the LCA of CO_2 Injection in Saline Aquifers", 14-18 September 2009, Krakow, Poland.
5. 49th RTU Scientific Conference with a presentation "Geological Storage of Carbon Dioxide Emissions: Energy Consumption", 13-15 October 2008, Riga, Latvia.
6. International Conference "Trondheim CCS conference" with a presentation "Decomposition Analysis of CO_2 Emissions Scenarios for Latvian Energy Sector", 16-17 October 2007, Trondheim, Norway.
7. 48th RTU Scientific Conference with a presentation "Geological Mineralizaton of Carbon Dioxides for CO_2 Storage in Latvia", 13-14 October 2007, Riga, Latvia.
8. 48th RTU Scientific Conference with a presentation "Applying CO_2 Capture Technologies for Small Scale Cogeneration Plants in Latvia", 13-14 October 2007, Riga, Latvia.
9. International Conference "EcoBalt' 2005" with a presentation "Ecoindicators Analysis in Latvian Energetic Sector", 5-6 May 2006, Riga, Latvia.

10. Conference organized by the Latvian Ministry of Environment and British Council "Development and implementation of Climate policy” with a presentation “Assessment of CO_2 sequestration in Liepaja region”, 11 November 2011, Riga, Latvia.
11. 46th RTU Scientific Conference with a presentation “Geological Carbon Dioxides Sequestration - a Tool for Emissions Reduction in Latvian Energy Sector”, 11-13 October 2005, Riga, Latvia.
12. 4th International Symposium “Nordic Minisymposium on Carbon Dioxide Capture and Storage” with a presentation “Modelling of Sequestration of CO_2 in Underground Storage in Liepaja”, 8-9 September 2005, Espoo, Finland.

Publications

1. Simplified Dynamic Life Cycle Assessment Model of CO_2 Compression, Transportation and Injection Phase within Carbon Capture and Storage. Gusca J., Blumberga D. // Energy Procedia, Volume 4. – 2011. - p. 2526 –2532.
2. Evaluation of CO_2 Emissions from Energy Sources in Latvia. Blumberga D., Veidenbergs I., Gusca J., Rošā M. // Latvian Journal of Physics and Technical Sciences. – Volume 47. - 2010. - p. 30 - 39.
3. Carbon Capture and Storage: Cost Analysis of Electricity Production for Latvia. Gusca J., Naroznova I., Blumberga D., Volkova A. // International Journal of Energy. - Issue 3. - Volume 4. – 2010. - p. 37-45.
4. Modelling of a Carbon Capture and Storage System for the Latvian electricity sector. Gusca J., Naroznova I., Blumberga D., Volkova A.// Selected Topics in Energy, Environment, Sustainable Development and Landscaping. – Proceedings of the 6th International Conference “WSEAS International Conference on Energy, Environment, Ecosystems and Sustainable development”. – Politehnica University of Timisoara, Romania. – October 21-23, 2010. – p. 415-421.
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6. Modeling of Installed Capacity of Landfill Power Station. Blumberga D., Kuplais G., Veidenbergs I., Dace E., Gusca J. //Scientific proceedings of Riga Technical University. - Series 13, Volume 3. - 2009. - p. 19 – 26.
7. Geological Storage of Carbon Dioxide Emissions: Energy Consumption Model for Injection Phase. Gusca J., Demidko J., Blumberga D. //

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8. Is CO_2 Compressing and Piping Environmentally Feasible? Djomo S. N., Romagnoli F., Gusca J., Blumberga D. // Scientific proceedings of Riga Technical University. - Series 13, Volume 1. - 2008. - p. 24 - 32.
9. Applying CO_2 capture technologies for small scale cogeneration plants in Latvia. Gušča J., Blumberga D., Blumberga M., Bērziņš Z. // Scientific proceedings of Riga Technical University. - Series 4, Volume 17. - 2008. - p. 221 - 226.
10. Geological Mineralizaton of Carbon Dioxides for CO_2 Storage in Latvia. Gušča J., Blumberga D., Valtere S., Baško A. // Scientific proceedings of Riga Technical University. - Series 4, Volume 17. - 2005. - p.265 – 272.
11. Analysis of Ecoindicators in Latvian Energetic Sector. Blumberga D., Blumberga M., Gušča J. //International conference Eco - Balt 2005. – Riga. – 2005. - 5 -6 May. – p. 58 -59
12. Modeling of Pellet Stoves for Dynamic Simulation of System and Estimation of Environmental Performances. Rochas C., Gusca J. //Scientific proceedings of Riga Technical University. - Series 4, Volume 14. - 2005. - p. 258 – 270.
13. Geological Carbon Dioxide (CO_2) Sequestration – a Tool for Emission Reduction in Latvian Energy Sector. Gusca J., Blumberga D., Blumberga M. // Scientific proceedings of Riga Technical University. - Series 4, Volume 14. - 2005. - p.250 – 257.
14. Kliedētās enerģijas ražošanas indikatori. Mazās koģenerācijas stacijas. Blumberga D., Veidenbergs I., Gušča J., Blumberga M., Kamenders A. // //Latvian Journal of Physics and Technical Sciences. - Volume 6. - 2005. – p.16 - 23.
15. Modelling of Sequestration of CO_2 in Underground Storage in Liepaja. Gusca J., Blumberga D. // "Nordic Minisymposium on Carbon Dioxide Capture and Storage". - 8-9 September 2005. - Espoo, Finland.
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Thesis outline

The thesis has been developed in Latvian and consists of the introduction, four chapters, conclusions and references. The introduction looks at the topicality of the work, the goal of the research and the methods, as well as the importance of the results of the research.

The first chapter of the thesis discusses the theoretical basis of carbon capture and storage processes and the previous research conducted on this subject. This chapter concludes by defining the goal and tasks of the research.

The second chapter of the thesis describes the methodology for modelling the development of Latvia's energy transformation sector from technical economic and environmental factors. An empirical equation is created and tested with the mathematical statistics method for the dependency of CO_2 emission optimization on the production of energy, the CO_2 emission factors of fuel and the efficiency of the energy sources.

The third chapter of the thesis outlines the results of the energy sector development scenarios and sets the values of the economic, technical and climate indicators for the introduction of CCS technologies.

The fourth chapter of the thesis provides a methodology for the valuation of environment factors for the transportation of CO_2 through pipelines and the values for the environmental factors of several environmental impact categories are determined.

The thesis consists of 117 pages, including 31 figures, 10 tables and a list of references with 126 sources. The summary does not include a review of literature.

1. The development model of Latvia's energy sector

The model developed in this thesis is the national level energy model of a specific country through which it is possible to produce results on the fuel structure, the volume of CO_2 emissions, trends in adopting new technologies, energy transformation costs and environmental factors in the period from 2012 and 2020. The model is based upon a direct connection between energy consumption and energy supply under specific economic and legislative conditions in the energy market.

2. The statistical processing of typical energy system data. Development of the empirical model

The interrelation between the many factors affecting an energy system can be defined by using data from real energy transformation equipment. Data from 72 energy sources which have participated in the 2^{nd} period of Latvia's emissions trading system have been processing and analysed in this dissertation and these create the statistical data cluster for the model. Statistical data and data gathered through direct and indirect measurements from the companies involved in emission quota trading have been used to evaluate the current situation in the energy transformation sector. The statistical data processing and the creation of the multi-factor empirical model have been conducted with the support of the STATGRAPHICSPlus computer programme.

Since an intermediate goal of the dissertation is to model the development of low CO_2 emissions technologies in Latvia, a empirical model is established that defines the creation of CO_2 emissions in Latvia's energy supply companies. The following values are used in the analysis:

- Installed capacities of energy transformation equipment (N_e, MW);
- Efficiency ratios of equipment ($\eta_{i,}$ %);
- The fuel used for energy transformation;
- The energy produced for each fuel (E_i, MWh/year);
- CO_2 emissions produced during the energy transformation process for each fuel type ($C_{i,}$ tCO_2/year).

The application of the empirical model is limited in certain data intervals that define concrete data selection. The data groups modelled in the dissertation are defined by the following:

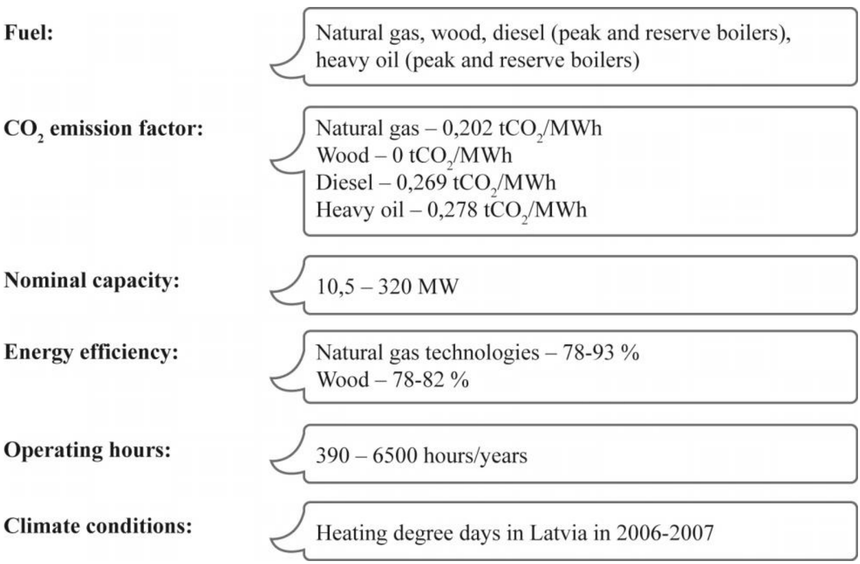

Figure 1. Boundaries of the empirical model

If the indications differ from those above, the application of the empirical model will be incorrect.

As a result of the research, a regression equation is developed (1) which indicates the dependence of the CO_2 emissions from the energy source on the energy efficiency of equipment, the fuel type and the volume of produced energy.

$$C = 4432{,}4 + 0{,}2427 \cdot E_e + 39526{,}9 \cdot c^0_{CO_2} - 16058 \cdot \eta_e \quad (1)$$

where

C – volume of created emissions, t CO_2/year;
E_e – energy produced MWh/year;
$c^0_{CO_2}$ – CO_2 emission factor of the fuel used, t CO_2/MWh;
η_e – efficiency of energy transformation.

Through the statistical processing of the empirical model data, the R^2 value - 0,94 - is calculated. This means that the developed model (Equation 1) describes 94% of the analysed data changes in correspondence to the regression zone. The development of the adequacy of applying the empirical equation is tested, by following the terms of regressions analysis:

- An autocorrelation test is conducted using the Durbin–Watson test and processing the statistical data, the DW criterion is defined. That values is 1,67, which exceeds 1,4 which means that no significant autocorrelation of the residues is observed and that the evaluation of the achieved values is not crippled in the process of the least squared method evaluation.
- The dependant changing variable (CO_2 emissions of the energy source) complies with the normal allocation rule (see Figure 2).

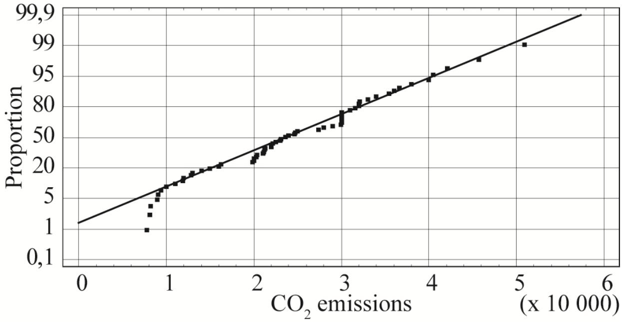

Figure 2. The distribution of CO_2 emission values from energy sources

- A Heteroscedasticity test is performed in a graphic way, checking the allocation of the residues as a function of energy efficiency of the technologies (see Figure 3).

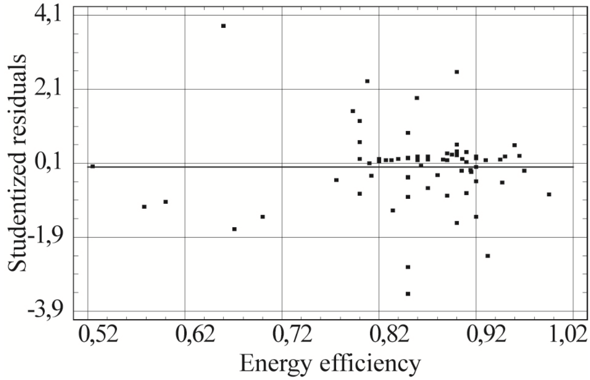

Figure 3. Allocation of the residues depending on energy efficiency

- There are no significant changes in the allocation of the residues depending on the energy efficiency and the residues values are similar within the energy efficiency diapason.
- A multicolinearity test is developed analysing the correlation matrix of the calculated coefficients of the regression equation and the results show that the correlation between the coefficients and thus also the independent changing variables is insignificant. This is indicated by the low values of the correlation values (from 0,0473-0,35) – they do not exceed 0,5, and thus the coefficient values of the equation are correct.

The empirical and calculated data analysis (see Figure 4) shows a very good correlation between both data groups and confirm the correct use of the model created.

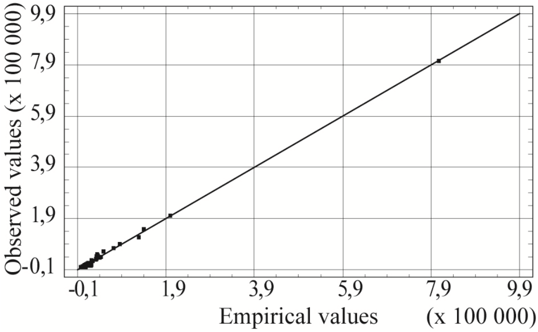

Figure 4. Comparison of the empirical and observed data of the CO_2 emission values of the energy sources

The empirical model is developed based on the electrical power station without the CCS data and this model can be applied only in similar stations and within the boundaries of the model's parameters. Since no CCS technologies have been introduced in Latvia and thus no statistical data (or measurements) are available, it is not possible to develop an empirical model that would characterize power station with CO_2 capture of CO_2 emissions dependence on other energy sources.

3. Development scenarios of the energy transformation sector

The model on the development of the energy sources consists of four calculation models that are interrelated: enginner-technical calculation model, economic calculation model, climate estimation model and environmental factor model. The engineer-technical, climate and economic models are created with the support of a dynamic linear programming method. The environment factor analysis applies a dynamic life cycle analysis method.

The algorithm of the model used in the work is shown in Figure 5.

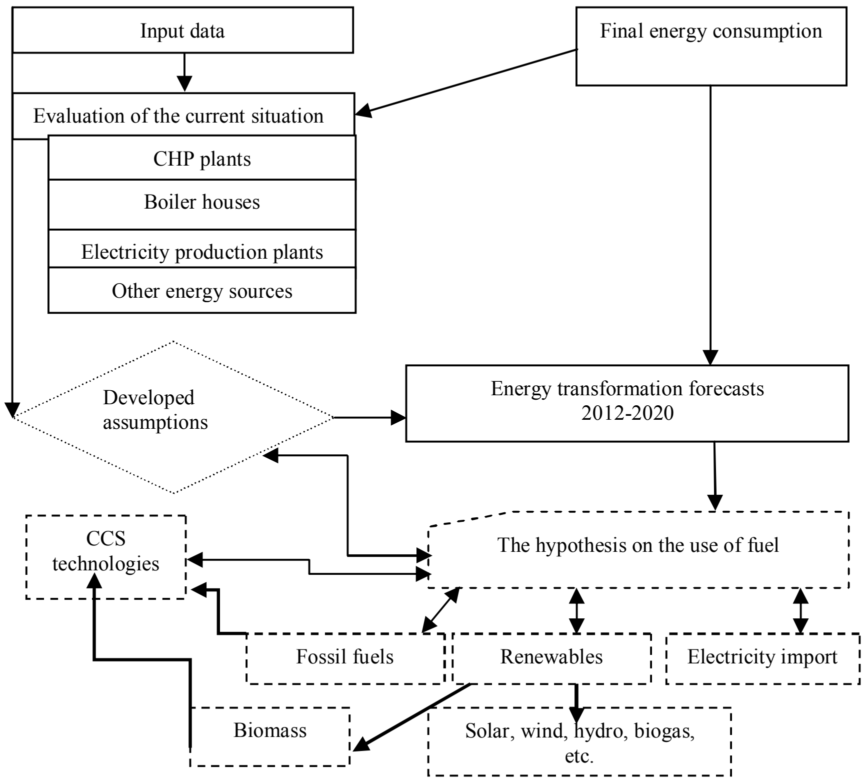

Figure 5. Model of the algorithm of the energy supply sector

The analysis is based on the assumption, that the driving factor for the development of the energy sector is the demand for energy from the consumer. The algorithm for the energy end use is illustrated below. This model developed can be considered a results-oriented model, the purpose of which is to create a demand for alternative energy, if within the choice of technological solution preference is given to energy technologies that are geared to reducing the CO_2 and environmental pollution emitted into the atmosphere from the energy supply sector.

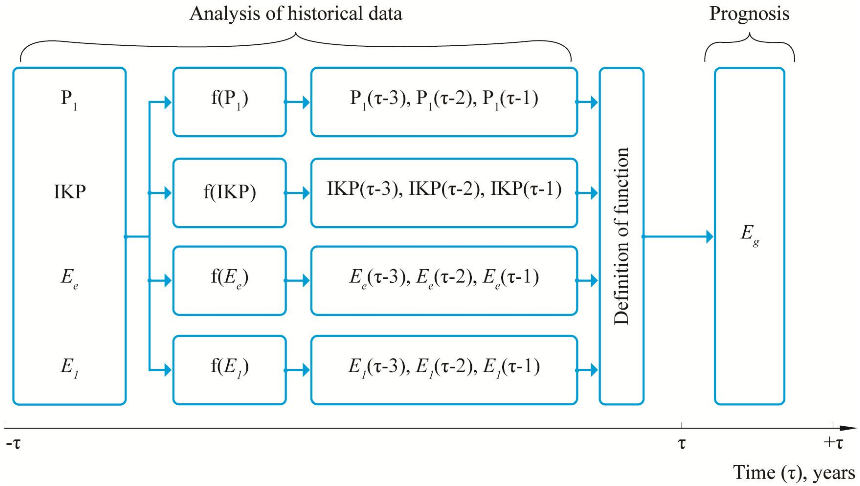

Figure 6. Model for the prognosis of energy end use
(P_1- population, IKP – Gross domestic product, in thousands of Latvian Lats (LVL); E_e – produced energy, MWh/year; E_1 – imported energy, MWh/year; E_g–final energy consumption, MWh/year, τ - time, years)

The prognosis of the energy final consumption is made based on an analysis of the statistical data and the estimates of trends in the changes in the demographic, economic and energy consumption. The prognoses are divided into three economic sectors – households, industry and services (see Figure 7).

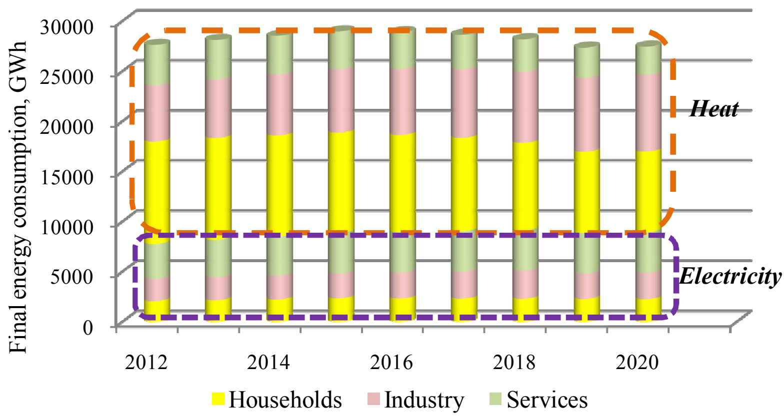

Figure 7. Final electricity and heat consumption from 2012 - 2020

Mathematical statistic methods - correlation and regression analysis – have been used to evaluate relations between CO_2 emissions from energy sources and technical and climate factors (described in Chapter 2).

The development of the energy sector prognosis in the work is looked at through four possible scenarios:

- **Scenario A** – energy transformation is dominated by fossil fuel energy sources;
- **Scenario B** – renewable energy resources are used to their maximum potential for energy transformation;
- **Scenario C** – energy transformation is dominated by fossil fuel energy sources, however from the year 2015 CCS technologies are introduced in the existing and planned fossil fuel energy sources with an installed capacity over 20 MW.
- **Scenario D** – energy transformation is based to the maximum on the use of renewable energy sources and all energy sources (existing and planned) with an installed capacity over 20 MW (regardless of the type of fuel used for production – fossil or biomass fuels) are installed with CCS technologies.

Within the work it is assumed that CCS technologies are not introduced in boiler houses and power stations with a low capacity and thus the emissions created are emitted into the atmosphere.

3.1. Engineer-technical valuation

The energy transformation model describes the mathematical equation illustrated below:

- <u>Energy demand-supply structure</u>

$$\begin{cases} \sum E_p \cdot \zeta_{ee} \leq \dfrac{\sum E_r}{\eta_p} \\ \sum J_p = \left(\sum_{\tau-q}^{\tau}(J_n^{AER} + J_n^F) + \sum_{\tau}^{\tau+q}(J_n^{AER} + J_n^F)\right) \cdot \sigma_n \end{cases} \quad (2)$$

where

E_p – energy demand, GWh/year;
E_r – energy supply, GWh/year;
J_p – demand for energy supply capacity, GW/year;
J_n^{AER} – capacity of renewable energy technologies, GW;
J_n^F – capacity of fossil fuel technologies, GW;
ζ_{ee} – impact factor of energy efficiency measures on energy demand at the end consumer;
η_p – efficiency of energy supply from the producer to the consumer , %;

σ_n – depreciation ratio of the energy producing technologies, %;
q – operational lifetime of power station, years;
τ – time unit.

- <u>Efficiency of the energy transformation source</u>

$$\begin{cases} \sum E_k \geq \dfrac{\sum E_{rez}}{\eta_e} \\ \sum E_k + \sum E_{rez} \geq \sum E_p \end{cases} \quad (3)$$

where
E_k – fuel consumption for the energy transformation demand, GWh/year;
E_{rez} – reserve of energy supply (reserve capacity or import), GWh/year;
η_e – energy transformation efficiency.

- <u>CO_2 capture</u>

$$\begin{cases} C_e \leq \sum N_u \\ E_{p,u} = \sigma_{p,u1} \cdot C_e + \sigma_{p,u2} \cdot N_u \\ E_{s,u} = \sigma_{s,u1} \cdot C_e + \sigma_{s,u2} \cdot N_u \end{cases} \quad (4)$$

where
C_e – CO_2 emitted from energy sector in τ year, t CO_2;
N_u – productivity of all installed energy sector capture technologies (capacity for capture), t CO_2/year;
$E_{p,u}$ – primary energy consumption (p) for all capture technologies, MWh/year;
$E_{s,u}$ – secondary energy consumption (s) for all capture technologies, MWh/year;
$\sigma_{p,u1}$, $\sigma_{p,u2}$ – specific primary energy consumption for the operation of CO_2 capture technologies, MWh/t CO_2;
$\sigma_{s,u1}$, $\sigma_{s,u2}$ – specific secondary energy consumption for the operation of CO_2 capture technologies , MWh/t CO_2;
$_u$ – characteristic index of the capture stage;
$_p$ – primary energy index;
$_s$ – secondary energy index.

- CO_2 compression and transportation through pipelines

$$\begin{cases} E_{s,k} = k_k \cdot ln\frac{p_{k2}}{p_{k1}} \cdot C_k^1 \\ N_k \geq C_e \\ N_c - N_k \leq \lambda_c \\ N_c \geq \frac{A_c}{w_c} \cdot C_c \end{cases} \quad (5)$$

where

$E_{s,k}$ – secondary energy consumption (s) for CO_2 compression, MWh/year;
k_k – specific electricity consumption for compression of 1 tonne CO_2, kWh_e/tCO_2;
p_{k1} – CO_2 pressure upon entry into the compressor, MPa;
p_{k2} – CO_2 pressure upon exit from the compressor, MPa;
N_k – CO_2 compressor productivity, t CO_2/year;
C_k^1– volume of CO_2 emissions conveyed to the compressor, t CO_2/year;
C_e – CO_2 emitted by the energy sector in one year, t CO_2/year;
C_c – volume of CO_2 emissions transported through the compressor, t CO_2/year;
N_c – productivity of the pipeline, t CO_2/year;
λ_c – CO_2 emission losses from CO_2 transported via pipelines, t CO_2 /year;
w_c – CO_2 flow through the pipeline, km · tCO_2/year;
A_c – pipeline length (from the point of CO_2 capture to the CO_2 compressor), km;
$_k$ – characteristic index of the compression stage;
$_c$ – characteristic index of the stage of transportation along the pipeline.

- CO_2 injection and storage

$$\begin{cases} C_k^2 - N_{ie,j} \leq \lambda_{ie,j} \\ N_{ie,j} \leq V_r \\ V_r = C_n^{\tau} - C_n^{\tau-1} \\ \lambda_r = \frac{C_n^{\tau} - C_n^{\tau-1}}{A_r} \\ \lambda_r \cdot A_r \geq \lambda_{ie,j}, \lambda_r \neq const_r \\ E_{k\&ie,s} = \sigma_{s,k1} \cdot E_{k,z} + \sigma_{s,k2} \cdot \frac{p_k}{A_r} + \sigma_{s,k3} \cdot \frac{p_r}{} \end{cases} \quad (6)$$

where

$N_{ie,j}$ – CO_2 injection productivity from j wells, t CO_2/year;
C_k^2 – volume of CO_2 emitted from the compressor, t CO_2/year;
$\lambda_{ie,j}$ – CO_2 emission losses from the injection wells, t CO_2 /year;
V_r – volume of CO_2 injected in the reservoir in the concrete reservoir during the year of exploitation, t CO_2/year;
j – number of injections wells;

C_n – volume of CO_2 emissions stored in τ year, t CO_2/year;
λ_r – CO_2 emission losses from the reservoir, t CO_2 /year·km;
A_r – CO_2 injection depth, km;
$E_{k\&ie,s}$ – secondary energy consumption during compression and injection, MWh/year;
p_k – CO_2 pressure at the entry compressor, MPa;
p_r – pressure at the geological reservoir, MPa;
d_r – diameter of injection pipe, km;
$\sigma_{s,\ k\ 1}$ – specific secondary energy consumption at CO_2 compression, MWh/t CO_2;
$\sigma_{s,k2}$ – specific secondary energy consumption for the compensation of pressure loss on the transportation length, MWh · km/MPa;
$\sigma_{s,k3}$ – specific secondary energy consumption for the compensation of pressure losses on the injection depth, MWh · km/MPa;
$_{ie}$ – characteristic index of the injection stage;
$_{r}$ – characteristic index of the geological reservoir.

3.2. Economic valuation

The valuation of the economic aspect of the scenarios defined in the work are conducted by calculating and comparing the total costs and capital expenses of the primary energy source which are created by the capacity of a new electrical and cogeneration power station in the time from 2012 to 2020. Additional economic indicator data come from the analysis of cash flow from CO_2 emission trading.

- Energy transformation and capture costs

$$I_\partial = \sum_{x,\tau} \left(B_\partial \cdot i_{kur,\partial}\right) + \left(W \cdot i_{kap,\partial}\right) + \left(E_e \cdot i_{eks,\partial}\right) + \left(E_e \cdot i_{a,\partial}\right) + \left(A_p \cdot i_{zt,\partial}\right) \quad (7)$$

where
I_∂ – energy transformation costs in a standard electrical power station (without CCS), LVL/year;
B_∂ – fuel consumption for energy transformation in a standard electrical power station, MWh_k[1];
i_{kur} – price of fuel, LVL/MWh_k;
W – capacity of energy transformation equipment, MW;
i_{kap} – scale of capital investments per installed capacity LVL/MW;
E_e – volume of energy produced, MWh;

[1] MWh_k – amount of energy expressed through fuel consumption.

i_{eks} – volume of operational and service costs per each unit of energy produced, LVL/MWh;
i_a – costs associated with the management of byproducts (ash, slag, emissions) per each unit of energy produced, LVL/MWh;
A_p – distance from the energy transformation enterprise to the consumer, km;
i_{zt} – specific expenses for averting energy transmission, LVL/km;
∂ – characteristic index of a standard power station (without CCS).

In case of CCS technologies (scenarios C and D) additional costs are created from costs for the implementation of the stages of CO_2 capture, compression, transportation and injection. Thus formula 7 is expanded by additional cost indicators.

$$\begin{cases} I_u = \sum_{x,\tau} (B_u \cdot i_{kur,u}) + (W_u \cdot i_{kap,u}) + (C_u \cdot i_{eks,u}) + (C_u \cdot i_{a,u}) + (C_u \cdot i_{dz,u}) \\ I_k = \sum_{x,\tau} (W_k \cdot i_{kap,k}) + (C_u \cdot i_{eks,u}) + ((C_c - C_u) \cdot i_{z,k}) \\ I_c = \sum_{x,\tau} (C_c \cdot i_{kur,c}) + (W_c \cdot A_c \cdot i_{kap,c}) + (C_c \cdot i_{eks,c}) + ((C_{ie} - C_c) \cdot A_c \cdot i_{z,c}) \\ I_{ie} = \sum_{n=1,\tau}^{j} (v \cdot (i_{pl.} + (i_{kap,ie} \cdot A_r)) + (p_{ie} \cdot C_{ie} \cdot i_{eks,ie}) + (c_{ie} \cdot i_{z,ie}), \qquad C_{ie} < C_u \\ I_r = \sum_{x,\tau} I_{eks,m} \end{cases} \quad (8)$$

where

I_Q – cost of electricity production in a CCS power station, LVL/year;
I_u – costs of the CO_2 capture stage, LVL/year;
I_c – costs of the CO_2 transportation along the pipeline stage, LVL/year;
I_k – costs of CO_2 compression stage, LVL/year;
I_{ie} – costs of CO_2 injection in the geological reservoir stage, LVL/year;
I_r – costs of CO_2 storage in the geological reservoir stage, LVL/year;
B_u – fuel consumption for CO_2 capture, MWh_k/year; $B_\partial > B_u$;
W_u – installed capacity of capture technologies, MW, $W_u = f(E_f;\ \eta_e)$;
C_u – volume of captured emissions, t CO_2/year;
$i_{kur,u}$ – specific costs for CO_2 capture per unit of produced energy, LVL/MWh_k;
$i_{kap,u}$ – specific capital investment costs per unit of installed capacity of captured system, LVL/MW;
$i_{eks,u}$ – specific costs for the exploitation expenses in the capture stage, LVL /t CO_2;

$i_{a,u}$ – specific costs for the management of byproducts at the capture stage, LVL /t CO_2;
$i_{dz,u}$ – specific costs for the cooling of the captured CO_2, LVL /t CO_2.
v – CO_2 flow rate, m/s;
W_k – capacity of the compressor/pump, kW;
C_u – volume of captured emissions, t CO_2;
C_c – volume of emissions transported along the pipelines, t CO_2;
$i_{kap,k}$ – specific capital investment costs of the compressor, LVL/kW;
$i_{eks,u}$ – specific coasts for operation of the compressor/pump, LVL/t CO_2;
$i_{z,k}$ – specific costs of averting CO_2 losses during the compression process, LVL/t CO_2.
W_c – capacity of the pipelines, t CO_2, $W_c = f(C_c)$;
C_{ie} – volume of injected emissions, t CO_2;
$i_{kur,c}$ – specific costs for CO_2 transportation, LVL/t CO_2;
$i_{kap,c}$ – specific capital investment costs per unit of transportation system, LVL/t $CO_2 \cdot$ km;
$i_{eks,c}$ – specific costs of exploitation costs at the transportation stage, LVL/t CO_2;
$i_{z,c}$ – specific costs for reducing CO_2 losses in the pipeline network, LVL/t CO_2 ·km.
$i_{pl.}$ – costs associated with the construction of the injection wells (place inspection, planning, land purchase, licensing, etc), LVL;
$i_{kap,ie}$ – specific capital investment costs for the establishment of injection wells (including drilling work, well construction and preparation), LVL/km;
$i_{eks,ie}$ – specific costs for the exploitation expenses of the injection stage, LVL/t CO_2·MPa;
$i_{z,ie}$ – specific costs for reducing CO_2 losses from the injection wells, LVL/t CO_2;
p_{ie} – CO_2 injection pressure, MPa;
c_{ie} – CO_2 losses during the injection process, tCO_2;
$I_{eks,m}$ – monitoring costs of the CO_2 storage area, LVL/year;
ϱ – characteristic index of the CCS processes.

In order to evaluate the economic aspects of introducing CCS technologies in depth, an analysis of the electricity tariffs in the event of complete implementation of CCS technologies is conducted for six energy transformation technologies:

1st technology – pulverized coal combustion with pre-combustion MDEA solvent capture;

2nd technology – integrated coal combined cycle technology with pre-combustion MDEA solvent capture;
3rd technology - natural gas combined cycle technology with pre-combustion MDEA solvent capture;
4th technology - natural gas combined cycle technology with chemical looping combustion capture;
5th technology - biomass-fired cogeneration plants based on an integrated gasification combined cycle technology with pre-combustion MDEA capture;
6th technology - biomass-fired plant based on a steam turbine technology with post combustion MEA solvent capture.

3.3. Valuation of climate and environmental factors

An additional analysis of climate in the research is conducted with the IPAT method, which characterises the dependence of the extent of CO_2 emissions from energy systems from economic, demographic and legislative factors.

The interrelation from the IPAT is based on the assumption that impact of human activity on the environment is affected by three factors – the population, the specific resource consumption level which is characterised by prosperity and the damage caused to the environment by technologies.

$$C_e = P_1 \cdot \left(\frac{IKP}{P_1} \cdot \frac{E_p^*}{IKP}\right) \cdot \left(\frac{E_f}{E_p^*} \cdot \frac{C_e}{E_f}\right) \qquad (10)$$

where
E_p^* – primary energy sources, MWh_k/year;
E_f – fossil energy resource consumption, MWh_k/year.

Within the thesis an assumption is established, that CCS technologies are introduced in Latvia's energy sources from the year 2015. In case of CCS, the emissions created as a result of fossil fuel combustion are allocated a CO_2 emission factor with the value 0 t CO_2 to 1GWh fuel, and for biomass energy source with the corresponding capacity is allocated a negative emission factor (-397) t CO_2 to 1 GWh fuel.

Evaluation of the Results

The results produced from the research are grouped in two levels:

1. according to technological principles – the energy system without and with the application of CCS technologies (Scenarios A and B and Scenarios C and D, respectively);
2. according to the valuation aspects – engineer-technical, economic, climate and environmental aspects.

The results of the engineer-technical valuation of the development scenarios reflect changes in the supply of electricity and fuel consumption during the planning period.

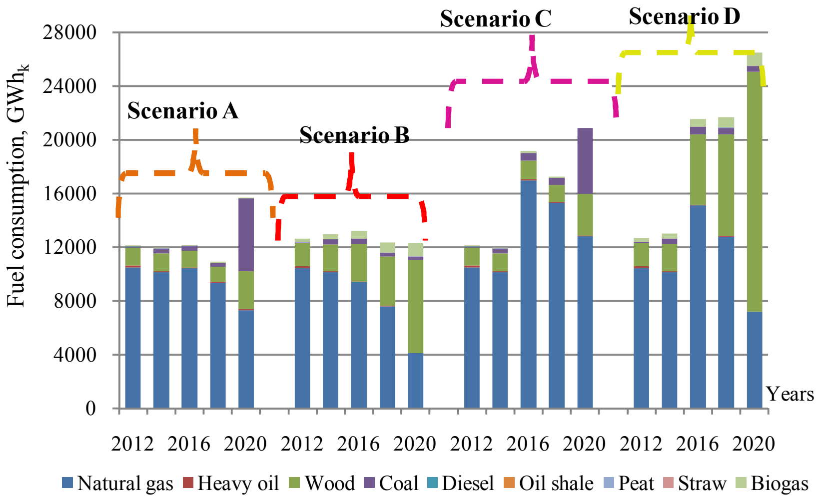

Figure 8. Energy consumption in the transformation sector

In case of the CCS technologies, the greatest increase of energy consumption per produced energy unit is achieved through biomass combustion technologies: biomass electrical power stations with CO_2 capture are currently at an early stage of development and have characteristically high energy consumption for CO_2 capture, which reduced the total operational efficiency of the energy system to 30–43%. Nonetheless this trend cannot be considered as constant and in the next ten years it is expected that development in this sector will increase, and due to the opportunities for biomass and CCS technology application, it would be possible to achieve the potential to decrease CO_2 emissions.

The introduction of CCS technologies has an affect on the ranges of the electricity tariff, but cannot influence the trends in tariffs – usually the costs of electricity in systems with CCS conform to the price distribution of the standard stations of the same fuel type. A fall in the tariff in the biomass model (in comparison with the standard power station) occurs when additional costs for introduction of CCS do not exceed the income from the sale of assigned quotas. In the fossil fuel models, a reduction in tariffs is possible when the costs for introduction and use of CCS do not exceed the amount of money which the energy producer invested in the purchase of emission quotas before commencing storage of CO_2 emissions.

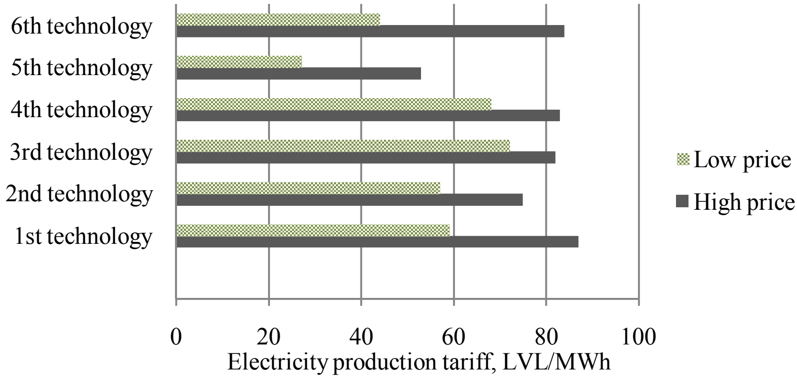

Figure 9. Electricity production tariffs in the event of CCS introduction

Figure 9 shows, that upon introduction of CCS in the biomass models, there is a reduction in the tariffs (4–47% - in case of the 5th technology and up to 33% - in case of the 6th technology).

The estimation of CO_2 emission quota prices in the European market indicates a rise in prices for quotas in the future. An increase in the proportion of biomass in the total transformation sector will increase CO_2 savings, thereby reducing the costs of CCS introduction on account of changes in the emission quota trading. This tendency in case of the CCS system (considering the assumptions for CO_2 emissions trading in the CCS systems used in this research) is considered as a support measure for CCS technologies and facilitates a shorter payback period and a decrease in tariffs. The data in Table 1 show the quota trading measure can stimulate producers to use CCS technologies (the calculation is made under the same circumstances: capital return rate of 12,2% and a capital return time period of 10 years). In case of the 5th technology, it is possible to reach full compensation of CCS expenses with the income generated from the sale of quotas - the income from quotas is up to two times higher that the expenses. This can be explained by the model's relatively low efficiency ratio values (14–30%), under which the fuel consumption for securing production processes increases, as do the emissions produced.

Table 1

Comparison of annual CCS costs with the expenses and income associated with emission quota trading

CCS technologies	CCS annual costs, LVL/Wh	Annual quota purchase expenses (-)/ income (+), LVL/Wh
1st technology	20–40	- (19–21)
2nd technology	14–23	- (20–22)
3rd technology	15–21	- (10–11)
4th technology	12–23	- (10–11)
5th technology	17–27	+(30–41)
6th technology	45–56	+(37–79)

In case of the 6th technology model, however, due to the high CCS costs (approximately two and a half times larger than in the 5th technology) the small range in income generated from quotas does not always serve to fully compensate the CCS costs and thus there is a much more significant increase in electricity tariffs (up to 11%). It was calculated that in case of the 6th technology, in order to fully compensate the CCS annual expenses (assuming the return period for capital expenses for CCS introduction is 10 years) there would need to be an increase in CO_2 emissions quota prices of 28 LVL/t CO_2 to 34 LVL/t CO_2.

A great deal of European research on the economic valuation of CO_2 is developed for fossil fuel power plants because the primary goal of CCS technologies is to limit CO_2 emissions into atmosphere from the combustion of fossil fuel resources (Figure 10).

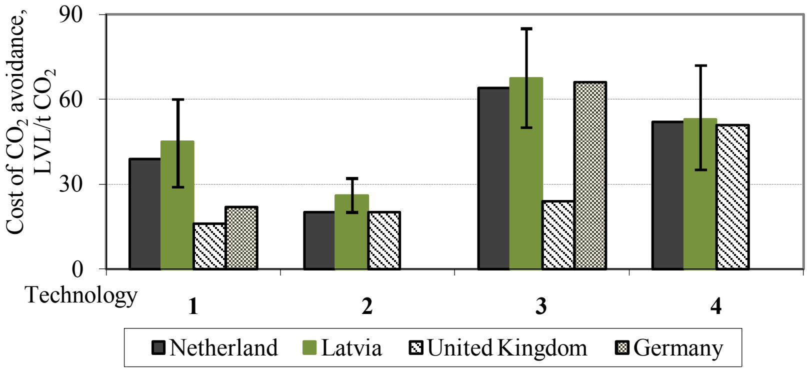

Figure 10. Comparison of the costs of CO_2 avoidance in fossil fuel powered technologies with CCS

The differences in specific costs of CO_2 emission avoidance in fossil fueled energy sources might be explained with different values of specific CO_2 emission factors related per one unit of electricity delivered to the end user:

- Germany - 0,624 t CO_2/MWh;
- United Kingdom - 0,543 t CO_2/MWh;
- Netherlands - 0,435 t CO_2/MWh;
- Latvia - 0,109 t CO_2/MWh.

A low emission factor is typical for Latvian electricity market, which makes the implementation of CCS technologies more expensive when calculating costs per tonne of CO_2 avoided.

Within the energy-technical climate valuation, GHG emissions in different energy system development scenarios are calculated. The changes in the dynamics of CO_2 emission in the analised scenarios is illustrated in Figure 11.

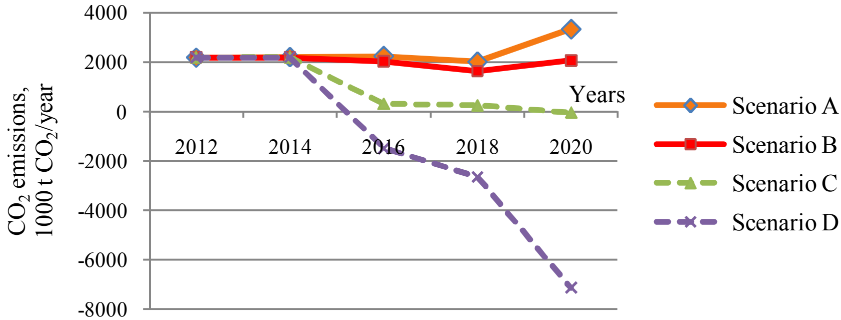

Figure 11. Changes in the dynamic of CO_2 emissions

Based on the engineer-technical and climate valuation sections of the calculations made, i.e. by attributing the energy consumption to the CO_2 emissions produced, specific CO_2 emission factors for Latvia's transformation sector from the year 2012 and 2020 are set.

Table 2

Specific CO_2 emission factors in Latvia's transformation sector in the years 2010 – 2020

Year	CO_2 emission factors, t CO_2/MWh_k			
	Scenario A	Scenario B	Scenario C	Scenario D
2012	0,180	0,173	0,180	0,172
2014	0,183	0,169	0,183	0,168
2016	0,184	0,154	0,016	-0,069
2018	0,184	0,132	0,015	-0,122
2020	0,212	0,168	-0,002	-0,269

Under certain technical-economic conditions, carbon capture and storage technologies can ensure the reduction of GHG emissions in Latvia's energy sector to reach negative CO_2 emissions. These kinds of climate measures, however, have a negative impact on the level of fuel consumption -- the efficiency of energy transformation decreases and the specific fuel consumption levels increase per unit of energy produced. Due to these circumstances, the argument that CCS systems are a "zero emission" technological solution is debatable.

In order to provide decisions makers and potential users of technologies with a more complete review of the environmental benefits of CCS technologies, the thesis is expanded with a life cycle analysis (LCA) of the stage of CO_2 transportation through the pipeline. The analysis of environmental factors from the CO_2compression, transport and injection phases is conducted with the life cycle analysis and life cycle cost analysis, using the *Ecoindicator - 99* method. The models that are analysed are:

- Alternative A – produced and captured CO_2 emission transportation via pipeline from a new gas turbine combined cycle power station (η_e = 43%) at a distance of 100 km;
- Alternative B – produced and captured CO_2 emission transportation via pipeline from a new gas turbine combined cycle power station (η_e = 43%) at a distance of 400 km;
- Alternative C – existing gas turbine combined cycle power station with integrated CO_2 capture (total η_e = 39%). The captured emissions are transported 100 km.
- Alternative D – existing gas turbine combined cycle power station with integrated CO_2 capture (total η_e = 39%). The captured emissions are transported 400 km.

Based on the LCA methodology, the thesis sets specific impacts on the environment from four models (Figure 12) and it is determined that the source of energy transformation and the efficiency of its operation produces an impact on the transportation stage: CO_2 transportation larger distances increases the total energy consumption for the maintenance of the system and decreases the rate of efficiency. As a result of these processes, the values of the impact on the environment increase. The environmental impacts score is given in milipoints (mPoints).

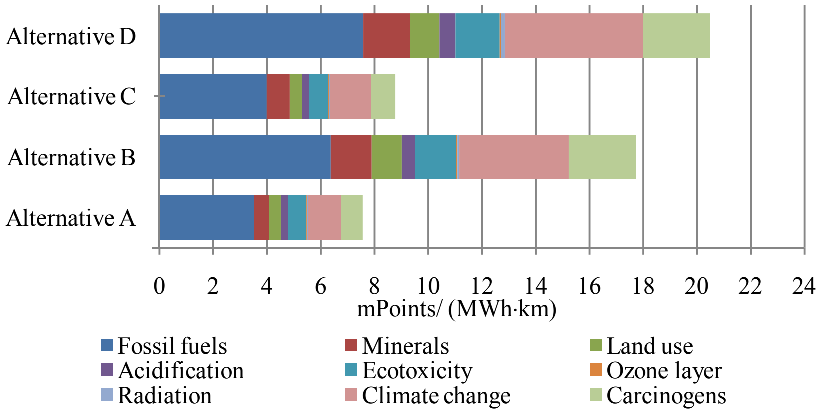

Figure 12. Specific impacts of the environment CO_2 transport and injection processes and their dependence on the transportation

The validity for CO_2 emissions transportation from the environmental-economic indicator perspective is determined by relating the environmental impact factor values against the costs of CO_2 transportation, compression and injection and this provides an estimation of how much it would cost to reduced the environmental impact (Table 3).

Table 3

Costs of reducing environmental impacts resulting from CO_2 transportation and injection processes

Impact category	**Environmental cost indicator, LVL/mPoint**			
	Alternative A	Alternative B	Alternative C	Alternative D
Fossil fuels	6,96	3,34	1,78	0,85
Minerals	1,56	0,78	0,28	0,21
Land use	0,78	0,43	0,21	0,14
Acidity	0,43	0,28	0,14	0,07
Eco-toxicity	1,28	0,71	0,36	0,21
Impact on ozone layer	0,07	0,00	0,00	0,00
Radiation	0,07	0,07	0,00	0,00
Climate change	2,70	2,27	0,64	0,50
Cancerous substances	1,56	1,07	0,43	0,28

Table 3 demonstrated that the highest costs for reducing environment impact are in the category of climate change. This means, that the CCS system's "zero" emission definition should be reviewed based on a valuation of the full cycle of environment factors related to CCS.

The results of the environmental factor evaluation show that, from the point of view of the environment and environmental costs, it is not viable to use electricity produced from existing energy sources fitted with CO_2 capture for the operation of the CO_2 transport and injection stages due to low levels of efficiency. In cases when the full cycle of operating CCS (transportation, compression and injection) introduction occurs, it is suggested that electricity is used from power stations that do not use CCS or use renewable energy sources, to reduce the environmental impacts and improve the overall efficiency of the system.

Conclusions

1. Regression analysis of the 2 year data of the energy sources taking part in the EU Emission Trading Scheme gives the possibility to develop an empirical equation which indicates the impact of independent values to the amount of CO_2 emissions. Mathematical evaluation testifies that the amount of the GHG emissions is impacted directly by three independent variable factors: energy efficiency of the energy sources, produced energy and emission factor of fuel. The adequacy of the use of this empirical equation is verified through a regression analysis. The equation can be applied within the range of concrete data groups and can be used to estimate the dependence of CO_2 emissions of enterprises within the set range on the volume of energy transformation, the efficiency of the energy course and the emission factor of the fuel.
2. A methodology developed for evaluation of the national energy sector development and planning is based on two entirely different hypotheses:
    - the primary energy resource structure of the energy sector is not changed till 2020;
    - the proportion of renewable energy sources in the total energy resource structure is increased to 40% from total energy consumption level.
3. A methodology for the analysis of captured CO_2 storage perspectives in case of the implementation of both these hypotheses indicates that in the event of introducing CCS technologies, the efficiency of fuel consumption per unit of produced energy reduces. The range of efficiency indicators of fuel consumption in the time period from the years 2012 – 2020 are:
    - Scenario A – 3,4–2,5 GWh_k/GWh;
    - Scenario B – 2,09–1,26 GWh_k/GWh;

- Scenario C – 2,01–2,38 GWh_k/GWh;
- Scenario D – 2,11–3,09 GWh_k/GWh.

These fuel consumption efficiency indicator values are explained because of the low efficiency ratios of CCS technologies.

4. Economic analysis of the full cycle of CCS technologies is resulting into a methodology for determination of tariffs. The methodology is tested and the results obtained are compared to the indicators developed by the scientists of the Greenhouse Gas R&D Programme of the International Energy Agency, World Coal Institute and Utrecht University. The theoretical approbated results indicate that the results acquired are feasible and the methodology can be applied for setting CCS tariffs. This makes it possible to conclude that the methodology can be used for development of CCS systems in other countries.
5. Results developed in a process of searching for a the direct correlation between CO_2 quotas prices and CSS costs show that, at a CO_2 quota price of 28 LVL/t CO_2, it is possible to fully compensate the introduction of CCS technologies in biomass energy sources. In the case of natural gas energy sources, emission quota trading makes it possible to reach a compensation of costs of 35–47%, and in the case of coal – depending on the capture technologies – at 50–100%. The most critical CO_2 emission quota price, at which the introduction of CCS technologies is fully compensated, is 70 LVL/t CO_2.
6. Valuation indicators for the exploitation costs of CCS technologies – specific costs per one tonne captured CO_2 show that, as far as costs concern, carbon capture is least expensive in production systems where fuels with a higher emission factor are used. When calculating CCS costs per one tonne captured $CO_{2,}$ the least expensive models are those using biomass, where one tonne captured CO_2 costs 12–26 LVL/t CO_2 and 20–34 LVL/ t CO_2.
7. A prognosis of the volume of CO_2 emissions into the atmosphere is developed in the climate module. The results indicate that a transformation in the energy sector to renewable energy resources and the introduction of CCS in fossil fuel and biomass energy sources would make it possible to reach a negative CO_2 level in the year 2016 reaching a 1,488 Mt CO_2 saving in 2016 and -7,124 Mt CO_2 in 2020.
8. Based on the calculations conducted in the engineer-technical and climate valuation modules and empirical model, estimated specific CO_2 emissions factors are set for Latvia's transformation sector from 2012 to 2020.
   - Fossil fuel energy resource scenario (Scenario A) – from 0,180 t CO_2/MWh_k to 0,212 t CO_2/MWh_k;
   - Renewable energy resource scenario (Scenario B) – from 0,173 t

CO_2/MWh_k to 0,168 t CO_2/MWh_k;
- Fossil fuel energy resource scenario with CCS (Scenario C) – from 0,180 t CO_2/MWh_k to -0,002 t CO_2/MWh_k.
- Renewable energy resource scenario with CCS (Scenario D) – from 0,172 t CO_2/MWh_k to -0,269 t CO_2/MWh_k.

9. A methodology for the valuation of environmental factors for the transportation of CO_2 through pipelines and injection in a geological reservoir gives the opportunity to assess the environmental impacts caused by these processes. The methodology is centred on a life cycle analysis. The methodology is tested by analysing two technological parameters – the length of the pipeline and the efficiency of the electricity production source. It is determined that the energy sources have an indirect impact on the environmental valuation of the CO_2 transportation and injection stages through the electricity consumption.
10. A cost indicator for the elimination of environmental impacts is defined and attributed a value with the application of the life cycle cost analysis method. Depending on the impact categories and the indicator of the energy sector development scenario, the value varies in a broad range from 7 LVL/mPoint to 0,07 LVL/mPoint.