RIGA TECHNICAL UNIVERSITY
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Doctoral program in Environmental Science

ECODESIGN OF BIOMETHANE PRODUCTION AND SUPPLY SYSTEM

Summary of the Doctoral Thesis

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

To be granted the scientific degree of Doctor of Environmental Engineering, the present Doctoral Thesis will be publicly defended on 08 June 2017 at 14:00, Room 115 at the Faculty of Power and Electrical Engineering of Riga Technical University, Āzenes iela 12/1.

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DECLARATION OF ACADEMIC INTEGRITY

I hereby declare that the Doctoral Thesis submitted for the review to Riga Technical University for the promotion to the scientific degree of Doctor of Environmental Engineering is my own and does not contain any unacknowledged material from any source. I confirm that this Thesis has not been submitted to any other university for promotion to any other scientific degree.

Māra Rēpele ....(signature)

Date: ....

This Doctoral Thesis is written in Latvian. It contains an introduction, four chapters, conclusions, a bibliography with 157 sources of reference and 8 annexes. The Doctoral Thesis is illustrated by 8 tables and 49 figures. The total volume of the present Thesis is 166 pages.

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OVERVIEW

The Topicality of the Thesis

Renewable energy sources (RES), which are fossil fuel alternatives, help to reduce the environmental impact caused by greenhouse gas emissions. At the same time, RES also reduce dependence on fossil fuels and promote diversification of energy supply, which is an especially important aspect for Latvia due to its current geo-political circumstances. Another important factor is that the RES cycle starts and ends in the same country, complementing both the national and local budgets, creating employment both directly and indirectly. Currently, the renewable energy sector in the European Union (EU) employs around 1.2 million people [1]. The socio-economic benefits associated with the use of RES evolve from technological development, production, installation, operation and maintenance. Furthermore, not only is business promoted with the use of RES, but also education and science. The European Union, in expanding its legal framework, promotes the use of renewable energy sources [1] and seeks to ensure that all Member States have a common understanding of the essential aspects of the transition to low-carbon systems, providing the necessary certainty and stability [2]. The European Commission (EC), identifying areas that should receive more attention in the future, seeks to ensure that renewable energy technologies become more competitive and cheaper. In addition, the EC is trying to achieve that investments in RES technologies are stimulated by gradually moving away from subsidies for fossil fuels [1]. If a common approach would be introduced across Europe for the efficient use of RES, it would be possible to save as much as a quarter of the necessary costs [2]. In addition, in order to rapidly start to inform potential investors about the policies that will be implemented after 2020, the European Union has issued the Energy Roadmap 2050 [2]. Moreover, multi-scenario analyses show that the greatest share of energy supply technologies in the future will be for energy from renewable sources [2]. It is also stated that by 2030 the share of renewable energy must be at least 30 % [1], and by 2050 at least 55 % of gross energy consumption shall be achieved [2]. At the same time, it is also recognized that Europe will have a difficult task – to provide market participants with the opportunity to reduce renewable energy costs, expand research and broaden supply systems, develop technologies to reduce their costs, and implement and introduce more effective policies and support mechanisms [2].

The Goal of the Work and Main Tasks

The aim of this Doctoral Thesis is to perform an eco-design of the biomethane production and supply system, to reduce the environmental impact caused by the natural gas-using industrial processes and to promote the use of renewable energy sources in Latvia's energy supply system. To reach the objective of the Thesis, the following tasks were set:

- To characterize the environmental impact of building material in order to identify the life cycle stages and processes which create the most significant environmental impacts.
- To evaluate environmental aspects of renewable energy alternatives for replacement of natural gas, via life-cycle analysis.
- Perform life-cycle analysis and technical and economic assessment of the biomethane production and supply system.
- To create a model, with the assistance of which it would be possible to devise a policy to support biomethane production and supply and to perform a scenario analysis to determine the optimal solution for the support mechanism.

Methodology of the Research

The structure of the applied research methods is presented in Fig. 1. The applied research methods incorporate qualitative and quantitative research techniques: literature analysis, data collection and analysis, life cycle analysis and system dynamics modelling. *SimaPro* life cycle assessment software with the *ReCiPe* impact assessment method, as well as GEMIS database, GIS and Powersim Studio software were used to carry out the research.

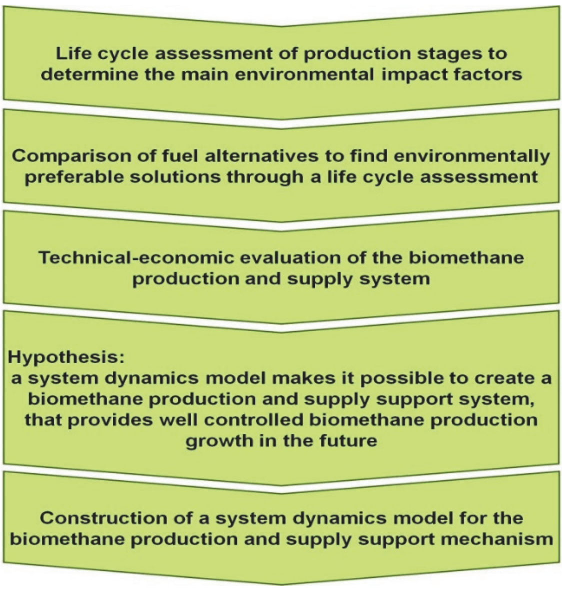

Figure 1. Generic description of the methodology applied to implement eco-design of the biomethane production and supply systems.

Scientific Significance and Main Results

The Thesis is of high scientific significance due to the fact that the eco-design of the biomethane production and supply system is implemented, using a life cycle analysis, technical and economic assessment, as well as system dynamics modelling. The results obtained can be used in Latvia and other countries, creating support systems for renewable energy.

The life-cycle analysis of a plant, which uses natural gas as a fuel, was carried out; calculations were made and the production stage which generates the greatest environmental impact was identified. The calculation results show that the environmental impact caused due to the use of natural gas is more than 75 % of the total environmental impact of production.

An evaluation of the environmental impact of renewable energy alternatives for replacement of natural gas was carried out. Environmental performance of biosynthetic natural gas, biomethane, the first and the second-generation biofuel, and natural gas was compared. The results indicate that the most significant reduction in environmental impact could be achieved if natural gas is substituted by biomethane.

Results of the life-cycle analysis and economic assessment of the biomethane supply system were described. The environmental impact of biomethane transportation, including connection to the grid, was assessed, and the costs of biomethane produced and injected into the grid were calculated. Results of the life-cycle analysis show that the gas supply infrastructure is an important factor that should be taken into account when biomethane production and supply systems are planned and installed. The results also indicate that the biomethane production and supply shall be supported financially if it is to be competitive with the price of natural gas.

A system dynamic model for the biomethane production and supply support mechanism was developed, which has been tested for conditions in Latvia. The created model, in contrast to other previously developed models, allows analysing the impact of the support mechanism system structure on the resource growth character. Risk assessment with sensitivity analysis for different scenarios was conducted. Results of the sensitivity analysis show that, in spite changes of the main factors, it is possible to get results with a relatively small dispersion when using the development system dynamic model. Therefore, it can be assumed that the developed system dynamic model can be considered plausible and applicable to create and analyse the biomethane production and supply support mechanism.

The research conducted constitutes a systemic eco-design of power supply system improvements. It also includes the method for the practical implementation of improvements – a system dynamics model, which helps to achieve a significant reduction of environmental impacts. Thus, the study also makes a contribution to the development of eco-design and the system dynamics modelling research sector.

Practical Significance

The thesis is of high practical significance since for the first time a system dynamics model for a biomethane production and supply support system is developed and adapted for Latvian conditions. It allows achieving a well-controlled growth of biomethane production and supplying volumes. The developed method makes it possible to replace the existing electricity support mechanism with a biomethane support system, and it can be used to develop other renewable energy support systems in Latvia and abroad.

Approbation

The research results are included in scientific publications:

Šķēle A., **Rēpele M.**, Bažbauers G. Characterization of Environmental Impact of Building Materials for the Purpose of Ecodesign. *Environmental and Climate Technologies*. Vol. 6, 2011, pp. 106–111. ISSN 1691-5208.

Rēpele M., Dudko M., Rusanova J., Valters K., Bažbauers G. Environmental Aspects of Substituting Bio-Synthetic Natural Gas for Natural Gas in the Brick Industry. *Agronomy Research*, 2013, Vol. 11, No. 2, pp. 367–372. ISSN 1406-894X. (indexed in SCOPUS).

Repele M., Paturska A., Valters K., Bazbauers G. Life Cycle Assessment of Bio-Methane Supply System Based on Natural Gas Infrastructure. *Agronomy Research*, 2014, Vol. 12, No. 3, pp. 999–1006. ISSN 1406-894X. (indexed in SCOPUS).

Repele M., Bazbauers G. Life Cycle Assessment of Renewable Energy Alternatives for Replacement of Natural Gas in Building Material Industry. Energy Procedia, 2015, Vol. 72, pp. 127–134. ISSN 1876-6102 (indexed in Web of Science, SCOPUS).

Paturska A., **Repele M.**, Bazbauers G. Economic Assessment of Biomethane Supply System Based on Natural Gas Infrastructure. Energy Procedia, 2015, Vol. 72, pp. 71–78. ISSN 1876-6102 (indexed in Web of Science, SCOPUS).

Repele M., Ramanis M., Bazbauers G. Biomethane supply support policy: system dynamics approach. Energy Procedia 2016, Vol. 95, pp. 393–400. ISSN 1876-6102 (indexed in Web of Science, SCOPUS).

Repele M., Udrene L., Bazbauers G. Support Mechanisms for Biomethane Production and Supply. Energy Procedia (*in print*) (indexed in Web of Science, SCOPUS).

Porubova, J., Klemm, M., Kiendl, I., Valters, K., Markova, D., **Rēpele, M.**, Bažbauers, G. Influence of Temperature and Pressure Change on Adiabatic and Isothermal Methanation Processes. Environmental and Climate Technologies 2012, Vol. 9, pp. 22–27. ISSN 16915208 (indexed in SCOPUS).

Statements to Defend

- For industries that use natural gas, the largest environmental impact occurs as a result of fuel consumption.
- Biomethane, compared with biofuels, from a life cycle impact point of view, is the best renewable energy alternative to replace natural gas.
- Biomethane production and supply can be provided by using existing biogas plants and natural gas infrastructure, but this needs financial support.
- The developed support mechanism, created on the basis of a system dynamics model, is able to provide a stable and controllable growth of biomethane production volumes.
- The feed-in premium for biomethane energy with 15 years of contribution period is the optimal support model, compared to the other assessed alternatives.

Structure of the Thesis

The Doctoral Thesis has been written in Latvian. It contains an introduction, four chapters, conclusions, a bibliography with 157 reference sources and 8 annexes. The Doctoral Thesis is illustrated with 8 tables and 48 figures. The total volume of the present Thesis is 166 pages.

The introduction of the Thesis emphasizes the novelty and topicality of the research, defines the objective and tasks of the study. In the first chapter, the life-cycle analysis of a plant, which uses natural gas as a fuel, was carried out to determine which production stage generates the greatest environmental impact, and to set eco-design tasks. In the second chapter, an evaluation of environmental impacts of renewable energy alternatives for replacement of natural gas was carried out. In the third chapter, the results of the life-cycle analysis and economic assessment of the biomethane supply system were described. Environmental impact of biomethane transportation, including the connection to the grid, was assessed, and costs of biomethane produced and injected into the grid were calculated. The fourth chapter describes the system dynamic model that was developed for the biomethane production and supply support mechanism and tested for conditions in Latvia. In addition, the results of the risk assessment with sensitivity analyses for different scenarios were described. In the final part of the Thesis, the key results of the research and conclusions are summarised, and the list of references and the annexes are provided.

1. CHARACTERIZATION OF ENVIRONMENTAL IMPACT OF BUILDING MATERIALS FOR PURPOSE OF ECODESIGN

In the first chapter life-cycle analysis of the plant, which uses natural gas as a fuel, was carried out to determine which production stage generates the greatest environmental impact, and to set eco-design tasks. It is well known, that the building material manufacturing sector is one of the most consuming sectors of fossil fuel resources. In addition, the construction industry is Europe's largest industrial employer, and construction activities consume more raw materials than any other industrial sector, while the built environment accounts for the largest share of greenhouse gas emissions in terms of energy end-use as it is mentioned in the reports [3, 4]. Because of this, the construction industry faces a considerable environmental challenge, bigger than any other industrial sector [4]. Life cycle analysis was carried out for one of the plants which represent the building materials industry: Joint Stock Company (JSC) „LODE", which is the largest producer of ceramic building materials in the Baltic countries [5].

The "cradle-to-gate" study was carried out according to ISO standards [6, 7]. The data used in the present LCA study consist of raw data that were given by the brick production plant; and calculated data which are based on published information [8]. The three cultural perspectives (I (individualist); E (egalitarian); and H (hierarchic) described by *DeSchryver* [9] and *Marceau*, *VanGeem* [10]) of the *ReCiPe* methodology [16] are used to conduct an environmental characterization of the building materials to obtain the total impact indicator. The LCA software "*SimaPro 8.1*" [14, 15] was used to model environmental impacts caused during the product's life-cycle. The following databases were used: *EcoInvent* (v2.2), *European Life Cycle Database* (*ELCD* v2.0) and *U.S. Life Cycle Inventory* (*USLCI*).

1.1. Goal and Scope, Functional Unit, Reference Flow, System Boundaries

The main goal is to calculate and assess the environmental impact of the manufacturing processes, to define solutions for improvements, especially in terms of energy consumption and greenhouse gas emissions, which is linked directly to the brick manufacturing stage.

For the purposes of the present study, one ton of a specific type of brick [5] has been chosen as a functional unit. Reference flow is a ton of bricks.

The product system consists of a variety of products entering and leaving the system. Different raw materials (mainly clay) and various combustible additives, such as straw and sawdust, as well as natural gas used for the manufacture of the required heat and electricity, are used in brick production. Outgoing products of the product system are mostly air emissions resulting from the combustion of natural gas. The manufacturing process results in a small amount of domestic waste, water and solid waste, but the amount of waste is very small and the effects are considered minor and hereby not included in this study. The clay brick system boundaries included clay extraction, storage and processing, shaping, drying and firing of bricks, and packaging.

1.2. Life Cycle Inventory

Data sources for the system input and output flows in annual terms is a factory and published data [8]. The baking process is the most energy consuming process of the studied brick production process. Due to natural gas consumption, 338.28 kWh of primary energy are consumed. There are also 25.46 kWh of electricity used during the process. Approximately 40 % of all electrical energy that is used in the manufacturing process is consumed during clay processing. Natural gas is the main energy source in brick production. The use of natural gas and combustive additives contributes to SO, CO and NO production.

1.3. Impact Assessment and Conclusions

The main goal of this stage of the research was to carry out life-cycle analysis of the plant, which uses natural gas as a fuel; to calculate and determine the production stage, which generates the greatest environmental impact; and to define solutions for improvements. Taking into account that it was necessary to compare the relative differences, the absolute value of the impact points was not of significant importance; and the results were expressed as a percentage.

The results show (Fig.1.1.) that:

- the highest value of environmental impact, i.e., approximately 76 % to 78 %, is for the firing process for all three different perspectives. The main contributor to the impact is the usage of natural gas for the industrial baking furnace;
- electricity consumption causes a greater impact on the environment compared to the use of natural gas for heating: approximately 6 % – 11 %;
- materials used for packaging (polymer film and wooden pallets), as well as other materials and processes (such as clay extraction and transport to the plant, lubricants for equipment maintenance, etc.) causes approximately 1 % to 4 % of the total environmental impact.

The results of the research confirm that (Fig.1.1.) the building materials production is an energy intensive process. The greatest impact on the environment (>75 % of the total impact) is caused due to the use of natural gas for brick firing. Most of the emissions are directly related to fuel (natural gas) consumption. Although natural gas, compared to coal and oil, is seen as fuel causing less environment impact, the use of renewable energy sources could reduce the environmental impact even more. In addition, usage of the local renewable resources would also reduce Latvia’s energy-dependence, reducing imports of natural gas.

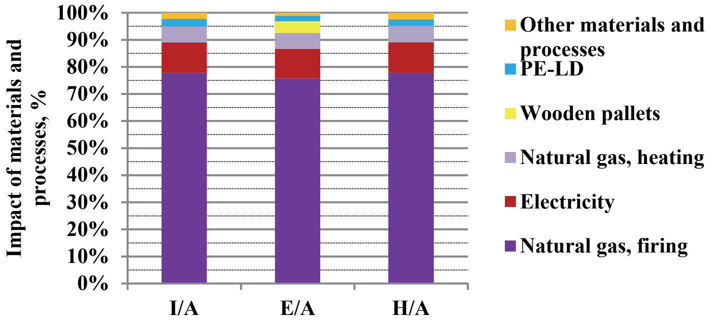

Figure1.1. Environmental impact caused by materials and processes.

2. EVALUATION OF ALTERNATIVE FUELS SUBSTITUTING RENEWABLE ENERGY SOURCES FOR NATURAL GAS

Scientists have conducted various studies on possibilities to optimize the performance of kilns and plants [16–18], research has also been done regarding improvements in energy efficiency or usage of renewable energy sources [19, 20] with the objective to reduce greenhouse gas emissions. However, it seems that less attention has been paid to research on the effects of environmental changes that could result from fuel replacement. In the Reference Document on Best Available Technologies in the Ceramic Manufacturing Industry, it is noted that mainly natural gas is used for firing, in some countries also liquefied petroleum gas, or other liquid fuel, such as liquefied natural gas, biogas, biomass, electricity, fuel oils and solid fuels (such as coal, coke) [21]. In this Reference Document, it is stated that environmental impact could be reduced by fuel substitution, for example, if fuel oil or solid fuels are replaced by natural gas (or the liquefied petroleum gas or liquefied natural gas). It is also noted that renewable energy sources could play a role as energy sources for burners to reduce environmental impact, but there still is a lack of information on emissions and data on consumption [21].

Due to environmental and geopolitical circumstances, the issue on the replacement fossil fuels with renewable energy alternatives is becoming increasingly topical. In addition, the industrial sectors that use natural gas as fuel, the usage of fuel is directly related to the most significant environmental impacts. Thus, the replacement of non-renewable energy sources with renewables is considered as one of the most effective approaches to reduce the environmental impact, as well as to promote energy independence. In their research, *Ellersdorfer* and *Weiß* have described the integration of biogas plants in the cement industry from the energy and economic point of view [20]. However, a more detailed study based on life cycle assessment and considering other alternatives, e.g. bio-fuels is needed.

The research questions for this chapter are the following: how environmental impacts change if energy sources used for the production, i.e. fuel for heat supply and electricity mix, are varied. The results were primarily targeted for the purpose of eco-design applied to industry sectors, which uses natural gas as a fuel, as well as to reduce environmental impact. The results described in this chapter continue research from previously published studies [22–24], where: environmental impact of building materials for the purpose of eco-design were characterized (Chapter 1); environmental aspects of substitution of the natural gas by bio-synthetic natural gas were analysed (Chapter 2.1. in the Thesis); as well as life cycle assessment of biomethane supply system was carried out (described in Chapter 3), by considering more fuel alternatives and using life cycle assessment methodology with the *ReCiPe* impact assessment method [14, 15].

2.1. Goal and Scope, Functional Unit, Reference Flow, System Boundaries, and Life Cycle Inventory

The study described in this chapter aims to assess the changes of the environmental impacts when natural gas which is currently used in a brick firing furnace, is replaced by biomethane and liquid bio-fuels. The influence of electricity supply mix on environmental impacts was studied as well.

In this stage of the research, like previously, the functional unit and the reference flow is a ton of bricks. Factory construction in this study was not evaluated. Life cycle inventory data are described in Section 1.2.

2.2. Materials and Methods

To analyse environmental impact of the life cycles production phase, "*SimaPro 8.1.*" [14, 15] software and the following databases were used: *EcoInvent* (v2.2), European Life Cycle Database (ELCD v2.0) and US Life Cycle Inventory (USLCI). Only system processes from the databases were selected for this study. Environmental characterization of the "cradle-to-gate" phase was made using the *ReCiPe* assessment method.

Although, in order to assess the potential environment impact, three different cultural perspectives (described in Chapter 1) for the methods have been defined: Egalitarian, Hierarchist and Individualist [14]; only one of them – Hierarchist (H) perspective has been used in this section. This cultural perspective is considered as a basic (or default) perspective and is described as a perspective that perceives the environment as a balanced value [9–12].

Only those impact categories, which had at least 2 % of the total environmental impact, were chosen for further analysis and are shown in the results. Hence, the following seven impact categories of the *ReCiPe* method were considered: (1) fossil depletion, (2&3) climate change (human health and ecosystem), (4) particulate matter formation, (5) toxicity, (6) agricultural land occupation and (7) terrestrial ecotoxicity.

2.3. Types and Source of Data

The study was based on one-year operational data obtained from site visits to the factory and data reported in the polluting activities permit issued to the company [8].

Life cycle impact of production depends on electricity sources which in turn depend on power market conditions. Therefore, the assessment was started by setting up two electricity supply mixes which are referred to as "A" and "B" (Fig. 2.1.) in order to find out the influence of electricity market conditions on environmental impact. When the electricity prices in "*Nord Pool Spot*" market during the winter are relatively high, domestic natural gas-fired cogeneration plants are competitive and produce circa 40 % of gross annual power consumption (Scenario "A"). Another 40 % of the gross annual power consumption is supplied by local hydropower plants and the remaining 20 % are imported. However, if the market electricity prices are low, district heat is produced by heat-only boilers and the share of cogeneration plants reduces to 20 % while the share of imported electricity increases to 30 % (Scenario "B"). The remaining electricity is supplied by hydropower plants. Since a large share of imported electricity in Latvia is supplied from Estonia, it was assumed that 90 % of the electricity import comes from Estonia and 10 % from the Nordic countries.

In order to analyse the life cycle impact of production depending on fuel, four different fuel scenarios, referred to as "N", "M", "F1" and "F2", were created (Fig.2.1.). Scenario "N" refers to the existing situation where natural gas is used for firing furnaces. Scenario "M" refers to using biomethane instead of natural gas. Life cycle impact when 1st generation and 2nd generation bio-fuels are used for the production was assessed in scenarios "F1" and "F2", respectively. Construction of the bio-fuel plants was not included in the study.

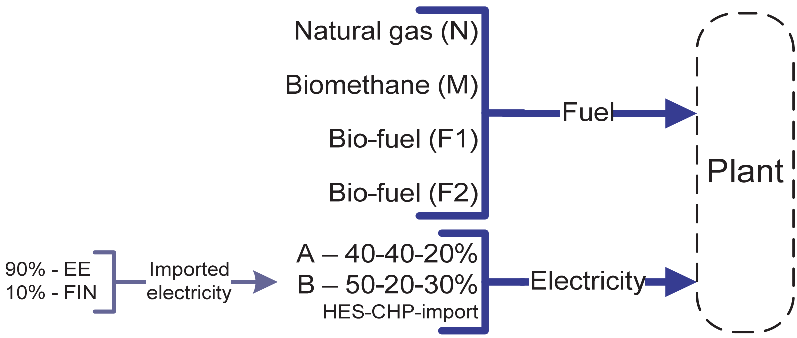

Figure 2.1. Schematic presentation of scenarios. N – natural gas; M – biomethane; F1 – 1st generation bio-fuel; F2 – 2nd generation bio-fuel; A un B – electricity supply mixes.

2.4. Results and Discussion

Results of environmental impact of the electricity mix obtained with the *ReCiPe* method for scenarios “A” and “B” are 13.8 mPt/MJ and 13 mPt/MJ, respectively. The result obtained for Scenario “A” and the result available in the ELCD database [14] for Latvia’s medium voltage electricity mix corresponds very closely. When the electricity Scenario “B” is used instead of “A”, the environmental impact per functional unit, expressed as a single score, reduces by only 0.6 % for *ReCiPe*. Since the variation of electricity mix does not significantly impact the resulting total impact, only the electricity mix of Scenario “A” was used for further analysis.

Assessments of environmental impacts of the production of 1 ton of ceramic building materials show that the largest share of the environmental impact for all scenarios is associated with the consumption of firing fuel and electricity. (Table2.1.).

Table 2.1.

Environmental impacts related to the production processes per functional unit, %

Scenario	N	M	F1	F2
Fuel	84	68	92	62
Electricity	11	21	6	26
Clay extraction	1	2	0	2
Packaging	4	9	2	10

When natural gas is replaced with biomethane (Scenario “M”), a total environmental impact is reduced by ~48 %. If 2nd generation bio-fuel is used instead of natural gas (Scenario “F2”), impact is reduced by ~56 %. In contrast, the use of the 1st generation bio-fuel (Scenario “F1”), instead of natural gas, would greatly increase environmental impact by circa 97 %. This increase of environmental impact may be associated mainly with cultivation of rapeseeds, requiring use of land and fertilizers.

2.5. Conclusions

The total single score results indicate that the most substantial decrease of environmental impact may be achieved if natural gas is substituted by biomethane. It is important to notice that this option would not require technical changes of burners. The second best alternative from the environmental point of view would be a use of the 2nd generation bio-fuel. However, in this case technical adjustments may be required. Use of the 1st generation bio-fuel would have the greatest impact on the environment by far exceeding the scenario where natural gas is used as the fuel. The vast impact in this case may be related to land use, all of the agricultural activities, including also fertilization. Variation of electricity mix due to power market conditions does not have a significant effect on the total environmental impact of the studied electricity supply system: environmental impact per functional unit reduces by only ~0.6 %. Supply of biomethane to industry could be done via the existing natural gas supply infrastructure. Technical, environmental and economic criteria of alternatives for development of a biomethane supply system, which is based on the natural gas grid, need to be studied to find out optimal solutions.

3. TECHNICAL-ECONOMIC AND LIFE CYCLE ASSESSMENT OF BIOMETHANE PRODUCTION AND SUPPLY SYSTEM BASED ON NATURAL GAS INFRASTRUCTURE

Biogas plants in Latvia are mostly decentralized and located relatively far from large heat consumers. Thereby, many sites for biogas production currently do not have sufficient heat load to provide power production in combined heat and power generation mode. The alternative to relatively inefficient power-only production could be a production of biomethane. Biomethane, unlike wind energy, is an easily manageable energy resource that can be stored and distributed using the existing well-developed infrastructure, as well as used in the same way as natural gas. Therefore biomethane is known as one of the most important renewable options for gas supplies [25]. In addition, the use of renewable energy sources is an important factor to reduce energy dependence on imported resources. In addition, it is one of the EU objectives, thereby also binding for Latvia [26]. Latvia has committed to increase the share of renewable energy sources in final energy consumption to 40 % by 2020 [27] and biomethane production could help to achieve this target. Although in Europe the number of biogas upgrading stations is increasing every year [28], there is no biogas treatment plant in Latvia.

Under the current market circumstances, biomethane cannot yet compete with natural gas in terms of selling prices [26, 27, 29]. Therefore, biogas upgrading technologies [30–32] were compared. Also, studies are carried out to find the most cost-effective and technically suitable way, considering also environmental benefits, for biogas and/or biomethane utilization [33–37], including grid injection and distribution [38–41], or through the integration of biogas plants in the industry [20, 42]. Research on the technical and economic potential of biomethane production and injection into the natural gas grid is also carried out in Latvia [24, 43, 44].

This chapter describes the results obtained from the life cycle assessment of the system for biomethane production and supply to industrial plant via the natural gas grid. The analysed system includes biomethane production and transport to the natural gas pipeline including the infrastructure. Total production costs were calculated for the three different biomethane production scenarios and five biogas upgrading methods. The functional unit is 1 MWh of biomethane energy injected into the natural gas grid.

3.1. Life Cycle Analysis

Seven biogas plants were chosen for this study – those which were nearest to the factory in Latvia selected for the study. The analysed system includes bio-waste collection and transport to the plant, biomethane production and transport to the natural gas pipeline including the infrastructure (Fig. 3.1.). The functional unit is 1 MWh of biomethane energy injected into the natural gas grid. The study was based on the data reported in the polluting activities permits issued to the biomethane production plants in Latvia [45–51] and the data obtained from earlier studies [52]. Life cycle assessment software "*SimaPro 8.1*" [14] with *EcoInvent* (v2.2) database [53] were used to model and analyse environmental impacts caused by biomethane production and transportation from the biomethane production facility to the natural gas transmission pipeline via the connecting pipe. *Europe ReCiPe H/A* method [11, 54] was used to assess the environmental impact. To estimate the most appropriate scenario for biomethane injection into the natural gas grid, biomethane production capacity and distance to the natural gas network was taken into account.

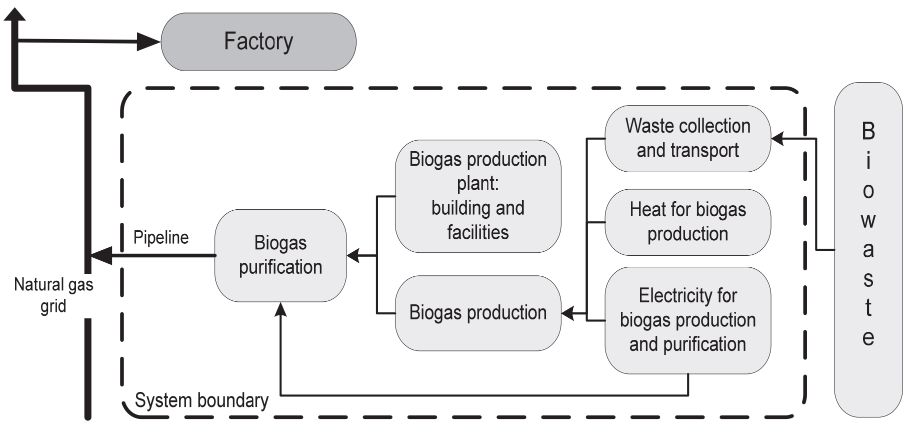

Figure 3.1. Processes considered within the system boundary.

For this study seven (marked with numbers '1' to '7') existing biogas plants with different capacities were selected. The volume of produced biogas and upgraded biomethane varies among the plants due to the different sizes of the plants, i.e. installed electrical capacities, amounts and contents of input and other factors. The plants chosen are located at different distances from the natural gas network. Plant No. 1 is located ~0.8 km away, while Plant No.7 is located ~19 km from the natural gas network. Distance to the natural gas grid was determined by the *ArcGis* [55] program. The aim of the research at this point was to determine the possible environmental impact, if the produced biogas is upgraded and injected into the natural gas grid instead of producing electricity.

According to the calculations using the *EcoInvent* (v2.2) database, results of the environmental impact of 1 MWh energy from the biomethane Plant No.1, including infrastructure, varies from 9.92 Pt MWh^{-1} to 10.38 Pt MWh^{-1} for Plant No. 7. For comparison, the environmental impact of 1 MWh of natural gas energy is 15.3 Pt MWh^{-1} [14].

Analysing environmental impact caused by biomethane production, transportation and infrastructure (pipelines), it can be concluded that, if the plant is less than a kilometre away from the natural gas network (in this case Plant No. 1), the biomethane production accounts for ~99.78 % of the total environmental impact, pipelines for ~0.2 %, but biomethane transportation generates only ~0.004 % of the total environmental impact. In case the site is located almost 20 kilometers away from the natural gas network (for example – Plant No. 7), then biomethane production accounts for ~95.36 % of the total environmental impact, while pipeline and transportation generate ~4.56 % and ~0.08 % of the total environmental impact, respectively. Thus, results show that, although the share of the environmental impact from the infrastructure which connects distributed biomethane production facilities to the natural gas pipeline infrastructure is rather insignificant, in the case when the plant is located in close proximity to the natural gas grid, the impact nevertheless increases with distance. It was found that infrastructure and transport can represent more than 10 % of the total environmental impact for the complete biomethane generation and injection if the distance between the biomethane production plant and the natural gas grid is increased up to ~45 km. However, it can be concluded, that even if the percentage of environmental impact of the biomethane injection infrastructure is lower in case of smaller distance from the grid, it is still rather an important element and should be taken into account when new energy supply systems are considered.

3.2. Technical and Economic Evaluation of Biogas Purification Methods and Biomethane Supply System Based on Natural Gas Infrastructure

The aim of the study described in this chapter was to determine the production costs of biomethane produced in distributed generation units via five methods of the biogas upgrading and injected into the natural gas grid using Latvia's conditions as the case study. In 2014, 54 biogas plants were in operation in Latvia with a total installed capacity of 54.92 MW [56]. In 2013, while working with an average of 75 % load, over 275.22 GWh of electricity was produced [56]. Three biogas stations were selected for technical and economic analysis with the aim to determine an optimal biomethane production and injection solution. To estimate biomethane production costs, five commercially available biogas upgrading technologies were used for calculations – (1) water scrubbing, (2) amine scrubbing, (3) membrane separation, (4) physical scrubbing with organic solvents and (5) pressure swing adsorption [57]. To find the most cost-effective biomethane production method, three different scenarios for the selected biogas plants were considered:

A. each biogas plant has an upgrading facility and biomethane is produced at each individual biogas plant and delivered to the natural gas grid;
B. biogas from each plant is delivered to the large upgrading plant for biomethane production and subsequent injection into the natural gas transmission line. In this scenario, the biogas upgrading costs are lower than if the biogas is upgraded to where it is produced (*Scenario A*), due to lower total specific investments for upgrading facilities;
C. instead of distributed biogas production, raw materials, required for three separate biogas plants, are delivered from the farms to a single joint biogas and biomethane production facility, using the existing road infrastructure. At the end, biomethane is injected into the natural gas grid. In this scenario, biomethane production costs are the same as for *Scenario B*, except the biogas production and transportation costs.

Results of calculations show that the most economically advantageous biomethane production scenario, regardless of the selected upgrading method, would be if biomethane is produced in one common single-site (*Scenario C*) instead of a number of separate biogas plants. For *Scenario B*, if biogas from individual plants is transported to an upgrading plant, the total production costs would be about 2 % to 4 % lower (depending on the chosen upgrading method), than in a *Scenario A*. In turn, the total costs of *Scenario C* is by circa 22 % to 27 % lower (depending on the type of upgrading method and on the economic lifetime) than in S*cenario B*.

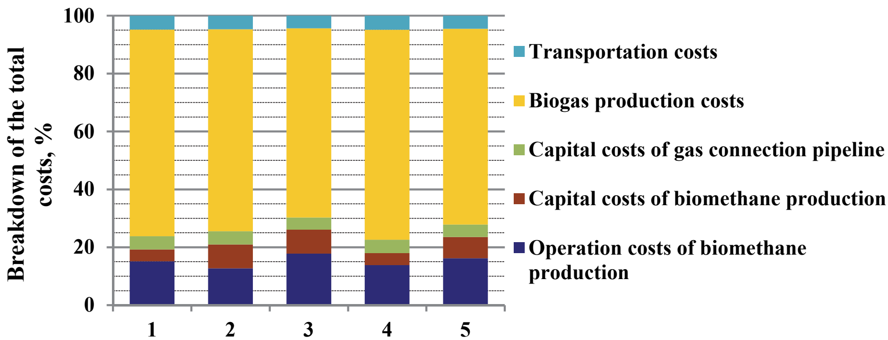

Figure 3.2. Comparison of the total cost of biomethane production for all five biogas-upgrading methods. Biogas upgrading methods: 1 – water scrubbing, 2 – amine scrubbing, 3 – membrane separation, 4 – physical scrubbing with organic solvents, 5 – pressure swing adsorption.

It can also be concluded that the cheapest biogas upgrading methods are amine scrubbing and physical scrubbing with organic solvents. All five discussed biogas upgrading methods are commercially available [33]. The greatest share of the total costs of biomethane production (~65 % to ~73 % – depending on the biogas upgrading method) is taken by the biogas production costs (Fig. 3.2.), and that is true for all other scenarios. Biogas upgrading costs are ~13 % to ~18 % of the total costs. In turn, pipeline construction costs and the costs of raw material transportation is in the ~4 % to ~5 % range, but capital costs of the biomethane plant, depending on the selected treatment methods, are ~4 % to ~8 % of the total costs.

Results of the study, when the most favourable upgrading method and 20-year economic lifetime is used for the calculations, show that the total cost of the biomethane produced and delivered to the natural gas grid is approximately 2 times higher than the natural gas market price. Therefore, under current conditions, biomethane production would need financial support to make the costs compatible with the price of natural gas. Results of this study also show that if the biogas producers could co-operate in constructing larger joint biogas production and upgrading facilities (*Scenario C*), this would be the most economically attractive solution. Nevertheless, for the existing biogas plants, the option to consider would be to construct joint biogas upgrading facilities as stipulated in *Scenario B*.

4. SYSTEM DYNAMICS MODEL OF BIOMETHANE PRODUCTION AND SUPPLY MECHANISM

The development of a power supply system and energy policy planning is a complicated process, given that the system is affected by many factors. In order to plan the support mechanisms and to analyse consequences of the various scenarios, it is necessary to use a tool, suitable to analyse complex and dynamic systems. Therefore, to define the support mechanism, an interdisciplinary system dynamics (SD) [58–60] approach was chosen. The SD approach, as a planning tool for power systems, has been successfully used to address different issues related to energy policy [61–67]. The SD approach is also used in a number of the issues related to Latvia's energy supply system [68–70].

The biomethane production chain dynamics in the Netherlands is analysed with the SD approach, and the authors admit that there are several factors that complicate development of the biomethane industry, such as availability of resources, demand, power installation, profitability, as well as competition between biomethane and electricity industry, because of the availability of biogas and biomass resources [65]. Results of the study show, that, in such circumstances, support incentives with a relatively low subsidy amount may exist, when they are introduced for a sufficiently long time. But it should be noted that the results of the support mechanism may be influenced by the producers' willingness to invest, which can be reduced by the uncertainty regarding investment economic benefits [65]. The German biomethane market is also modelled using an SD approach [71]. Through the application of this model, the success of the historical energy and climate policy was assessed, and an impact on the power and heat sector was estimated, as well as new policies were simulated and evaluated, in order to determine which policies to recommend for policy makers to provide a sustainable and efficient biomethane market in the future [71].

In this chapter, using the SD approach, a model is created and described. With this model, unlike the above-described studies and models, it is possible to analyse support mechanisms of the biomethane production and supply chain, as well as its structure in detail. In addition, it is possible: (1) to assess impact caused by the dynamic of the permit granting rate on the support mechanism; (2) to evaluate the maximum volume of biomethane, which can be produced from the raw materials available in Latvia; (3) to estimate costs related to construction of biomethane plant and connection pipeline to the natural gas network, dynamics of the natural gas market price; and other aspects. The significance of this study and the SD model novelty is that the support mechanism and dynamics of the biomethane production capacity development is analysed in more detail compared with the above-mentioned studies. The main research question is how to ensure the desired biomethane production growth dynamic within the limits of the provided financial assistance? Thus the model is a tool for policy design, that defines the parameters and their values, which policy-makers must take into account in order to create a sustainable policy to support biomethane (and other RES) production.

4.1. Dynamic Problem and the Aim of the Model

The most significant local energy resources in Latvia are wood biomass and hydro energy. In 2012 up to one-third of the total primary energy consumption were provided by the local energy resources (int. al. 1.1 % by biogas). The rest of the part of the energy resources were imported from different countries of the Baltic region, the EU and also from third countries, including Russia [72]. Although the share of renewable energy sources (RES) in Latvia in the final energy consumption is quite high (35.8 %), Latvia is still heavily dependent on natural gas supplies from Russia [73, 74] providing 26.7 % of the total primary energy consumption [72].

Latvia has set a goal to increase the RES proportion in the gross final energy consumption by up to 40 % and 50 % in 2020 and 2030 accordingly, and to reduce energy import from current third country suppliers by 50 % compared to 2011. [75]. Several problems will have to be addressed in Latvia's energy policy in the future, i.e. – (1) requirements for biogas injection into the natural gas transmission system have not been established [75]; (2) no requirements for the gas quality have been defined; (3) current national support schemes create an additional burden on end users.

The dynamic problem of this study is the expected development of production capacities, which will be different from the planned (Fig.4.1.), taking into account that a granting of production permits is suspended for a long period of time. This situation has arisen because policy makers did not carry out analysis of the dynamic processes of the support mechanism.

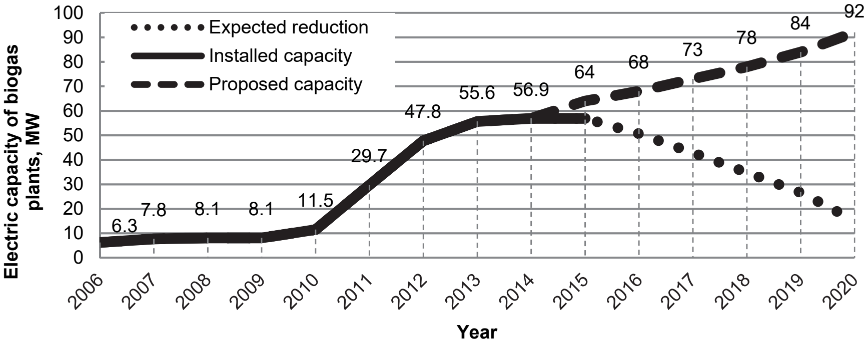

Figure 4.1. The actual (till 2015) and the proposed [76] total installed electric power capacity of biogas cogeneration plants and the expected reduction due to the change in the laws and regulations. The reduction curve shows potential change in character, rather than the calculated numerical values.

The aim of the study was to create the model that helps to devise biomethane production support policy. According to the purpose, the initial model was created. The validation of it showed that it can sufficiently and precisely describe the historical development of the biogas sector in Latvia, showing what the expected trends are in the future, if the existing policy instruments will be used (Fig.4.1.). In turn, the initial system dynamics model served as a sound base to establish a support mechanism providing controllable and stable growth of the biomethane production over time avoiding relapsed "overshoots and oscillations" in the system. With the model, various aspects and scenarios of the support mechanism can be analysed.

4.2. Dynamic Hypothesis

The hypothesis was defined to develop a biomethane supply support mechanism: the support mechanism is stable and sustainable, i.e. it ensures that a number of total subsidies does not exceed the amount set by the government, but at the same time at the same time fully utilizing the latter. The support mechanism positively effects the number of permits granted, increasing also the granting rate (Fig. 4.2., [77]). Capacity in operation also increases, which is influenced by the willingness to invest and availability of resources for biomethane production. In turn it increases the volume of produced biomethane and the amount of disbursed subsidies. The market price of natural gas directly affects the amount of disbursed subsidies – if the market price of natural gas falls, the amount of payable subsidies (the difference between the biomethane production costs and prices of natural gas) will increase and vice versa. Once the limit of the total subsidies is reached, the permit granting rate is restricted.

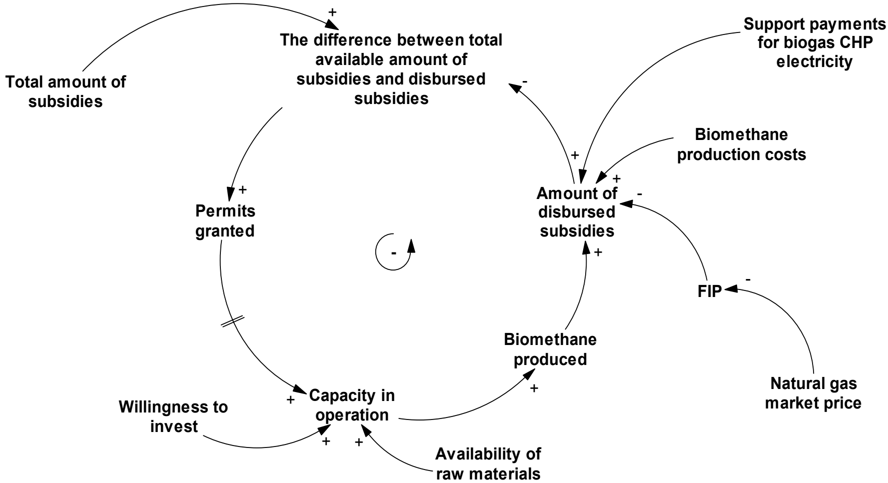

Figure 4.2. Causal loop diagram representing the structure of the biomethane support mechanism [77].

The following factors and criteria were taken into account to define the hypothesis:

- there is a limit to the total available amount of subsidies for biomethane production;
- both biogas and biomethane production is affected and limited by the availability of raw materials;
- the political will, as well as stability and sustainability of the support mechanism, has a significant influence on investors' willingness to invest in the production of biomethane;
- when choosing a biomethane support mechanism, the natural gas market price level shall also be taken into account, as well as the dynamics of the average price growth. When calculating the future price trend, the historical dynamics of the natural gas price was taken into account. The calculation results show that, in the future, the price of natural gas will increase. In the Energy Roadmap 2050 issued by the European Commission, it is noted that energy prices are rising worldwide [2].

The developed model can help to analyse and predict the behaviour of the real system and changes over time and, depending on a variety of policy instruments, to check and to identify the factors that change results of the whole support mechanism. For example, how the biomethane production and supply system is affected by the availability and price of raw materials, or what is the role of time allowed for construction or duration of the support period on the support mechanism as a whole, etc. Parameters and factors implemented into the model, which can influence policy-makers and biomethane producers, are displayed in Figure 4.3.

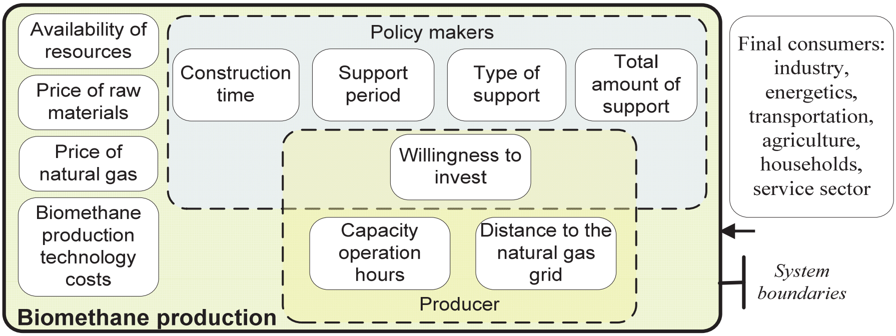

Figure 4.3. Factors and parameters influencing biomethane production, system boundaries.

It was important to develop a model structure very carefully, to enable that it best describe and predict a real support mechanism in action, including all the essential elements of the system and the characteristic direct and feedback loops, instead of using the precise numerical values, which are often not available because of the lack of information. The modelled system does not include the behaviour of biomethane final consumer – production of heat or electricity from biomethane or usage of biomethane in the transport system (Fig.4.3.).

4.3. Formulation of the Model and Initial Calculations

The model includes action and interaction of the potential investors, biomethane producers and policy-makers, which determines the system dynamic behaviour. Modelled system consists of several parts:

- biomethane production and supply support mechanism module;
- calculations of the average amount of subsidies per unit of biomethane (AAS), that include costs of a biomethane plant construction and connection to the natural gas network, and the natural gas price dynamics;
- calculations of the maximum volume of biomethane, which can be produced in Latvia;
- raw material price calculations and other supporting calculations.

Successful development of the biomethane industry depends on the sustainable support mechanism. Therefore, the biomethane production and supply support mechanism module is a key part of the system dynamics model. Other parts of the model – calculations – are designed to ensure the successful implementation of the developed support mechanism. With the created model, the support mechanism is assessed – impact of the AAS on Latvian's energy system, that is, impact on the biogas and biomethane industry.

The national government selects and defines a support mechanism and a total maximum amount of subsidies, and, according to these conditions, a granting rate to set capacity flow is regulated. Given that the EC encourages to choose a support mechanism which follows market changes [27], it is assumed that similar to the so-called feed-in premium (FIP), such support mechanism will be introduced in Latvia. Premium to the price of electricity purchased is a market-oriented support mechanism when the trader receives a premium to compensate biomethane production-related costs by covering the difference from the price of natural gas. For the purpose of the study, it is assumed that the manufacturer has a guaranteed income and the amount of the premium varies with the changes in the natural gas market price. A necessary support for one megawatt is calculated by setting the difference in production costs of one biomethane unit and the price of natural gas. When calculating the cost of production of 1 MWh of biomethane, the fact that specific investment will diminish over time is taken into account. However, calculating the average amount of subsidies per 1 MWh of biomethane (AAS), it is assumed that the natural gas price will rise in the future.

Consequently, it is determined what volume of the annual biomethane production could be supported, given the politically set limit for the total amount of subsidies (Fig. 4.4.). Knowing the biomethane volumes produced and taking into account the potential willingness to invest, as well as taking into account the time it takes starting from the moment when a permit is received until production is put into operation, the dynamics of the granting rate is calculated. The permit expiry dynamics were also taken into account when performing these calculations. The model also takes into account restrictions related to the availability of raw materials for biomethane production. The closer the volume of raw materials actually used is to the maximum available, the lower the willingness to invest will be.

Stakeholders, knowing these conditions and certainly taking into account the availability of raw materials (agricultural land, livestock or domestic waste), express a willingness to invest (Fig. 4.4.). If the support mechanism is more sustainable and an entrepreneur has the opportunity to work without losses, and raw materials are freely available, then the biomethane industry begins to develop more rapidly, the production of biomethane volume and simultaneously also the amount of subsidies increases. If the availability of raw materials decreases or the support mechanism becomes volatile and unpredictable, the willingness to invest will decrease. Thus, the stagnation of biomethane industry will begin; biomethane production volume will not grow and smaller amounts of subsidies will be paid. In turn, the total maximum amount of subsidies set and the selected support mechanism is associated with the calculation module of the necessary support that takes into account market price of the natural gas and in turn also affects the biomethane production volume and thus the amount of subsidies paid. However, biomethane production volume and thus the subsidies paid directly affects the granting rate.

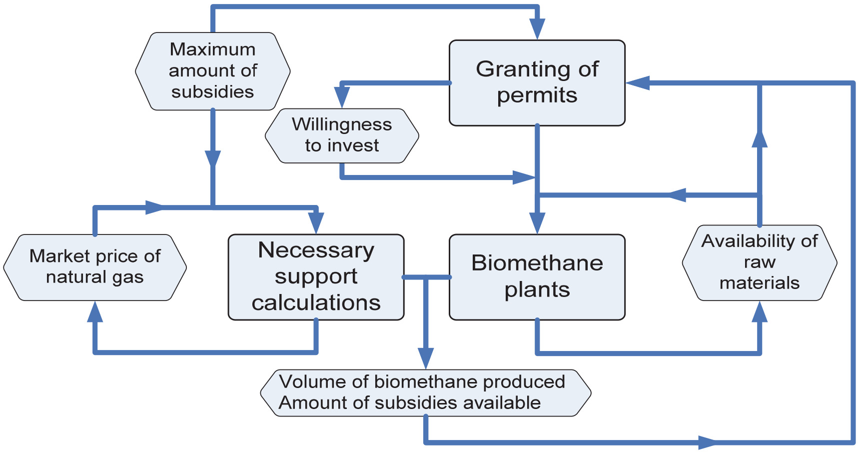

Figure 4.4. Schematic description of the structure of the biomethane support mechanism.

The SD model was developed using the Powersim Studio 8 software platform, and the simulation period was selected to be 2017–2030 with the time step of 0.1 year. To build the model, data published by the Ministry of Economics, the Public Utilities Commission and the Central Statistical Bureau were used. The amount of electricity generated at a biogas CHP plants was calculated, as well as the availability of raw materials in Latvia. The time needed for the plant construction was aligned with time prescribed by regulatory enactments and with the actual time mentioned in case reports. In addition, data published on costs, including the capital costs, for biogas and biomethane production, costs of pipeline construction, changes in natural gas market prices, etc. were used for the study. [27, 72–76, 78–85]

The aim of the model was not to obtain accurate numerical results but to verify and determine which of the biomethane production and supply support mechanism factors affect and contribute to the successful development of the support mechanism (policy) most significantly.

To develop the biomethane production and supply support mechanism several assumptions were made:

- the maximum amount of available subsidies is set to 40 million euros per year. This amount roughly corresponds to the amount of subsidies (price above the market price) paid for electricity produced in biogas plants 2013 and 2014 according to the mandatory procurement component set by the Public Utilities Commission [86]. The model allows changing the maximum amount of subsidies and it can variate in time. It is also possible to model the desired dynamics of the granting rate. This means that the maximum amount of subsidies does not affect the principal operation of the model;

- willingness to invest (VI) is 0.75, i.e., 75 % of the total permits granted leads to the real investments and increases production capacity;
- time allowed to invest (IAL) is 2 years;
- time for construction (BPL) is 1.5 years;
- capacity utilization hours is 7500 hours per year;
- a technical lifetime of facilities (TKI) is 20 years;
- period of support (AtbP) is 10 years;
- after period of support ends, half of the plants continue to produce biomethane.

The biomethane production and supply support mechanism module consists of four stocks with the relevant flows (Fig. 4.5.): „Permits granted"; „Capacity under construction", and „Capacity in operation with subsidies", as well as „Capacity in operation without subsidies".

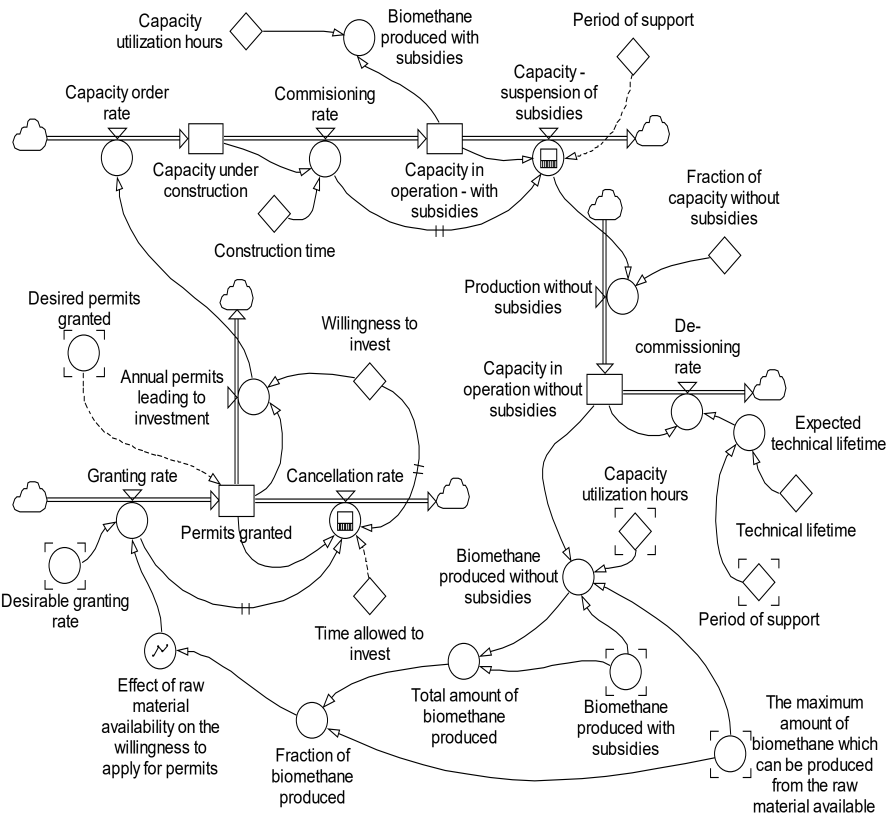

Figure 4.5. Stock and flow diagram of biomethane production and supply support mechanism.

The stock „Permits granted" consists of one ingoing flow and two outgoing flows. The stock shows how many permits have been granted (4.1.). Ingoing flow determines how many permits have been issued within one year (4.2.). Outgoing flows determine how many of the permits granted lead to real investment (4.4.) and how many permits are cancelled after two years, which is the time allowed for investments (4.3.):

$$PA(t) = \int_{t_0}^{t} [AP(s) - AA(s) - IAI(s)]\,\mathrm{d}s + PA(t_0), \tag{4.1.}$$

where *PA* – permits granted, m^3/h;
AP – granting rate, m^3/h per year;
AA – cancelation rate, m^3/h per year;
IAI – annual permits leading to investment, m^3/h per year.

The granting rate (*AP*) is affected by two parameters: the „preferred granting rate" and the parameter which characterizes how the availability of resources affects the willingness to apply for a permit:

$$AP = VAP \times RPI, \tag{4.2.}$$

where *VAP* – preferred granting rate, MW per year;
RPI – effect of raw material availability on the willingness to apply for permits; it was assumed that, willingness to apply for permits decreases along with the availability of raw materials.

The cancelation rate shows the amount of permits cancelled, if investments are not realized within the certain time allowed:

$$AA = \mathrm{MIN}(PA; \mathrm{DELAYPPL}(AP \times (1 - VI); IAL; 0)), \tag{4.3.}$$

where DELAYPPL – "conveyor belt" function;
VI – willingness to invest, %;
IAL – time allowed to invest, years.

$$IAI = \mathrm{MIN}(PA \times VI; PA), \tag{4.4.}$$

The stock „Capacity under construction" describes one ingoing and one outgoing flow:

$$BEJ(t) = \int_{t_0}^{t} [BU(s) - JNE(ts)]\,\mathrm{d}s + BEJ(t_0), \tag{4.5.}$$

where *BEJ* – capacity under construction, m^3/h;
BU – capacity order rate, m^3/h per year;
JNE – commissioning rate, m^3/h per year.

$$JNE = BEJ/VBL, \tag{4.6.}$$

where *VBL* – average time for construction.

The stock „Capacity in operation with subsidies” describes one ingoing and one outgoing flow:

$$DEJaA(t) = \int_{t_0}^{t} [JNE(s) - JAP(s)]\, \mathrm{d}s + DEJaA(t_0), \tag{4.7.}$$

where *DEJaA* – Capacity in operation with subsidies, MW;
JAP – capacity suspension of subsidies, MW per year.

$$JAP = \mathrm{MIN}\big(DEJaA; \mathrm{DELAYPPL}(JNE; AP; 0)\big). \tag{4.8.}$$

Also the stock „Capacity in operation without subsidies” is described by one ingoing and one outgoing flow:

$$DEJbA(t) = \int_{t_0}^{t} [DTbA(s) - JIE(s)]\, \mathrm{d}s + DEJbA(t_0), \tag{4.9.}$$

where *DEJbA* – capacity in operation without subsidies, MW;
DTbA – production without subsidies, MW per year;
JIE – de-commissioning rate, m^3/h per year.

$$DTbA = JAP \times JDbA, \tag{4.10.}$$

where *JDbA* – fraction of capacity without subsidies, %.

$$JIE = DEJbA/ATKI, \tag{4.11.}$$

where *ATKI* – expected technical life-time, years.

$$ATKI = TKI - AtbP, \tag{4.12.}$$

where *TKI* – technical life-time, years;
AtbP – period of support, years.

The stock „Capacity in operation without subsidies” is connected with the granting rate flow with a feedback loop (Fig. 4.5.). The total volume of biomethane produced with and without subsidies is calculated. Then, taking into account the maximum volume of biomethane, which can be produced from the raw materials available in Latvia, the fraction of biomethane produced is calculated. This in turn is linked with the effect or raw material availability on the willingness to apply for permits and regulates the granting rate.

The amount of desired permits granted is determined by taking into account a number of permits granted, as well as calculating the desired volume of biomethane produced with subsidies. This, in turn, depends on the total amount of subsidies available and on the average amount of subsidies per 1 MWh of biomethane. The module also takes into account the capacity installed of existing biogas cogeneration plants, the amount of electricity produced at these plants and hence the certain amount of subsidies for the biogas plants.

The average amount of subsidies per 1 MWh of biomethane (AAS) is estimated considering costs related to the construction of biogas plants, biogas production and upgrading, as well as costs needed to provide a connection to the natural gas network and dynamics of the natural gas market prices.

For the AAS calculations, the assumption was made that the specific investment costs will decrease over time, for biogas plants as well as for biogas upgrading facilities due to the evolution (learning effect), distribution and availability of technologies.

The geographical location of plants was not considered, but investments for the construction of the gas pipeline on average 18 km (estimated average distance from the plant to natural grid) were included [85].

The maximum volume of biomethane that can be produced due to the availability of raw materials in Latvia, was calculated using data from the Central Statistical Bureau [87] on total number of livestock, the area used to grown green forage and corn, and the volume of silage obtained from it, and Eurostat data [88] on the volumes of waste produced in Latvia. The fraction of the maximum volume of biomethane that can be produced does not affect the operation of the model and it is a changeable condition.

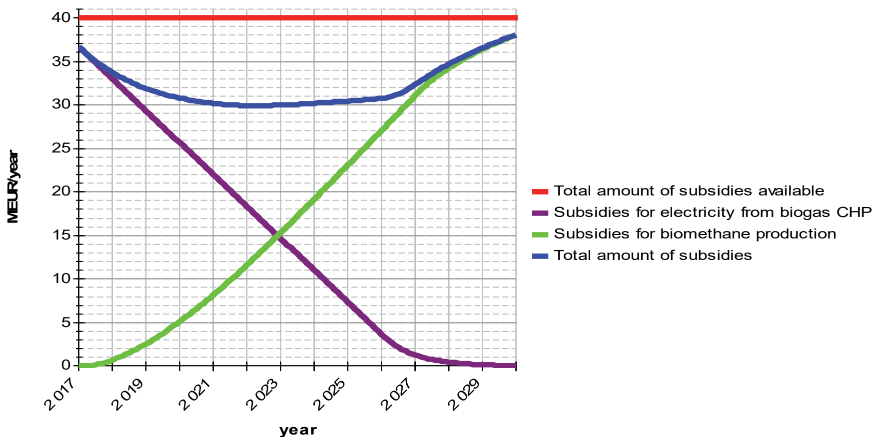

Figure 4.6. Costs of the biomethane support mechanism.

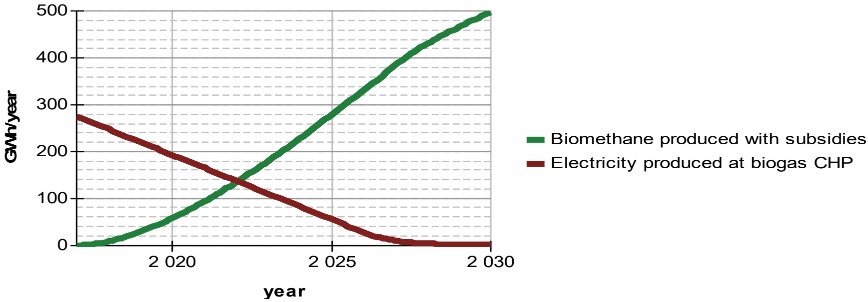

Figure 4.7. Volume of biomethane and electricity produced.

Simulation results show that the main parameters, that affect the stability of the support mechanism, are feedback links that bind the total amount of subsidies, a number of permits granted and subsidies paid, willingness to invest, availability of resources, as well as delays in time, caused by those feedback links. The results show that if the so-called FIP-based (feed-in premium) support incentive is introduced, then the biomethane industry will develop slowly and the total amount of subsidies would not be exceeded (Fig. 4.6.). In addition it would not cause relapsed „overshoots and oscillations" in the system. Moreover, because of the FIP-based support mechanism, produced biomethane volume could reach 500 GWh in 2030 (Fig. 4.7.) and the average amount of subsidies would be ~68 EUR per 1 MWh of biomethane.

4.4. Model Validation

Validation of the model was carried out using different tests [89]. Validation was performed for the initially developed model for the support mechanisms of biogas CHP plants. The initial model was used to define the biomethane support mechanism.

According to the theory, system behaviour is determined by its structure [89]. So at the beginning, the structure of the developed model was checked. Given that during the development of the model consultations were held with both the energy industry and the system dynamics modelling experts, and that the model parameters are compared and based on the reference information, it can be considered that the assumptions, used in the model about the operation of the system, characterizes its design correctly. Also, the numerical values are reasonable and meet the real system values within the confidence limits. The values of parameters are tested directly and compared with historical data. The model was validated using the data about historic dynamics of increase in the capacity of the biogas cogeneration plants in Latvia from 2006 to 2015. The historical data were gathered from the registers of the Ministry of Economics and Central Statistical Bureau of Latvia [73].

Test of the model behaviour and validation with the historical data showed that the initial model is able to reproduce the historical development of the biogas CHP plant industry in Latvia with sufficient accuracy (Fig. 4.8.). It also shows what are the expected trends in the future if the granting rate will not be restored (Fig. 4.1.) or if other suitable support mechanisms will not be introduced.

As it was mentioned above, the main parameters that affect stability of the support mechanism are feedback links that bind the number of permits granted and the total amount of subsidies, as well as willingness to invest. The fact that the modelled results correspond with the historical data confirmed conviction that the structure and behaviour of the developed model correspond to the real historical situation in Latvia and that the model results are stable, with no fluctuations. Consequently, this initial model, while maintaining its basic structure (which reflects the real system behaviour), was used to develop a system dynamics model for biomethane support policy.

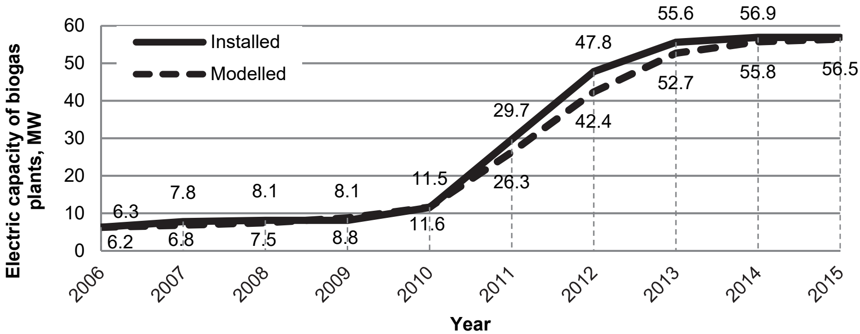

Figure 4.8. Comparison of the actual (till 2015) and modelled total installed electric capacities of biogas CHP plants.

When examining the model, it can be concluded that the willingness to invest is reversibly bounded and interferences with the essential parameters – capacity under construction and capacity in operation, as well as produced volume of biogas. This confirms the hypothesis that the development of the biogas industry in Latvia is directly dependent on the willingness to invest in production facilities. Furthermore, with extreme conditions and extreme policy test it was assessed that the behaviour of the developed model is appropriate in those circumstances.

4.5. Scenario Analysis

In order to determine how the volume of the biomethane produced and the total amount of support payments, as well as the average support payment per 1 MWh of biomethane is affected by the time allowed to start an investment, duration of the support period and the maximum amount of annual subsidies, eight support mechanism scenarios were defined and analysed. The following criteria were chosen for selection of the most appropriate conditions for the support mechanism: maximum volume of biomethane produced; a minimum total amount of subsidies; and a minimum average amount of subsidies per 1 MWh of biomethane. The base scenario (Scenario 0 in Table 4.1) assumes that (1) the time allowed to start the investments (i.e. the allowed period of time to initiate construction of plant) is 2 years, and (2) the period in which an entrepreneur is eligible for subsidies, is 10 years (these two time periods are determined by the existing laws and regulations [76, 90, 91], and (3) the total available amount of subsidies is 40million Euros per year. By changing and combining these three parameters, the other seven scenarios have been developed. The value ranges of the support mechanism's scenario parameters and scenario results are summarized in Table 4.1

Table 4.1.

Support mechanism scenarios and results

Scenario	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Time allowed to start investments (years)	2				3			
Period of support (years)	10		15		10		15	
The total available maximum amount of subsidies (MEUR per year)	**40**	40+(*)	40	40+	40	40+	40	40+
Results								
Volume of biomethane produced in 2030 (GWh per year)	**499.3**	587.2	630.1	740.1	498.9	586.9	629.9	740.0
Total production of biomethane in the whole period (GWh)	**2845**	3269	3436	3945	2854	3278	3447	3958
Amount of subsidies in 2030 (MEUR per year)	**38.03**	44.68	41.05	48.05	38.02	44.68	41.07	48.07
Total amount of subsidies in the whole period (MEUR)	**231.7**	265.7	236.2	270.6	232.5	266.7	237.1	271.6
Average amount of subsidies per 1 MWh of biomethane (EUR/MWh)	**81.43**	81.28	68.76	68.58	81.47	81.31	68.79	68.61

(*) – The total available maximum amount of subsidies increases annually.

From the scenario results, it can be concluded that the time allowed to start investment – 2 or 3 years – has no significant effect on either volume of biomethane produced or a number of subsidies paid, and not on the average amount of subsidies per 1MWh of biomethane. If the period allowed to start investment is 3 instead of 2 years, then the total volume of biomethane produced increases by about 0.3 %, but the total amount of subsidies paid is only about 0.4 % higher, and the average amount of subsidies (AAS) paid per one unit of biomethane energy is about 0.05 % higher. Those three mentioned parameters are affected more by the period of support and by the total amount of subsidies available. If the duration of the support period is increased from 10 to 15 years, the AAS per 1 MWh of biomethane is reduced by ~16 %, and at the same time, cumulative volume of biomethane produced is increased by ~21 %, regardless of whether the total available maximum annual amount of subsidies is fixed or increases annually. Using the developed SD model, it is possible to simulate a situation where the support period is 20 years. In this case, if the duration of support period is increased from 15 to 20 years, the average amount of subsidies per 1 MWh of biomethane decreases by ~8 %, and cumulative volume of biomethane produced increases by ~9 %. This means that the changes are still observed but to a lesser extent. However, from the entrepreneurs' (potential investors and producers of biomethane) point of view, a longer support period creates a greater sense of stability and increases the willingness to invest, and thus promotes a development of the biomethane sector.

The results show that by setting a longer period for subsidies and increasing the total amount of subsidies, understandably, the volume of biomethane produced will increase, and the average amount of subsidies paid per 1 MWh of biomethane will reduce. When deciding on the conditions of the support mechanism – time allowed to start investments, the length of the support period and the total amount of the subsidies paid – it must be taken into account that:

- the period to start investments shall be sufficiently long to enable the entrepreneur to complete all the necessary formalities and begin construction. Nevertheless, it shall also be short enough to be easily foreseeable and monitoring authorities can follow the development of the project. Therefore, one year would be too short a period, but by allowing three years instead of two to start investments and construction, this would not lead to significantly higher biomethane production volumes. Moreover, not the total amount of subsidies paid nor the AAS per 1 MWh of biomethane will decrease significantly;
- the period of support plays a key role both to reduce the AAS per 1 MWh of biomethane and to obtain higher biomethane production volumes. In addition, a longer period of support makes entrepreneurs more confident and increases their willingness to invest which is an essential factor for the development of each industry. However, it must be noted that the support period is limited by the technical lifetime of the equipment. Moreover with time technologies become more common and hence more accessible (the necessary capital investments per unit of capacity decreases), and at the

same technologies become more energy efficient. It is understandable that the longer period of support is provided, the more biomethane at a lower average price can be produced. Therefore the recommended period of support could be 15 or even 20 years, which corresponds to the length of period of support in other EU countries (e.g. in Germany and the UK, the period of support is 20 years, in the Netherlands – 12 years);

- the national economic situation determines what will be the total available maximum amount of subsidies. If the country's economic situation is stable, but there is no increase in growth, then the total amount of subsidies shall be constant. However, if the country develops economically, then in order to promote both the development of the sector and reduction of energy dependency on external suppliers, by increasing biomethane production volumes, it is advisable to increase the total available amount of subsidies gradually. However, it should be noted that whether the total maximum amount of subsidies is fixed, or is increased gradually, the average amount of subsidies paid per one unit of biomethane energy is not affected significantly.

Considering all the above-mentioned arguments, it can be concluded that the preferred support mechanism scenario would be as follows: time allowed to start investment – 2 years; support period – at least 15 years or more; with the fixed or, if possible, with an annually increasing total available maximum annual amount of subsidies.

4.6. Risk Analysis

In order to assess the dependence of the models' main results on the values of most important parameters, an uncertainty analysis was carried out. The most significant parameter of the model, which cannot be directly affected by policy-makers, the "willingness to invest" was assessed and its effect on the following main results of the model:

- the total amount of subsidies paid,
- the total volume of biomethane produced,
- the average amount of subsidies paid for 1 MWh biomethane, and
- a number of permits issued.

To verify the robustness of the support mechanism, tests were performed using the *Latin Hypercube* method available in Powersim Studio 8 software platform with a maximum resolution in 40 run counts. Results obtained with this method were considered with the same confidence as results obtained with the *Monte Carlo* method in 400 run counts [92]. The calculation period is from 2017 to 2030, the time step is 0.1 year, and the uniform distribution type for the "willingness to invest" was chosen (the range is from 0.1 to 0.8). A base value of the "willingness to invest" is 0.75.

Assessing sensitivity of the parameters – "the total amount of subsidies paid"; "the total volume of biomethane produced" and "the average amount of subsidies paid per 1 MWh of biomethane", it can be concluded that the distribution range of probability is very narrow, which indicates a high level of robustness of the developed support mechanism. This means that the willingness to invest in biomethane production facilities, which is not predictable and is a variable parameter, affects the main results of the support mechanism insignificantly. This means that the developed support mechanism can ensure a stable amount of subsidies paid, even if the willingness to invest differs from what was forecasted.

In turn, assessing the sensitivity of the granting rate, it can be concluded that distribution range of probability is very wide. This point to the fact that the stability of the biomethane support mechanism is achieved by the granting rate module, reducing the dispersion of the results of sensitivity analysis for the rest of the parameters.

Results of the uncertainty analysis show that the developed support mechanism is with a relatively high robustness. Thus, the results obtained can be considered reliable and the developed model itself – as suitable to develop and to analyse a support mechanism for the biomethane production and supply system.

CONCLUSIONS

1. The "cradle-to-gate" study conducted on the building materials production indicated that this is a very energy intensive process. This is confirmed by the calculation and evaluation results of the research conducted – the environmental impact caused due to the use of natural gas, is more than 75 % of the total environmental impact of production. Most of the emissions are directly related to the consumption of fuel (natural gas) in the industry.
2. The results of the study indicate that the most significant reduction of environmental impact could be achieved, if natural gas is substituted by biomethane. It should be pointed out that in this case no technological changes are required. The next best alternative from an environmental impact point of view is the use of a second-generation biofuel, but this alternative requires certain technological changes.
3. The most economically advantageous biomethane production scenario, regardless of the selected biogas upgrading method, would be if instead of distributed biogas production, biomethane is produced at a single joint plant and subsequently is injected into the natural gas grid. Although this method may be the most difficult to implement for existing biogas plants, it could be the most economically advantageous solution for new plants. For the existing biogas plants, the scenario where biogas from a number of smaller biogas plants is delivered to one larger upgrading plant for biomethane production could be the preferred solution.

4. The total costs per unit for biomethane production, transportation and injection into the natural gas grid, is higher than the import price of natural gas (for 2017 – about 1.6 times; for 2030 – about 20 % higher). Therefore, under current conditions, biomethane production would need financial support to make the costs compatible with the price of natural gas.
5. It can be concluded that the preferred support mechanism scenario, to achieve greater total volume of biomethane production for lower average amount of subsidies for one unit of biomethane energy, would be as follows: time allowed to start investment – 2 years; support period – at least 15 years or more; with the fixed or, if it is possible, with annually increasing total available maximum annual amount of subsidies.
6. The risk analysis shows that the developed support mechanism has a relatively high robustness. This means that the developed model for support policy includes a flexible granting rate mechanism that provides low dispersion around the average value for the key parameters: the total amount of subsidies, the total volume of biomethane produced and the average amount of subsidies paid for one unit of biomethane energy. Therefore, the results obtained can be considered reliable and the developed model itself – as suitable to develop and to analyse support mechanisms for biomethane production and supply system.

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