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Doctoral Program in Environmental Science

CLEANER PRODUCTION IN BIOWASTE MANAGEMENT

Summary of doctoral thesis

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DISSERTATION PROPOSED FOR DOCTORAL DEGREE IN ENVIRONMENTAL ENGINEERING AT RIGA TECHNICAL UNIVERSITY

This dissertation is proposed for obtaining the doctoral degree in Environmental Engineering and will be defended on June 27, 2014 at the Faculty of Power and Electrical Engineering of the Riga Technical University, 1 Kronvalda boulevard, room 21.

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CONFIRMATION STATEMENT

I, the undersigning, hereby confirm that I have developed this dissertation submitted for consideration at Riga Technical University for obtaining the doctoral degree in Environmental Engineering. This study has not been submitted to any other university or institution for the purpose of obtaining scientific degree.

Jelena Pubule ………………………………

Date: 12.05.2014.

This dissertation is written in English and contains: introduction, 5 chapters, conclusions, bibliography, 49 figures, 13 tables and 96 pages. The bibliography contains 183 references.

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Background and current situation

Currently, global attention, including in Latvia, is being paid to two aspects of the energy crisis – energy dependency and climate change. The global experience has proven that with an increase in the consumption of energy, a deficiency of energy resources occurs. In this situation, public officials have increased the importation of energy resources, rather than encourage a reduction of consumption. Consequently, the state becomes more dependent on imported energy resources. At the same time, scientists are researching alternative energy resources, and the development of new technology.

Resource scarcity is thus the 1st dimension of the problem. The 2nd dimension of the problem faced in the power industry is energy dependency. The power industry in Latvia has acquired a stable position in the national economy. The move from a fossil fuel economy to an economy of renewable energy sources (RES) is a complicated process which requires a long-term development strategy as well as a concerted effort to ensure its implementation.

The target for renewable energy as a share of total consumption is 40% by 2020 according to the EU-Directive 2009/28/EC on the promotion of the use of energy from renewable sources. At the same time, the main practice for waste management is landfilling in many European countries. Only in the most developed countries do biogas plants use organic waste for biogas production. European countries have to comply with the Landfill Directive 1999/31/EC, and with the Waste Framework Directive 2008/98/EC to considerably reduce the landfilling of the biodegradable portion of municipal solid waste (MSW). Unfortunately, the implementation of the European targets is still lagging behind. The use of biowaste as a resource will help to reach the above mentioned targets regarding the use of renewable energy and the reduction of landfilling as a part of the biodegradable part of the MSW.

The use of biowaste as a resource allows Latvia to move closer to the EU's common objectives by reducing the amount of waste disposed in landfills. There are possibilities to utilize biowaste for energy production in Latvia. Thus, the 3rd dimension of the problem that Latvia is facing is the undeveloped biowaste management system. The 4th dimension of the problem is the lack of a harmonized methodology for impact assessment and cleaner production in waste management.

The primary motivation for this research came from the above mentioned four dimensions of the problem. Since there is only one planet for all of us, and resources are limited, it is important to do our best to keep this earth suitable for living for the next generations.

The situation across Europe is very different in relation to waste treatment technology; for example, the biowaste sector is underdeveloped in the Baltic States, while in Germany the plant operators, due to overcapacities, are ready to import waste for treatment from other European Countries. A great number of waste incinerators, facilities for waste and refused derived fuels, have been built and have often been controversially discussed. Since the price of primary energy carriers has increased in the last years, waste as an energy resource becomes more and more attractive.

Using biowaste as a resource is required in order to meet the EU common objectives for waste management. Biowaste management should be considered from the economic, environmental, and social perspectives. The resulting complexity constitutes an important barrier to the implementation of biowaste planning projects. There are different methods for biowaste utilization, e.g. biogas production, anaerobic digestion, and the burning of composted materials. In order to promote the development of renewable energy sources, the potential amount of biowaste must be assessed and, based on that, the optimal transformation into an energy method has to be found.

A new assessment method based on a combination of different methods for performing the impact assessment of the waste sector, and the implementation of cleaner production in biowaste management, should be developed.

To summarize, the motivation for this thesis research work constitute the following:

1. The problems faced by the energy sector with resource scarcity and energy dependency;
2. EU targets for minimization of the deposited amount of biodegradable waste and REC must be achieved;
3. The principle of cleaner production in waste management should be implemented;
4. An effective quantitative tool to assess, compare, and screen biowaste management alternatives that stakeholders can apply to their specific situations must be developed.

Objectives

The aim of this thesis is to develop, apply, and evaluate a methodology for the integration of cleaner production principles into biowaste management. In particular, this thesis focuses on a methodological development addressed to policy- and decision-makers specifically (1) to evaluate biowaste management options, (2) to assess the sustainability of bioenergy projects, and (3) to find an optimal solution for biowaste treatment given the conditions in a particular region. This thesis applies a modelling approach based on a combination of Multi-Criteria Analysis (MCA) and Correlation and Regression analysis (CRA) and on a combination of MCA and System Dynamics (SD).

In order to reach the research goals, the following objectives have been set:

1. Identification and analysis of indicators for the evaluation of different biowaste management scenarios;
2. Development of a methodological approach based on the combination of MCA and CRA method;
3. Definition of the regression equation which will characterize the cleaner production principles in biowaste management;
4. Development of a methodological approach based on the combination of MCA and SD method;
5. Development of the methodology for the integration of the principles of cleaner production into biowaste management;
6. Validation of the proposed methodology as applied to the case of the Baltic States – Latvia, Lithuania and Estonia.

Research methodology

The research methodology is based on three interconnected modelling parts. The first part is based on the use of the Multi-Criteria Modelling for the evaluation of biowaste management options from environmental, economical, technical, and social aspects. To find and evaluate the optimal treatment scenario, TOPSIS (the Technique for Order of Preference by Similarity to Ideal Solution) is applied. The second part is based on the use of two statistical data processing methods: correlation and regression analysis. The interrelationship, and its proximity between two magnitudes, has been determined through a correlation analysis. The statistical analysis of data, and the multi-factor empirical model, were developed using the computer program STATGRAPHICS. A regression analysis was used to determine a multiple factor regression model, and the statistical significance of its coefficients. The third part is based on the use of SD modelling. To simulate the problems in the Powesim program, a simplified dynamic system model of biodegradable waste management has been created. The model has been consciously created in a simplified fashion to be used in combination with MCA and SD in the field of waste management.

Scientific significance

The scientific significance of the thesis is based on the following aspects:

1. Method implemented in the modelling tool addressed to policy- and decision-makers (1) to evaluate biowaste management options, (2) to assess the sustainability of bioenergy projects, and (3) to find an optimal solution for biowaste treatment given the conditions in a particular region have been proposed;
2. Implementation of indicators for the integration of principles of cleaner production into biowaste management;
3. Development of a method based on the integration of MCA and SD and MCA and CRA which is effective in assessing, comparing, and selecting the optimal biowaste management alternatives which stakeholders can apply to their specific situations;
4. Integrating MCA, SD, and CRA accomplishes several things: it helps to structure the complex multidisciplinary problems involved in biowaste management; it responds to the interests of different stakeholders; it avoids the weaknesses inherent in each individual modelling approach; and, it provides an integrated overall assessment of a complex problem.

Practical significance

The practical significance of this thesis can be addressed to different stakeholders at different levels, particularly:

1. The governmental and regional level – the results of this thesis are useful for the evaluation of different biowaste management options in Latvia, Lithuania, and Estonia. Results allow policy- and decision-makers to compare various alternatives from environmental, economical, technical, and social perspectives.
2. The waste management and energy sector – the proposed methodology allows for the evaluation of biowaste management options to assess the sustainability of bioenergy projects, and to find an optimal solution for biowaste treatment in the given conditions.
3. The environmental protection sector – the results of this thesis are useful for the assessment of biowaste projects during the planning, environmental impact assessment, implementation, and improvement phase.
4. The scientific level - MCA and SD methodologies combined in the way proposed here can be used not only for waste management, but also in other fields dealing with decision-making in complex and dynamic systems. Future research based on the results of this study should take into account national boundaries, and the level of detail available.

Approbation

The results of the research have been discussed and presented in the following conferences:

1. Pubule J., Kamenders A., Valtere S., Blumberga D. Cleaner production in biowaste management // 5th International Conference "Biosystems Engineering 2014", Estonia, Tartu, May 08-09, 2014.
2. Pubule J., Veidenbergs I., Valtere S., Kalnins S.N., Eihvalde D. Indicators for the assessment of biowaste treatment through anaerobic digestion // The 9th International Conference "Environmental Engineering", Lithuania, Vilnius, 22-23 May, 2014.
3. Pubule, J., Blumberga, D. An assessment of the potential and optimal method for biowaste energy production in Latvia // "Energy and Sustainability 2013", Romania, Bucharest, 19 – 21 June, 2013.
4. Pubule, J., Romagnoli, F., Blumberga, D. Finding an Optimal Solution for Biowaste Management System in the Baltic States // 8th Conference on "Sustainable Development of Energy, Water and Environment Systems", Croatia, Dubrovnik, 22-27 September, 2013.
5. Pubule, J., Blumberga, D., Romagnoli, F. An Assessment of the Potential and Finding the Optimal Method of Biowaste Treatment in Latvia. // 21st European Biomass Conference and Exhibition, Denmark, Copenhagen, 3-7 June, 2013.
6. Pubule, J., Bergmane, I., Blumberga, D., Rošā, M. Development of an EIA Screening Phase for Biogas Projects in Latvia // "Environmental impact 2012", England, New Forest, 3-7 July, 2012.
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9. Pubule J., Romagnoli F., Blumberga D. Analysis of Environmental Impact Assessment of Power Energy Projects in Latvia // 8th Annual Conference of Young Scientists on Energy Issues CYSENI 2011, Lithuania, Kaunas, 26.-27. May, 2011.

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Structure of the thesis

This dissertation is written in English and contains: introduction, 5 chapters, conclusions, bibliography, 49 figures, 13 tables and 96 pages. The bibliography contains 183 references. The literature review and bibliography are not included in this summary.

1. METHODOLOGY

To achieve the goal of this study, which is to propose an effective quantitative tool to assess, compare, and screen biowaste management alternatives that stakeholders can apply to their specific situations a combination of MCA, SD modeling and Correlation-Regression analysis (CRA) has been developed.

The developed methodologies for the assessment of biowaste management scenarios and the implementation of cleaner production principles in biowaste management are investigated by simulating different biowaste treatment scenarios. In the study, planning, impact assessment, implementation, and improvement phases in biowaste management are described.

1.1. Inventory of Cleaner production indicators

It is crucial to offer an evaluation tool that reflects the criteria of applicability, consistency, reliability and affectivity from a practical point of view. Within the framework of this work, a quantitative and qualitative analysis of existing waste management, environmental impact assessment, and energy projects practice was performed. The work identifies qualitative and quantitative indicators of the materiality of effect. The inventory phase includes a selection of criteria for the assessment of principles of cleaner production in biowaste management.

1.2. Multi Criteria Analysis

The following is the second phase of the methodology based on the use of MCA for the evaluation of biowaste management scenarios. To find and evaluate the optimal treatment scenario, TOPSIS was applied.

1.3. Correlation and Regression analysis

Empirical data from the inventory phase and MCA has been processed by using two statistical data processing methods: correlation and regression analysis. The interrelationship, and its proximity between two magnitudes, has been determined through correlation analysis. Regression analysis was used to determine a multiple factor regression model, and the statistical significance of its coefficients.

The statistical analysis of data, and the multi-factor empirical model, were developed using the computer program STATGRAPHICS.

1.4. System Dynamics

During the research, a system dynamics method has been used for the evaluation of biowaste treatment options.

Furthermore, during the research a combination of both MCA and SD modeling has been developed. Multi-Criteria (sustainability) Analysis allows for the assessment and prioritization of different technologies from technical, ecological, economic, and social perspectives.

The MCA method focuses on decisions influencing local problems. It does not assess the impact of these decisions on the system as a whole. Besides this, MCA cannot be used for forecasting, or to make predictions. Because this method does not take into account dynamic changes in the system occurring over time, control (over the system) cannot be applied. An analysis of the structure of the problem under study is crucial in understanding the causes of the system's behaviour and in determining an action plan for managing the situation. It is at this point that MCA can benefit from the SD modeling approach.

Because decision-makers are typically confronted with a large set of complex data, MCA is a very valuable method for decision-makers and others to identify an optimal course of action. SD modeling helps decision-makers and others acquire an understanding of these systems.

Integrating MCA and SD methods can help to structure complex problems, respond to the interests of multiple stakeholders, avoid the weaknesses of each individual modelling approach, and perform an overall assessment of complex problems. System dynamics converts results obtained from MCA into a mathematical model of waste management to allow for the prediction of a system's behaviour over time.

The developed methodologies for the assessment of biowaste management scenarios, and the implementation of cleaner production principles in biowaste management, were investigated by simulating different biowaste treatment scenarios. The algorithm of the work is shown in Figure 1.

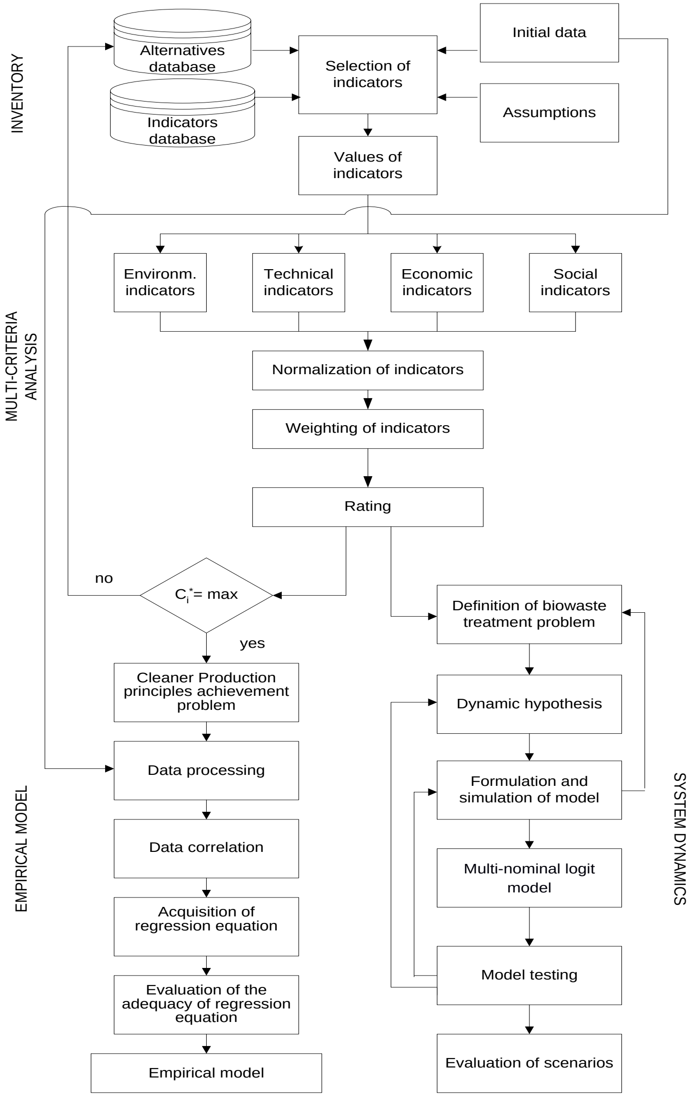


Fig. 1. Methodological algorithm

2. IDENTIFICATION AND ANALYSIS OF CLEANER PRODUCTION INDICATORS

For the development of biowaste management scenarios, the experience of other countries as well as different existing biowaste management technologies were analysed. These included mechanical–biological treatment, incineration, bio-gasification, biodegradation of waste in reactors, anaerobic digestion, composting and pyrolysis.

During the research, seven scenarios found to be suitable for the conditions found in the Baltic States were analysed:

1. separate collection with anaerobic digestion;
2. separate collection with composting;
3. mechanical biological treatment (MBT) with mechanical biological pre-treatment and anaerobic digestion;
4. MBT with mechanical biological pre-treatment composting;
5. incineration with energy recovery;
6. incineration without energy recovery;
7. landfilling with the collection and utilization of landfill gas.

Five of these scenarios use the existing waste collection and transport system for unsorted municipal waste and regional waste landfills. To date, there is still no separate biowaste collection for households in some areas. To produce a clean material from biowaste treatment, it is necessary to develop a separate system for collecting organic waste. Two scenarios have been developed that separate the collection and transportation systems.

2.1. Biowaste management in the Baltic States

The European Union has set targets to minimize the amount of biodegradable waste deposited in landfills. European countries are required to comply with Landfill Directive 1999/31/EC and Waste Directive 2006/12/EC to reduce the landfilling of the biodegradable fraction of municipal solid waste. Member states are also obliged to comply with Renewable Energy Directive 2009/28/EC.

During the last decade, clear indications on identifying management solutions different from the landfilling of municipal solid waste have been highlighted. Nevertheless in the year 2010, 16 EU countries had a share of landfilled MSW which was higher than 50%. Waste management policies in European countries (and other developed nations) focused on reducing the amount of biowaste landfilled. In many European countries, large quantities of biowaste are still landfilled with unsorted MSW. This has resulted in the largest portion of greenhouse gas emissions generated being attributed to waste management. At the same time, the proportion of recycled MSW has increased substantially in recent years. Progress has been made in the rate of recycling due not only to the recycling of waste materials, but also to a lesser degree to the recycling of biowaste. There is, however, still need to improve the management of biowaste in order to promote diversion from landfills in line with the Waste Framework Directive's waste hierarchy.

The Baltic States have a generally similar climate and geography. They are close in size of territory and population. Latvia and Lithuania are classified as middle-income economies. Estonia moved up to a high-income economy in 2006. The Baltic States have similar social characteristics and development patterns, and have few differences in their respective energy sectors. Their main renewable energy sources are firewood and hydro. Latvia has the highest share of renewable energy in gross electrical consumption among the most recent EU member states and the highest share of renewable energy in the final consumption of energy.

During the last 20 years, waste management systems have been introduced throughout the region. Landfills have been built and a legislative framework created. Today, there are 25 regional waste management regions with 27 municipal waste landfills in the Baltic States. A system for managing waste in the region has also been developed, but there is still a great need for improvements in that system.

The vast majority of MSW is still landfilled in Latvia. In Lithuania, the figure is more than 90%, and in Estonia more than 75%. Waste management in Lithuania is less developed regionally, since not all of the country is covered by a municipal solid waste collection scheme, and only 5% of MSW is recycled. A landfill tax was introduced in Lithuania in 2013. The lack in previous years of a landfill tax combined with relatively low management and landfilling fees did not encourage recycling and waste pre-treatment in Lithuania. In Latvia only 9% of MSW was recycled in 2010, and organic recycling (compost and other biological treatment) was applied to less than 1% of organic material in 2010.

Estonia has the most developed waste management system in the region. Twenty percent of MSW in Estonia was recycled in 2010. Large scale composting and separate biowaste collection is well developed there.

The Baltic States do not have highly-developed separate biowaste collection and treatment systems. Composting is the only method used in the Baltic States for reducing the amount of biowaste. During development of the waste management system, several landfill operations in Latvia established composting facilities. The aim of the composting facilities was to minimize the amount of biowaste to be landfilled. However, experience demonstrated that these composting areas are not being used to their full potential. This is partly because the prepared material is not in demand by the market. It is also because of the lack of an administrative mandate as well as poor control of biowaste facilities and enforcement of regulations. Taking all this into consideration, alternative methods to minimize the amount of biowaste deposited in landfills are urgently needed. Construction of new waste incineration plants in Lithuania and Latvia has recently been completed.

2.2. Biowaste management indicators

Indicators for the technical, environmental, economic, and social dimensions were developed for the evaluation of the competing scenarios. These indicators were established by reviewing the literature and gathering the opinion of experts in this area. Twelve main indicators were used to evaluate the biowaste management options.

Table 1

Indicators used for the assessment of the biowaste scenarios

Dimension	Indicator	Unit	Preferable outcome
Environmental	Greenhouse gas emissions	t / t of biowaste	Min
	Leakage	m^3/t of biowaste	Min
	Water usage	m^3/t of biowaste	Min
	Fossil fuel substitution	%	Max
Technical	Biogas production	m^3/t of biowaste	Max
	Energy consumption	kWh/t of biowaste	Min
	Energy production	kWh/t of biowaste	Max
	Heat production	kWh/t biowaste	Max
Economic	Operational costs	€/t of biowaste	Min
	Capital costs	€/t of biowaste	Min
	External environmental damage costs	€/t of biowaste	Min
Social	Public participation and acceptance	%	Max

Values for the environmental dimension included greenhouse gas emissions, leakage, water usage, and fossil fuel substitution. Indicators were taken both from the literature and from Latvian waste management companies. Values for the technical dimension included biogas production, energy consumption, energy production, and heat production. Again, Indicators were taken from both the literature and from Latvian waste companies. For the economic value, data from the European Commission for Lithuania, Latvia, and Estonia were used. The social value indicator was based on expert opinion.

During the research, seven biowaste treatment scenarios were evaluated and compared in order to find the most feasible alternative (see Table 2).

Table 2

Designation of biowaste treatment scenarios

Designation	Biowaste handling practice
A_1	Separate collection - Anaerobic Digestion
A_2	Separate collection – Composting
A_3	MBT - mechanical biological pre-treatment – Anaerobic Digestion
A_4	MBT - mechanical biological pre-treatment – composting
A_5	Incineration with energy recovery
A_6	Incineration without energy recovery
A_7	Landfilling

These indicators must be analysed during all project development stages, starting with Planning and Environmental Impact Assessment until the Implementation and Improvement of the project. An analysis of the set indicators should be done continuously.

The proposed indicators can be used in the Environmental Impact Assessment process of biowaste management projects, especially during the screening phase of the procedure. These indicators help to identify basic conditions for the introduction of principles of cleaner production in biowaste management.

3. RESULTS AND APPROBATION OF THE METHODOLOGY FOR INTEGRATION OF CLEANER PRODUCTION INTO BIOWASTE MANAGEMENT

3.1. Results of Multi-Criteria Analysis

Multi-Criteria Analysis is used to identify compromises for resolving complex policy planning problems like waste management. The advantage of the MCA method is that it allows the preferred alternative among several to be determined. A number of tools have been used to do MCA studies. However, there is still lack on research carried out on combining complementary environmental evaluation tools in waste management.

The multi-criteria analysis method mainly consists of a weighted sum of a set of criteria. In fact, this is the rather quick and simple method used in several studies concerning energy recovery from different types of waste, and the assessment of the sustainability within different renewable energy systems. The central core of the whole process is an optimization process based on a simple multi-objective matrix. The criteria identified within it are reduced into a single-score objective using a weighting procedure that determines its relative importance by multiplying each criterion with a weighing factor.

Within the multi-criteria analysis, the choice of the criteria categories is crucial because a quantitative evaluation must be carried out in relation to the reference indicators. Only in this way is the impact of each criterion provided.

For the evaluation and finding of the optimal treatment scenario, TOPSIS was applied. The aim of this method is to aid in multiple-attribute decision-making by ranking alternatives in accordance with how they match up with the ideal solution.

Twelve criteria from four impact dimensions were selected for the evaluation of biowaste treatment practices (Table 1).

Criteria weights ($w_1, w_2, \dots, w_m$) are equal for all three Baltic States, and were determined by experts. Normalized and weighted values from the decision-making matrix for the evaluation of biowaste management scenarios for Latvia, Lithuania and Estonia are displayed in Table 3.

Table 3

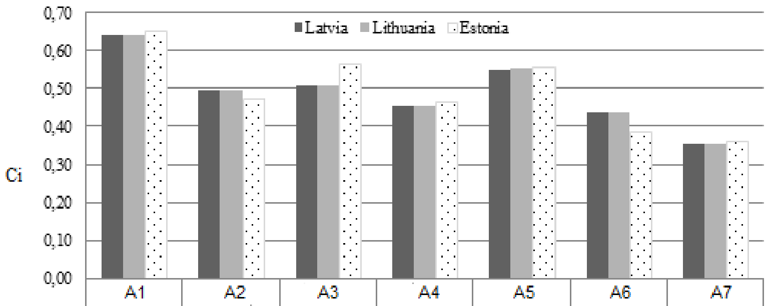
Normalized and weighted decision-making matrix

Criterion / Altern.	Environmental dimension				Technical dimension			
	GHG emissions w_1b_{i1}	Leakage w_2b_{i2}	Fossil fuel substitution w_3b_{i3}	Water usage w_4b_{i4}	Biogas production w_5b_{i5}	Energy consumption w_6b_{i6}	Energy production w_7b_{i7}	Heat production w_8b_{i8}
A_1	0.0234	0	0.0563	0.07	0	0.0124	0.0444	0.075
A_2	0.0234	0	0.1	0	0.1	0.0357	0.1	0.1
A_3	0.0613	0	0.0753	0.025	0.0318	0.0267	0.0678	0.086
A_4	0.0613	0	0.1	0	0.1	0.01236	0.1	0.1
A_5	0	0	0	0	0.1	0.1	0	0
A_6	0	0	0.1	0	0.1	0.1	0.1	0.1
A_7	0.2	0.07	0.0847	0.026	0.0818	0	0.0949	0.098

Criterion / Altern.	Economical dimension							Social dimension		
	Operational costs w_9b_{i9}			Capital costs $w_{10}b_{i10}$			External environ. damage costs $w_{11}b_{i11}$	Social participation and acceptance $w_{12}b_{i12}$		
	Latvia	Lithuania	Estonia	Latvia	Lithuania	Estonia		Latvia	Lithuania	Estonia
A_1	0.1	0.1	0.1	0.0476	0.0479	0.0481	0.0305	0.0333	0.0333	0.02
A_2	0.013	0.013	0.0125	0.001	0.001	0.001	0	0.0167	0.0167	0.06
A_3	0.1	0.1	0.1	0.0476	0.0479	0.0481	0.0305	0.0833	0.0833	0
A_4	0.0391	0.0391	0.0396	0.0107	0.0109	0.011	0	0.0667	0.0667	0.04
A_5	0.0652	0.0652	0.0667	0.1	0.0963	0.0961	0.0089	0.05	0.05	0.04
A_6	0.0696	0.0739	0.0708	0.0962	0.1	0.1	0.0254	0	0	0.1
A_7	0	0	0	0	0	0	0.12	0.1	0.1	0.08

The biowaste management scenarios evaluation using TOPSIS were completed for Latvia, Lithuania, and Estonia. The results obtained showed that separate collection is the optimal solution for all three Baltic States.

The biowaste management scenarios evaluation using TOPSIS were completed for Latvia, Lithuania, and Estonia. The results obtained showed that separate collection with anaerobic digestion (A1) is the optimal solution for all three Baltic States and has the highest Relative Closeness to the Ideal Solution (Ci). The TOPSIS analysis results showed that two more options exist for Latvia and Lithuania. These are incineration with energy recovery and MBT with anaerobic digestion. MBT with anaerobic digestion is the second best solution in Estonia, very closely followed by incineration with energy recovery (see Figure 2). These all share the highest rating. Selection between these options can be made based on different local factors, including the decision-makers' preference and the skill level necessary for the introduction of a specific biowaste treatment practice. Landfilling is the least desirable option in all three countries.



	A1	A2	A3	A4	A5	A6	A7
Latvia	0,64	0,50	0,51	0,45	0,55	0,44	0,36
Lithuania	0,64	0,50	0,51	0,45	0,55	0,44	0,36
Estonia	0,65	0,47	0,57	0,47	0,56	0,38	0,36

Fig. 2. Comparison of ratings

3.2. Results of Multi-factor empirical model

During the research, the cleaner production principles achievement problem was analysed, and a multifactor empirical model was created. The main aim of the created multi-factorial empirical model was a determination of the regression equation which could then determine the reduction of GHG emissions.

A database based on the existing biowaste treatment plants was created and analysed. During the research, the above mentioned cleaner production indicators and parameters of the existing plants was processed.

During the research, the indicators for the assessment of biowaste treatment through anaerobic digestion were analyzed. The reduction of GHG emissions is one of the main benefits from this use, or more specifically renewable energy sources. Therefore, a statistical analysis of data from the decrease in GHG emissions must be completed, and the most significant characteristic factors of equipment function, or independent parameters, must be determined. The regression equation which characterized the connection between the decrease in GHG emissions and the parameters that influence this decrease must be defined.

The goal of this task is to determine the parameter relationship using a single factor linear model to select the type of regression equation. The correlation of changing magnitudes of dependent and independent variables can be evaluated with the aid of the correlation coefficient. In the case of a single-factor mathematical model, the Pearson expression is used to estimate,

$$r = \frac{\sum_{i=1}^{m}(x_i - x)(y_i - y)}{(m-1)S_x * S_y}, \qquad (1)$$

where

x_i, y_i - pairs of independent magnitudes with their respective dependent magnitudes;

x, y - arithmetic average values of independent and dependent magnitudes;

S_x, S_y - dispersion of magnitude selections.

With the aid of correlation coefficients, this study evaluates how precise mathematical models describing correlation proximity are. It is accepted that correlation is effective if correlation coefficients are from 0.8 to 0.9. It must be noted that computer programs for statistical analysis usually calculate the square of the correlation coefficient. If the R^2 value is multiplied by 100, then a magnitude (as a percentage) is acquired. This describes the changes in dependent variable magnitudes gained from the empirical equations analysed. For example, R^2 = 0,9 indicates that the equation of the regression to be examined describes 90% of the changes dependent on random magnitudes.

- Production of biogas (B_g) per tonne of biowaste, m^3/t;
- Energy consumption (E_{ec}) per tonne of biowaste, kWh/t;
- Energy production (E_{ep}) per tonne of biowaste, kWh/t;
- Heat production (H_p) per tonne of biowaste, kWh/t;
- Fossil fuel substitution (F_{fs}), %.

Only the graphs showing a correlation between the dependent variable magnitude and independent variables are shown below. Changes due to a decrease in greenhouse gases GHG, depending on heat energy produced from biogas, are shown in Figure 3.

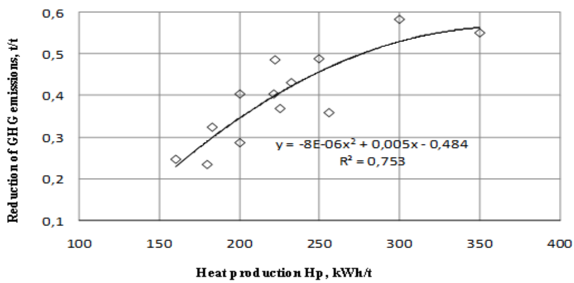


Figure 3. Decrease in GHG emissions depending on heat production

The figure shows that a mutual correlation between these magnitudes can be observed. The value of the square of the correlation coefficient R^2 = 0.75 and the correlation coefficient R = 0.87 were determined through analysis. The relationship between these two magnitudes is non-linear and described by the equation:

$$GHG = -8E - 06.Hp^2 + 0{,}005.Hp - 0{,}484 \qquad (2)$$

Equation (2) explains 75% of changes in the examined data, and it can be used for approximate calculations. 25% of the decrease in GHG emissions is due to the influence of other parameters.

The data correlation analysis shows that a certain correlation between the decrease in GHG emissions and the energy consumption E_{ec} exists. The changes in magnitude can be observed in Figure 4.

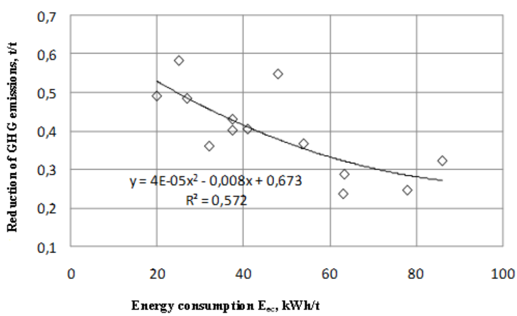


Figure 4. Reduction of GHG emissions depending on energy consumption

The mutual correlation between the magnitudes examined is characterized by the square of the correlation coefficient $R^2 = 0.57$, and the correlation coefficient R = 0.75. The connection between these magnitudes is non-linear and described by the equation:

$$GHG = 4E - 05.Eec^2 - 0{,}008.Eec + 0{,}673 \quad (3)$$

As the mutual correlation of magnitudes is worse, the equation (3) explains only 57% of the observed changes in data, compared to 75% in the previous example. Consequently, other parameters show a greater influence – 43% of the observed decrease in GHG emissions. While observing the correlation of other parameters, it has been determined that a significant correlation is observed between the decrease in GHG emissions and the dependent energy production E_{ep}. For this reason, a subsequent multi-factor regression analysis examined the changes in the dependent variable magnitude of the decrease in GHG emissions in light of three indicators – energy consumption, energy production, and heat production.

$$GHG = f\left(Eec; Eep; Hp\right) \quad (4)$$

The data correlation analysis conducted facilitates a further regression analysis, because it identifies a collection of data to be included in the multi-factor regression equation.

The goal of regression analysis is to acquire a multi-factor, empirical equation that quantitatively describes the reduction of GHG emissions based on the characteristic and statistically significant indicators from equipment using biogas, and serves as a basis for predictions and evaluations of the reduction of emissions.

The regression analysis determines the precise quantitative parameters of random magnitude changes, that is, determines the significance of the stochastic connection with functional relations.

The regression analysis in this project was conducted in this order:

- the law of distribution of the dependent variable magnitude in the reduction of GHG emissions was verified;
- a regression equation was determined, using the least squares method;
- a statistical analysis of the results obtained was conducted.

The results of the regression analysis are correct if the necessary rules of application are observed. There are many rules, and it is not always possible to follow them all in practice. The main conditions of applying a regression analysis are numerous. The application of the regression analysis is correct in cases where the dependent variable magnitude (reduction of

GHG emissions) follows the law of normal distribution. In effect, this requirement is not with respect to independent variable magnitudes. This means that the analysis begins with determining the distribution of dependent variable magnitudes and the analysis can be continued only if the distribution adheres to the law of normal distribution.

The results of the distribution test can be seen in Figure 5. On a logarithmic graph, a normal distribution is graphed as a straight line. In Figure 5, the data to be analysed lies close to the flat curve on the graph. Deviations can be observed at small and large values of capacity. This means that distribution is close to normal, and the application of a regression analysis is valid.

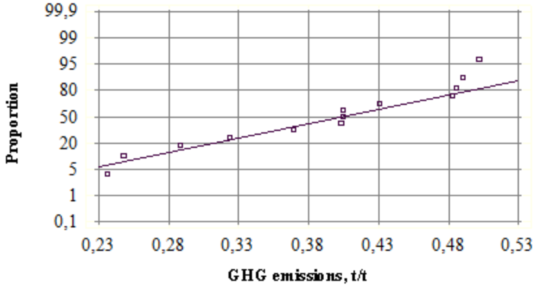


Figure 5. Distribution of GHG emission values

When creating empirical models in the form of regression equations, several essential questions must always be resolved: does the model include all independent variables that characterise the phenomenon examined, and does the model include superfluous, insignificant variable magnitudes which unnecessarily complicate the model. These questions are answered in the assessment of statistical significance of the magnitudes included in the created model, and the model's distribution analysis.

The regression equation determined in the project does not include double and triple interaction effects of independent variables, and it is expressed as:

$$y = b_0 + b_1 x_1 + b_2 x_2 + ... + bx = b_0 + \sum_{i=1}^{n} b_i x_i , \quad (5)$$

where

y – dependent variable magnitude;

b_0 – free agent of the regression;

$b_1 ... b_n$ – regression coefficients;

$x_1 ... x_n$ – independent variable magnitudes.

The regression equation obtained as a result of the statistical analysis corresponding to expression (1) includes statistically significant independent variables

$$GHG = b_0 + b_1.Eec + b_2.Eep + b_3.Hp \quad (6)$$

where
E_{ec} - energy consumption;
E_{ep} - energy production;
H_p - heat production.

The values of coefficients from the regression equation and their statistical assessment are provided in Table 4.

Table 4

The values of regression equation and their assessment

Coefficients b_i	**Values**	**t statistic**	**P value**
Constant b_0	0,2874	3,3968	0,0079
Coefficient b_1	-0,00242	-3,6296	0,0056
Coefficient b_2	0,000257	2,644	0,0998
Coefficient b_3	0,000653	2,225	0,0531

A significance level of P=0.1 was selected for data analysis. This corresponds to a reliability probability of 0.90. For the assessment of the statistical significance of the coefficients b_0 ... b_n of the regression equation (6), criterion t is used, which has a Stjudent distribution with f degrees of freedom

$$f = m - (n + 1) \,, \quad (7)$$

where
m – volume of the data collection to be analysed;
n – number of independent variables in the regression equation.

The degree of freedom is:

$$f = m - (n+1) = 13 - (3+1) = 9$$

The corresponding t criterion for these values from the Stjudent distribution tables is t_{tab} = 1.9. As shown in Table 4, the relationship in all cases is I t I > t_{tab}.

This means that all parameters are essential, and must be left in the equation.

As a result of this examination, a regression equation determining the reduction of GHG emissions was obtained, depending on the energy consumption E_{ec}, the energy production E_{ep} and the heat production H_p from biogas:

$$GHG = 0{,}2874 - 0{,}00241.Eec + 0{,}000257.Eep + 0{,}000653.Hp \qquad (8)$$

As a result of the statistical analysis of the data from the created empirical model, the determined R^2 value is 0.86. This means that the created model (8) explains 86% of the changes in the data to be analysed. The remaining 14% can be attributed to independent variables not included in the equation, or not defined in the project, or their mutually influential effects.

The assessment of the adequacy of the equation (8) is performed with the aid of a dispersion analysis, using the Fisher criterion F. To these ends, the dispersion ratio of the dependent variable magnitude to the remainder dispersion is reviewed:

$$F(f_1, f_2) = \frac{S_y^2(f_1)}{S_{rem}^2(f_2)}, \qquad (9)$$

where

$S^2_y(f_1)$ – dependent variable magnitude y dispersion;

$S^2_{rem}(f_2)$ – remainder dispersion.

The remainder is defined as the difference between the dependent variable magnitude and the value $y_i - y_i^{cal}$ which is calculated with the aid of the regression equation.

The value determined with the aid of the dispersion analysis conducted by the computer program is F = 19.16. The magnitude obtained is compared to the value in the criterion table, which is determined by the value of the degrees of freedom:

$$f_1 = m - 1 = 13 - 1 = 12 \quad \text{and} \quad f_2 = m - n = 13 - 3 = 10$$

The table value of the Fisher criterion is F_{tab}. = 2.9. As can be seen, the relation $F > F_{tab}$, is in effect, and this means that equation (8) is adequate and can be used to describe data within the limits of change:

- the reduction of GHG emissions from 0.24 to 0.68 t/t of biowaste;
- the energy consumption of biogas plant E_{ec} from 20 to 86 kWh/t of biowaste;
- the energy production E_{ep} from 146 to 380 kWh/t of biowaste;
- the heat production H_p from 160 to 350 kWh/t of biowaste.

Following the determination of the regression equation, it is possible to verify the proper applicability conditions of the regression analysis with the aid of a string of other indices. These are autocorrelation, multicolinearity and heteroscedasticity.

Autocorrelation test: using the Durbin-Watson test, a DW criterion has been determined during the course of the statistical processing and analysis of the data. Its value is 1.7, and that is larger than the limiting value of 1.4. This means that there is no significant remainder autocorrelation observed, and the magnitude assessments made through the analysis using the least squares method have not been distorted.

Multicolinearity test: this test was conducted in the project by analysing the coefficient correlation matrix calculated with the regression equation, and is shown in Table 5.

Table 5

Regression equation coefficient correlation matrix

Coefficient	**Constant**	E_{ec}	E_{ep}	H_p
Constant	1,0000	-0,7828	-0,1487	-0,7830
E_{ec}	-0,7828	1,000	0,0111	0,4978
E_{ep}	-0,1487	0,0111	1,000	-0,4207
H_p	-0,7830	0,4978	-0,4207	1,000

The analysis of the regression equation coefficient correlation matrix indicates that there is no significant correlation between coefficients and independent variable magnitudes. This is supported by the low values of the correlation coefficient in Table 5. The values observed in Table 5 are lower than, or close to, 0.5. This means that the assessment of the regression equation coefficients is correct.

Heteroscedasticity test: this test was conducted in the project by graphically verifying the remaining distribution depending on the energy consumption E_{ec} of the biogas plant. If an increase in variation is observed on the graph (points form a triangle or wedge), then heteroscedasticity is present.

The distribution of remainders is shown in Figure 6.

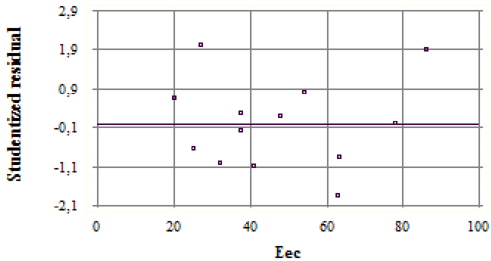


Figure 6. Remainder distribution depending on the energy consumption of a biogas plant

The figure shows that the collection of data has no significant changes in the remainder distribution when dependent on the energy consumption of the biogas plant E_{ec}. The remainder values are similar throughout the entire range of changes in E^{ec}. The project includes an examination of the remainder distributions dependent on other factors. The conclusion in all cases is that no heteroscedasticity can be observed, and the standard error has been correctly determined.

One of the ways to verify the regression equation is related to the verification of its member signs, and whether specific changes in the equation have a logical explanation from the aspect of the physical essence of the processes it describes. In the regression equation (8) which determines the reduction of GHG emissions, all parameters, except energy consumption E_{ec} have a positive sign, and an increase in their values increases the reduction in GHG emissions. When increasing the energy consumption E_{ec} of the biogas plant, the amount of deliverable energy useful to consumers is reduced. As a result, GHG emissions are reduced. The tendencies observed correspond to the actual processes, and can be logically explained.

One of the essential questions in the application of empirical equations is – how completely the results of the regression equation correlate to the data to be analysed. Only in the case of a satisfactory correlation can it be said that the model adequately describes the situation observed in practice, and that its applicability in the modelling of the situation is correct. To verify the adequacy of the empirical equation, empirical and calculated data are compared. Figure 7 shows this data comparison as a graph.

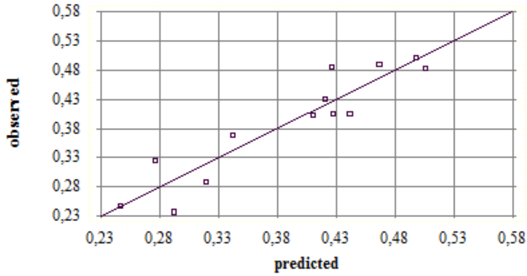


Figure 7. A comparison of analysable and calculated data showing a reduction of GHG emissions

As shown in Figure 7, a good correlation between both collections of data can be observed. If the reviewed data precisely correspond to the calculated value, then the points should lie on the flat curve seen in the figure. An increased distribution of points can be seen at low values in the reduction of GHG emissions.

3.3. Results of System Dynamics modeling

To simulate the problems in the Powesim program, a simplified dynamic system model of biodegradable waste management was created. The model takes into account the main stocks as well as the inflows, outflows, and variables that influence inflow and outflow. The main stock includes the total amount of waste, the amount of biodegradable waste, the amount of sorted biodegradable waste, and the amount of each kind of alternative accumulated processed waste.

The model has been consciously created in a simplified fashion to be used in combination with MCA and SD in the field of waste management. If required, it can be supplemented with waste sorting, environmental taxes, technological learning processes, etc. The structure of the model has been developed from interviews with experts in the field. The general stock and flow diagram of the model is shown in Fig. 8. This diagram is used to analyse the structure and behaviour of the biodegradable waste market.

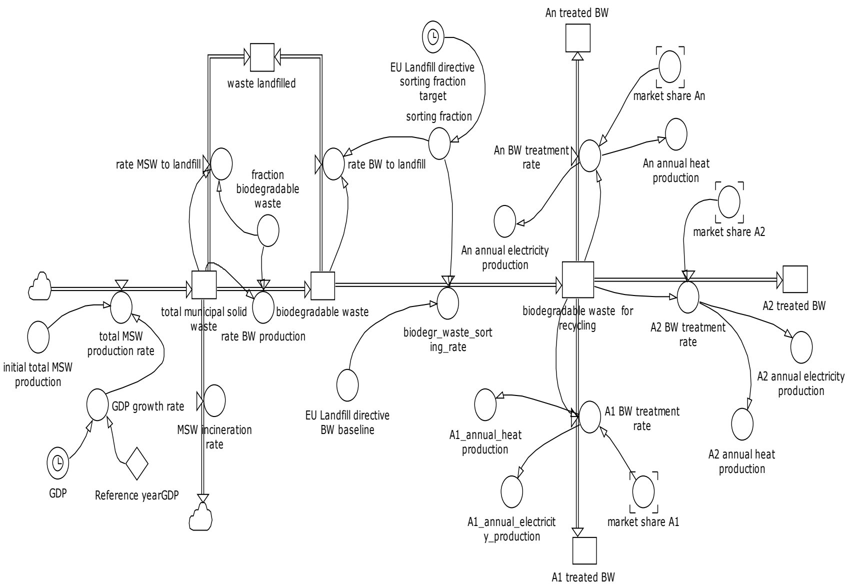


Figure 8. General stock and flow diagram

The results obtained in the TOPSIS analysis for each market share of alternative technological option are integrated into the system dynamics model using the multi-nominal logit model:

$$MS_i = \frac{exp^{-\alpha \cdot C_i}}{\sum_j exp^{-\alpha \cdot C_j}} \quad (10)$$

where

MS_i – market share of alternative;

α - coefficient that determines the steepness of the curve of share of the alternatives as a function of the Relative Closeness to the Ideal Solution from the TOPSIS analysis;

C_i - Relative Closeness to the Ideal Solution from TOPSIS analysis;

The amount of accumulated recyclable biodegradable waste is influenced by one inflow (biodegradable waste sorting rate), but several outflows. The number of outflows is dependent on the number of analysed alternatives:

$$Q_{BWR} = \int_{t=0}^{t=1} (BL_{BW} \times SF - \sum_{i=1}^{n} MS_i \times Q_{BWR})(t) \times dt + Q_{BWR}^{init} \quad (11)$$

where

Q_{BWR} – accumulated amount of sorted biodegradable waste, t;

BL_{BW} – EU directive 1999/31/EC [2] baseline of biodegradable waste, t/year;

SF – biodegradable waste sorting fraction, %;

Q^{init}_{BWR} – initial value of accumulated amount of sorted biodegradable waste, t.

The total municipal solid waste generated annually depends on the GDP growth rate. The rate of both MSW and biodegradable waste is determined by the accumulated amount of total municipal waste and the fraction of biodegradable waste. EU directive 1999/31/EC provides that the baseline amount of biodegradable waste and sorted fraction dictate the annual amount of biodegradable waste transferred to both landfill and recycling.

The sorted fraction depends on the EU directive 1991/31/EC sorting target. The amount of electricity and heat energy generated by each technology is calculated based on the treated amount of waste and specific energy production.

TOPSIS results shown in Figure 2 for each country were entered into the dynamic system model, shown in Fig.8. The initial values of the amounts used in calculations are from the TOPSIS model, together with statistical data (Eurostat) of 2010.

The development of the biodegradable waste market is modelled up until 2030. The sorted fraction of biodegradable waste is assumed to increase, reaching EU goals by 2030.

The amount of heat energy and electrical energy produced using each of the seven alternate biodegradable waste processing technologies. Changes in this amount can be analyzed over time using the system dynamic model.

The results from system dynamic modelling for energy produced in the form of both electricity and heat using various biodegradable waste processing technologies in Latvia from 2010 to 2030 are illustrated in Fig. 9.

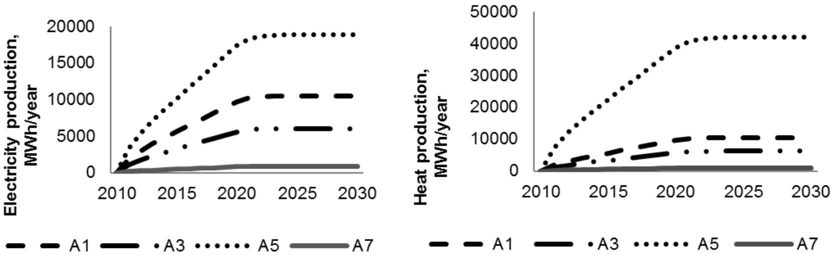


Figure 9. Simulated annual heat and electricity production rates for different biowaste treatment technological alternatives in Latvia

The figure shows that the most electrical energy can be produced using incineration with heat recovery (alternative A5) (thermal energy 42 GWh/year and electricity 19 GWh/year in 2030), followed by separate collection and anaerobic digestion (alternative A1) with an annual production of 11 GWh of heat energy and 11 GWh of electricity. Comparatively less energy can be obtained using the third alternative – mechanical biological pre-treatment and anaerobic digestion (heat production six GWh/year and electricity six GWh/year in 2030). The amount of energy produced using the remaining technology options is negligible. Even though incineration plants have been planned for construction in Estonia and Lithuania, this does not alter the overall trend line in the use of alternative biowaste recycling technologies. In Estonia, alternative A5 could be used to produce 29 GWh of heat energy and 13 GWh of electrical energy in 2030 (see Figure 10).

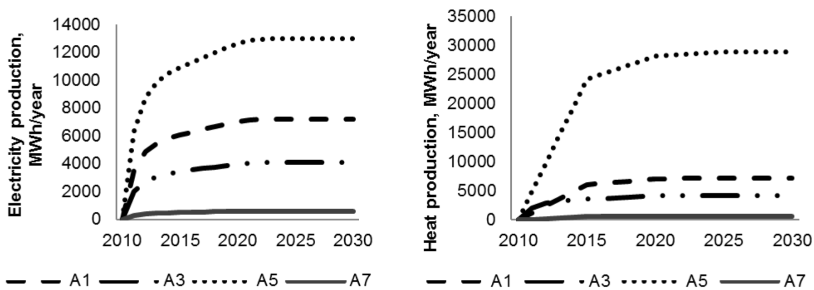


Figure 10. Simulated annual heat and electricity production rates for different biowaste treatment technological alternatives in Estonia

Seven GWh/year each of heat energy and electricalenergy could be produced using alternative A1, and, using alternative A3, four GWh of each type of energy could be produced annually

In Lithuania, by 2030, alternative A5 could produce 70GWh of heat energy and 31 GWh of electrical energy (see Figure 11). Using alternative A1: 17 GWh of each could be produced, and using alternative A3, ten GWh of each type of energy could be produced.

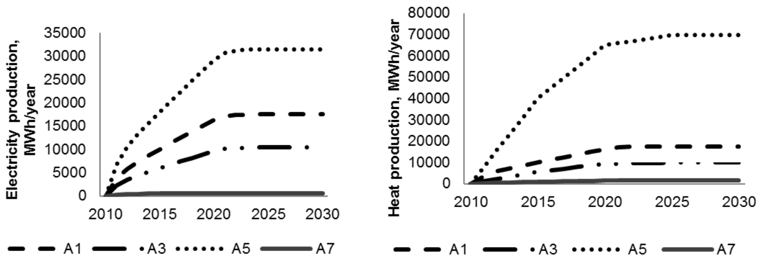


Figure 11. Simulated annual heat and electricity production rates for different biowaste treatment technological alternatives in Lithuania

CONCLUSIONS

1. A modelling framework for the assessment of biowaste management alternatives based on a combination of MCA and CRA ad MCA and SD modelling have been created, to assess, compare, and screen biowaste management alternatives that stakeholders can apply to their specific situations.
2. The aim of the proposed method implemented in the modelling tool is mainly addressed to policy- and decision-makers to evaluate biowaste management options, to assess the sustainability of bioenergy projects, and to find an optimal solution for biowaste treatment given the conditions in a particular region.
3. While MCA allows for the assessment and prioritization of different technologies from technical, ecological, economic, and social perspectives, SD provides a tool for an analysis of the structure of the problem under study. This is crucial in understanding the causes of a system's behaviour, and in determining an action plan for managing the situation. The value of the proposed modelling framework is that it provides the possibility to assess the impact of the results obtained by a static multi-criteria assessment of a dynamic and complex system.
4. In the statistical analysis of data from MCA, using the method of regression analysis, the most significant characteristic factors of equipment function, or independent parameters, have been determined. The connection between the reduction of GHG emissions and the parameters that influence this decrease determine the regression equation obtained during the processing of this data. During the regression analysis each aspect was subjected to verification of the specific step's correctness, and the opportunity to go on to the next step of the analysis.
5. The reduction of GHG emissions is determined by three statistically significant parameters: energy consumption; energy production; heat production.
6. A multi-factor regression equation to determine the reduction of GHG emissions has been obtained, and an adequacy test of the equation using the Fisher criterion has been conducted; the equation describes 86% of changes in the reduction of GHG emissions; the application of a data regression analysis is correct, because the dependent variable magnitude – the reduction of GHG emissions is subjected to the normal law of distribution; the application of the least squares method in the determination of magnitudes is valid, and the values of these magnitudes are not distorted, because the determined values of the DW criterion are larger than the limits allowed; the assessment of the regression equation

coefficients is correct, as there is no correlation observed among them; the standard error of data analysis has been correctly assessed, because the remainder distribution corresponding to the specific dependent and independent variables is even.

7. The Baltic region was used as the area of analysis for this study. The study shed light on how the biowaste management process can move forward in this region. The proposed method was used to evaluate seven competing solutions for the biowaste management systems of Lithuania, Estonia, and Latvia: Separate collection with anaerobic digestion; Separate collection with composting; MBT with mechanical biological pre-treatment and anaerobic digestion; MBT with mechanical biological pre-treatment composting; Incineration with energy recovery; Incineration without energy recovery; Landfilling with the collection and utilization of landfill gas.
8. The results obtained from case studies of the three Baltic States - Latvia, Lithuania, and Estonia show that separate collection and anaerobic digestion of biowaste is the best solution for all three Baltic States. Other acceptable options include incineration with energy recovery and mechanical biological treatment with anaerobic digestion. Simulation results showed that even though incineration plants have been planned for construction in Estonia and Lithuania, this does not alter the overall trend in the use of alternative biowaste recycling technologies.
9. The proposed study shows that different technological alternatives to transform biowaste into energy exist, and can be implemented in different conditions. However, the adoption of these technologies is highly dependent on many specific parameters.
10. The proposed approach integrating the methodologies provides a greater understanding of, and more insights into, the waste sector. MCA and SD and MCA and CRA methodologies combined in the way proposed here can be used not only for waste management, but also in other fields dealing with technology based decision-making in complex and dynamic systems.