

**RIGA TECHNICAL UNIVERSITY**

Faculty of Power and Electrical engineering  
Institute of Energy Systems and Environment

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Doctoral program in Power and Electrical Engineering

**CLEANER PRODUCTION IN  
BIOWASTE MANAGEMENT**

Doctoral Thesis

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## ANNOTATION

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. 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.

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.

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. 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.

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 and Correlation and Regression analysis and on a combination of Multi-Criteria Analysis and System Dynamics.

The results of this research can be addressed to different target groups and levels: the governments, waste and energy sectors, scientists and environmental activists.

The proposed approach, integrating the methodologies, provides a greater understanding of, and more insights into, the waste sector. Multi-Criteria Analysis and System Dynamics and Multi-Criteria Analysis and Correlation and Regression analysis 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.

## ANOTĀCIJA

Saskaņā ar ES direktīvu 2009/28/EK par atjaunojamo energoresursu izmantošanas veicināšanu Latvijā no atjaunojamās enerģijas saražotas enerģijas īpatsvaram 2020. gadā ir jāsasāda 40% no bruto enerģijas. Eiropas Savienības dalībvalstīm ir jāievēro ES direktīvas par atkritumu poligoniem 1999/31/EK un ES direktīvas 2008/98/EK par atkritumiem nosacījumus, kas paredz ievērojami samazināt atkritumu poligonos apglabājamo bioloģiski noārdāmo atkritumu.

Bioloģisko atkritumu izmantošana enerģijas ieguvei, ļaus sasniegt iepriekš minētos mērķus attiecībā uz atjaunojamās enerģijas īpatsvara palielināšanu un ļaus sasniegt atkritumu apglabāšanas poligonos apglabāto bioloģiski noārdāmo atkritumu apjoma samazinājumu.

Bioloģisko atkritumu kā resursu izmantošana ir nepieciešama tādēļ, lai sasniegtu ES kopējos atkritumu apsaimniekošanas mērķus.

Sarežģītais iznākums ir būtisks šķērslis bioloģisko atkritumu plānošanas projektu īstenošanā. Lai sekmētu atjaunojamo energoresursu izmantošanu, ir jāizvērtē iespējamais bioloģisko atkritumu daudzums un, balstoties uz to, ir jāatrod optimālākā metode to pārvešanai enerģijā.

Šā darba mērķis ir izstrādāt, piemērot un izvērtēt metodiku tīrākas ražošanas principu iekļaušanai bioloģisko atkritumu apsaimniekošanā. Īpaša uzmanība šajā darbā ir pievērsta metodikas izstrādei tieši attiecībā uz politikas jomu izstrādātājiem un lēmumu pieņēmējiem, lai 1) izvērtētu bioloģisko atkritumu apsaimniekošanas iespējas, 2) novērtētu bioenerģijas projektu ilgtspējību, 3) atrastu optimālu bioloģisko atkritumu apstrādes risinājumu, ņemot vērā apstākļus konkrētā reģionā.

Šajā darbā tiek izmantota modelēšanas pieeja, kas balstīta uz multikritēriju analīzi, korelācijas un regresijas analīzi, kā arī multikritēriju analīzes un sistēmdinamikas kombināciju.

Šī pētījuma rezultāti var tikt attiecināti uz dažādām mērķa grupām un dažādiem līmeņiem: valdības līmeni, atkritumu un enerģētikas sektoru, zinātniekiem un vides aktīvistiem. Šī pieeja, kurā izmantota minētā metodika, sniedz ieskatu atkritumu apsaimniekošanas nozarē un ļauj to labāk izprast. Multikritēriju analīzes un sistēmdinamikas, kā arī multikritēriju analīzes un korelācijas un regresijas analīzes metožu kombināciju iespējams izmantot ne tikai atkritumu apsaimniekošanā, bet arī citās nozarēs, kurās lēmumi tiek pieņemti sarežģītās un dinamiskās sistēmās.

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Jeļena Pubule

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## LIST OF PAPERS

This thesis is based on the following appended papers:

Indexed in SCOPUS:

- I. Pubule J., Blumberga A., Romagnoli F., Blumberga D. Biowaste Management in the Baltic States // Journal of Cleaner Production (2014), doi:10.1016/j.jclepro.2014.04.053.
- II. Pubule J., Kamenders A., Valtere S., Blumberga D. Cleaner production in biowaste management // Agronomy research. – Vol.12, No.2. (2014), p. 575-588.
- III. Pubule J., Blumberga D., Rošā M., Romagnoli F. Analysis of the Environmental Impact Assessment of Power Energy Projects in Latvia // Management of Environmental Quality: An International Journal. - Vol.23, No.2. (2012), p.190-203.
- IV. Pubule J., Blumberga D. Impact Assessment of Biogas Projects in Latvia. International Journal of Sustainable Development and Planning, - Vol.9, No.2, (2014), p.251-262.
- V. Pubule, J., Blumberga, D. An assessment of the potential and optimal method for biowaste energy production in Latvia // WIT Transactions on Ecology and the Environment. – Vol. 190, (2014), p.1067-1078.
- VI. Pubule, J., Bergmane, I., Blumberga, D., Rošā, M. Development of an EIA Screening Phase for Biogas Projects in Latvia // WIT Transactions on Ecology and the Environment. - Vol. 162, (2012), p.75.-86.
- VII. Laivina L., Pubule J., Rošā M. A multi-factor approach to evaluate Environmental Impact Statements // Agronomy research. – Vol. 12, No.1, (2014), p. 967-976.

Indexed in Web of Science:

- VIII. Pubule J., Veidenbergs I., Valtere S., Kalnins S.N., Eihvalde D. Indicators for the assessment of biowaste treatment through anaerobic digestion// Proceedings of the 9th International Conference “Environmental Engineering”: Selected Papers. Vol. I: Environmental Protection, Lithuania, Vilnius, 22.–23. may, 2014. CD proceedings, 45 (enviro.2014.045).

Pubule is the main author of the seven papers and the co-author of one paper above and has carried out data collection, modelling and analysis, and has also written the papers.

Dagnija Blumberga has been supervising this work and has contributed ideas, discussions and editorial suggestions of these papers. Rošā has been co-supervisor and had made similar contribution to Papers III, IV and VI. Andra Blumberga has been co-supervisor to Paper I and Veidenbergs to Paper VIII. Romagnoli has contributed ideas to Papers I and III. Bergmane, Valtere, Kamenders, Kalnins and Eihvalde have made editorial suggestions. Pubule has been supervising Paper VII.

## INTRODUCTION

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 1<sup>st</sup> dimension of the problem. The 2<sup>nd</sup> 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 [1] 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 [2], and with the Waste Framework Directive 2008/98/EC [3] 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 3<sup>rd</sup> dimension of the problem that Latvia is facing is the undeveloped biowaste management system. The 4<sup>th</sup> 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 [4]. 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.

Additionally, to reach the above mentioned objectives, the thesis aims to validate the following hypothesis:

**A cleaner production in waste management can be achieved by adopting the proposed methodology for impact assessment of biowaste management.**

### **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 // 5<sup>th</sup> 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 9<sup>th</sup> 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 // 8<sup>th</sup> 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. // 21<sup>st</sup> 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.
7. Pubule, J., Blumberga, D. Implementation and Impact Assessment of Biological Waste Management System in Latvia // The 53<sup>rd</sup> International Scientific Conference of RTU, Latvia, Riga, 12 October, 2012.
8. Pubule J., Romagnoli F., Blumberga D. Improvement of Environmental Impact Assessment in the Baltic States // The 8<sup>th</sup> International Conference “Environmental Engineering” // Lithuania, Vilnius, 19.-20. May, 2011.
9. Pubule J., Romagnoli F., Blumberga D. Analysis of Environmental Impact Assessment of Power Energy Projects in Latvia // 8<sup>th</sup> Annual Conference of Young Scientists on Energy Issues CYSENI 2011, Lithuania, Kaunas, 26.-27. May, 2011.

## Publications

1. Pubule J., Blumberga A., Romagnoli F., Blumberga D. Biowaste Management in the Baltic States // Journal of Cleaner Production (2014), doi:10.1016/j.jclepro.2014.04.053.
2. Pubule J., Blumberga D., Rošā M., Romagnoli F. Analysis of the Environmental Impact Assessment of Power Energy Projects in Latvia // Management of Environmental Quality: An International Journal. - Vol.23, No.2. (2012), p.190-203.
3. Pubule J., Blumberga D. Impact Assessment of Biogas Projects in Latvia. International Journal of Sustainable Development and Planning, - Vol.9, No.2, (2014), p.251-262.
4. Pubule J., Kamenders A., Valtere S., Blumberga D. Cleaner production in biowaste management // Agronomy research. – Vol.12, No.2. (2014), p. 575-588.
5. Pubule J., Veidenbergs I., Valtere S., Kalnins S.N., Eihvalde D. Indicators for the assessment of biowaste treatment through anaerobic digestion// Proceedings of the 9th International Conference “Environmental Engineering”: Selected Papers. Vol. I: Environmental Protection, Lithuania, Vilnius, 22.–23. may, 2014. CD proceedings, 45 (enviro.2014.045).

6. Pubule, J., Blumberga, D. An assessment of the potential and optimal method for biowaste energy production in Latvia // WIT Transactions on Ecology and the Environment. – Vol. 190, (2014), p.1067-1078.
7. Laivina L., Pubule J., Rošā M. A multi-factor approach to evaluate Environmental Impact Statements // Agronomy research. – Vol. 12, No.1, (2014), p. 967-976.
8. Pubule, J., Bergmane, I., Blumberga, D., Rošā, M. Development of an EIA Screening Phase for Biogas Projects in Latvia // WIT Transactions on Ecology and the Environment. - Vol. 162, (2012), p.75.-86.
9. Pubule, J., Romagnoli, F., Blumberga, D. Finding an Optimal Solution for Biowaste Management System in the Baltic States.// Conference Proceedings of the 8<sup>th</sup> Conference on Sustainable Development of Energy, Water and Environment Systems, Croatia, Dubrovnik, 22.-27. september, 2013. Dubrovnik, p. 0213-1.-0213-13.
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11. Rutz, D., Janssen, R., Ramanauskaite, R., Hoffstede, U., Hahn, H., Kulisic, B., Bosnjak, R., Kruhek, M., Ribic, B., Surowiec, M., Nogueira, M.A., Martins, A.S., Duarte, F., Albuquerque, M., Martins, M., Dzene, I., Niklass, M., Pubule, J., Schinnerl, D., Kalandyk, K., Zapora, D. The use of bio-waste for biomethane production in European cities // Proceedings of 20<sup>th</sup> European Biomass Conference & Exhibition, Italy, Milan, 18.-22. june, 2012, p.1481-1491.
12. Pubule J., Romagnoli F., Blumberga D. Improvement of Environmental Impact Assessment in the Baltic States // Proceedings of the 8th International Conference "Environmental Engineering": Selected Papers. Vol.I: Environmental Protection, Lithuania, Vilnius, 19.-20. May, 2011, p.300.-307.
13. Pubule J., Romagnoli F., Blumberga D. Why Biodiesel is Environmentally Better than Traditional, Fossil-Based Diesel: an LCA Approach // Environmental and Climate technologies. - Vol, 7, (2011), p.93.-99.
14. Pubule J., Blumberga D. Use of Benchmark Methodology in Environmental Impact Assessment // Environmental and Climate technologies. – Vol, 4, (2010), p.91.-96.
15. Romagnoli F., Pubule J., Blumberga D. Generation of Algal Biomass for Biogas Production: Energetic and And Environmental from a Life Cycle Assessment (LCA) Perspective // Progress in Biogas II - Biogas Production from Agricultural Biomass and Organic Residues, Germany, Stuttgart, 30.March-1. April, 2011, p.142.-148.
16. Pubule J., Romagnoli F., Blumberga D. Analysis of Environmental Impact Assessment of Power Energy Projects in Latvia // Proceedings of 8th Annual Conference of Young Scientists on Energy Issues CYSENI 2011 , Lithuania, Kaunas, 26.-27. May, 2011, p.230.-238.
17. Romagnoli F., Pubule J., Blumberga D. Life cycle assessment of biogas production with algae substrate // Proceedings of the 19th European biomass conference & Exhibition, Germany, Berlin, 6.-10. June, 2011.
18. Romagnoli, F., Pubule, J., Blumberga, D. Life Cycle Assessment for Biodiesel Production under Latvian Climate Conditions // Proceedings of Life Cycle Management Conference (LCM 2011), Germany, Berlin, 28-31 August, 2011. p.1-12.

19. Pubule J., Zušmane A., Bergmane I., Rošā M. Analysis and Improvement Facilities of Environmental Impact Assessment of Wind Energy Projects in Latvia // Environmental Protection Engineering: The 15<sup>th</sup> Conference of Lithuanian Junior Researchers “Science – Future of Lithuania””: A Collection of Articles", Lithuania, Vilnius, 12.-12. April, 2012, p.224.-230.

### **Structure of the thesis**

This thesis consists of two parts – introductory part and eight appended papers. The appended papers are free-standing contribution to the environmental impact assessment and biowaste management field, each of which has been reviewed and published in international scientific journals (indexed in Scopus) or conference proceedings (indexed in Web of Science). The introductory part aims to place these papers within the broader context of environmental assessment and biowaste management research. The introductory part includes through discussions of methodological choices and assumptions made in the study and their implementation for the findings.

Dissertation is written in English and contains: introduction, 5 chapters, conclusions, bibliography, 49 figures, 13 tables and appended eight papers.

The bibliography contains 183 references. The literature review and bibliography are not included in this summary.

## 1. LITERATURE REVIEW

### 1.1. An overview of the energy sector in Latvia

The Baltic States have a similar climate and geography. They are close in the size of the territory and population. Latvia and Lithuania are classified as middle-income economies. Estonia moved up to a high-income economy in 2006 [5]. The Baltic States have similar social characteristics and development patterns, and have few differences in their respective energy sectors [6]. 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 [7], and the highest share of renewable energy in the final consumption of energy [8].

Except for peat, which can be found in approximately 10% of its soil, Latvia has no fossil resources for energy production worth mentioning. Natural gas, oil products, and coal are mainly imported from Russia. However, renewable energy sources are substantial. Forests cover approximately 55% of Latvia's territory, making biomass the largest domestic resource currently used in heat generation.

Hydropower is already the biggest contributor to electricity generation, and still has unused potential. Wind power has gained importance in recent years, and has high potential as wind is abundant. This is particularly the case along the coast where, in addition, the transmission network is particularly well-developed.

The development of the national economy is unthinkable without an increase in the manufacturing sector. In turn, the development of the manufacturing sector is connected with the intensification of manufacturing capacity, and the resulting consequences to the environment.

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 and a concerted effort to ensure its implementation [9]. It is complicated to think in the long-term if one has to solve a short term problem – managing the increasing consumption of energy. It is very tempting to solve the problem by taking the path of least resistance – importing more energy resources. More attention is paid to the short-term solution; less of it is paid to the problem in the long run. As a result, RES principles are not sufficiently developed, nor utilized.

Energy security has sometimes been explained by the necessity to build new fossil fuel electric power stations, knowing in advance that it will only be a short-term solution. Seemingly, security is based on the opportunity to use natural gas from Russia, with no justification as to the sustainability of the natural gas sources.

Another aspect concerning the utilization of fossil fuels is related to the fact that no high efficiency power plants can be installed. Consequently, around a half of the available natural gas energy would be "thrown out" into the environment [10].

Sustainability in the power industry [11] is related to the constant development [12] of the power industry (energy production, energy supply and energy end users). The conditions for the sustainability of the power industry in Latvia include:

1. Development of renewable energy resources;
2. Increase of energy efficiency in power production;
3. Increase of energy efficiency in energy transformation;
4. Increase of energy efficiency in power use;
5. Development of systemic energy resources in the country [10].

Latvia has a great deal of potential in biomass. One of the most popular biomass fuel types is wood, which is currently used in a large scale in Latvia, and it is likely that power production from solid biomass fuel will reach the volume of 30 TWh/year [13].

One of the ways to implement the use of biomass in the power industry is to simultaneously combine the combustion of wood and fossil fuels. The current sustainable approach to energy supply defines the necessity for a more extensive availability of modern and effective bio-energy technology [14].

Such initiatives are aimed at technology related to having an environmentally friendly, technically, and economically beneficial use of biomass. It is expected that special plants, designed for the production of bio-energy, will increase the contribution of this sector in the future.

Incorrect solutions in the implementation of co-combustion and related problems in many countries occurred due to an inadequate knowledge of the technology available for co-combustion with fossil fuels.

The reason was an insufficient supply of biomass, and an inadequate development of the biomass market. This, in turn, arose from insufficient information and the incorrect organization of the potential biomass market system principles.

In spite of this lack of knowledge and information, the volume of biomass used for power production in Central and Eastern Europe is increasing. This might be even more beneficial for power producers, as well as power saving on a national level, if the increase is based on co-combustion technology.

## **1.2. Waste 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 [2] and Waste Directive 2006/12/EC [15] 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 [1].

During the last decade, clear indications on identifying management solutions different from the landfilling of municipal solid waste have been highlighted [16]. Nevertheless in the year 2010, 16 EU countries had a share of landfilled MSW which was higher than 50% [17].

Waste management policies in European countries (and other developed nations) focused on reducing the amount of biowaste landfilled [18]. 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 [19]. 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 [16] (see Figure 1.1).



Figure 1.1. Waste hierarchy [3]

Anaerobic digestion, incineration with energy recovery, mechanical biological treatment (MBT) with anaerobic digestion, and gasification are possibilities both to manage biowaste and a waste-to-energy option [20-25]. On top of this, composting and the use of digestate to stabilise and improve the humus content of soils [26-31] is a properly adaptable solution. The impact of MSW management alternatives depends on a number of local factors. For example, the selection of acceptable MSW and biowaste management options must be made based on research on the impact of different waste management scenarios on the social milieu, the environment, and the economy of each country.

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 [32-34]. 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 share of MSW treatment options are shown in Figure 1.2.

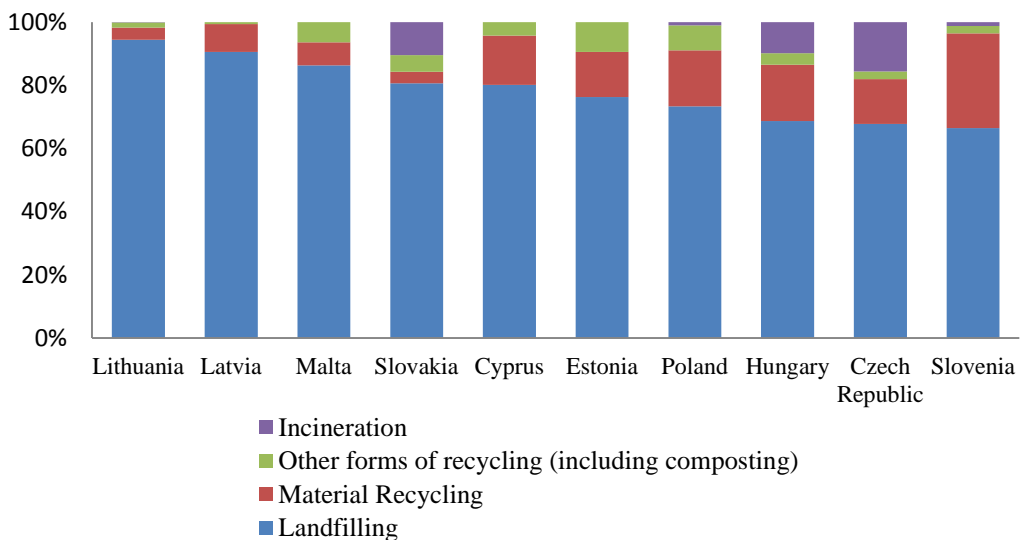


Figure 1.2. The 2010 share of the different treatment options for municipal waste in the countries involved in the 2004 enlargement of the European Union (Eurostat)

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 [35].

A landfill tax was introduced in Lithuania in 2013. The lack of a landfill tax in previous years, 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 [36].

Estonia has the most developed waste management system in the region. Twenty percent of MSW in Estonia was recycled in 2010 [37]. Large scale composting and separate biowaste collection is well developed there. Estonia also has the highest landfill tax in the region – 20 EUR per tonne in 2013. It will be 30 EUR per tonne in 2015 [38]. By comparison, since 2012 the landfill tax in Latvia has not moved from 10 EUR per tonne [39, 40].

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 the reduction of the amount of biowaste. During the 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 of this into consideration, alternative methods to minimize the amount of biowaste deposited in landfills are urgently needed. The construction of new waste incineration plants in Lithuania and Latvia has been recently completed [41, 42].

### 1.2.1. Waste management in Lithuania

There had been more than 800 dumpsites in the territory of Lithuania, but now there are 10 Regional Waste Management regions (see Figure 1.3.) with 11 landfills [32].



Figure 1.3. Waste management regions in Lithuania [46]

Landfilling of waste in dumpsites became prohibited in 2013. Waste management in Lithuania is regulated by the Waste Management Law [43]. Waste management in Lithuania is less developed regionally, since not all of Lithuania is covered by a municipal waste collection scheme, and only 5% of MSW are recycled in Lithuania [35].

A landfill tax has not been adopted in the country; however, a tax will be introduced in 2013. The lack of a landfill tax and the resulting low management and landfilling fees do not encourage recycling and the treatment of waste in Lithuania.

Lithuania is trying to differentiate energy production sources in Lithuania by increasing energy production for renewable and local sources, like wood biomass [44] or biogas and landfill gas [45].

During the next years, a waste conversion to energy project which will provide for the incineration of MSW will be implemented.

Construction of the Klaipeda waste incineration plant with a total capacity of 245 000 tonnes per year was completed in 2013. Heat from the Klaipeda plant is used for district heating, and the electricity produced is delivered into the power grid. This power plant produces roughly 140 GWh of electricity, and approximately 400 GWh of heat per year. It is noteworthy that Combined Heat and Power plants (CHP) will make up approximately 40% of the heat consumed in the city of Klaipeda.

About 15% of the total MSW produced in Lithuania is processed in this waste incineration plant.

### 1.2.2. Waste management in Estonia

Waste management in Estonia is the most developed in the region. Landfilling of waste is organized at 5 regional landfills (see Figure 1.4.).



Figure 1.4. Waste management regions in Estonia [33]

20% of MSW in Estonia was recycled in 2010 [37]. In Estonia, large scale composting and separate biowaste collection is well-developed. For example, in the Vaatsa region, the collection of separate biowaste started in 2007 [47]. In this region, 240-litre biowaste bins and small kitchen canisters for biowaste were distributed. Biowaste collected separately is composted.

A waste-to-energy project, which uses incineration, is currently under construction in Estonia. The total capacity of the plant, which will be located close to Tallinn, is 200 000 tonnes per year. The power plant is designed to produce about 17 MWe and about 50 MWh

per year. About 22% of the total MSW produced in Estonia will be processed in this plant, which is an extension of the existing CHP plant in Iru. This existing CHP plant is the main supplier of district heating for Tallinn. Currently, the Iru CHP plant uses natural gas. The new site will replace nearly 70 million m<sup>3</sup> of natural gas currently used each year. The heat from the new plant will be used for district heating, and the electricity will be delivered to the power grid.

A second planned waste incineration plant in Tartu was postponed due to uncertainty about the financing [41].

### 1.2.3. Waste management in Latvia

Waste management in Latvia is regulated by the Waste Management Law [48]. In accordance with this law, waste management throughout the state is carried out according to the Waste Management State Plan, and the regional waste management plans.

There are 10 waste management regions and 11 landfills in Latvia (see Figure 1.5).



Figure 1.5. Waste management regions and landfills in Latvia

Waste management in Latvia is regulated by the Waste Management Law [48]. In accordance with this law, waste management in the state is carried out according to the Waste Management State Plan and the regional waste management plans.

The waste management plan for 2006 – 2012 [49] envisages a series of measures to be implemented in the given time period regarding the biodegradable fraction which would improve the waste management situation in the country.

Looking back on the progress made, we may conclude that the measures have been partly fulfilled; for instance, the natural resource tax on biodegradable municipal waste disposal in landfills has been raised, and the local government binding regulations have been supplemented with a new section on biodegradable municipal waste management. At the same time, it should be noted that there are many unsolved issues hampering biodegradable waste treatment and its efficient use.

Currently, the largest portion of municipal, and similar, waste from trade and industrial enterprises and institutions, as well as separately collected waste, is deposited in landfills.

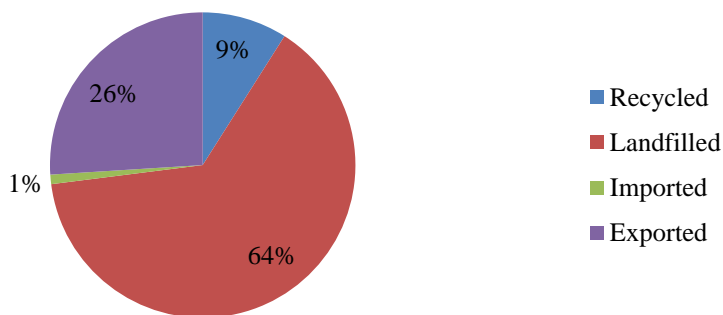


Figure 1.6. Management of waste in Latvia

According to the statistical data, 64% of all the collected municipal and residual waste, including the biodegradable fraction and packaging, were deposited in the solid municipal waste landfills in 2010 in Latvia [50] (see Figure 1.6).

To minimise the deposited amount of waste, there will be changes in the waste management system in the coming years. The Waste Management Law requires that waste be subject to treatment before it is landfilled.

Latvia does not have a highly developed separate biowaste collection and treatment system. The only method mentioned in Latvian legislation for minimising the amount of biowaste and biowaste treatment is composting. During the development process of the waste management system, several solid waste disposal landfills in Latvia established composting facilities (see Table 1.1).

The aim of the composting facilities was to minimise the amount of biowaste to be deposited in the country; however, practical experience shows that these composting areas are not being used to their full potential. Taking into consideration all of the above, it is necessary to introduce alternative methods for minimising the amount of biowaste deposited in landfills.

Table 1.1.

Composting plants in landfills	
Name	Compost plant (m <sup>2</sup> )
Križevnieki	2000
Cinīši	1050
Kaudzītes	2000
Janvāri	5038
Dziļā vāda	14000
Daibe	5632

Furthermore, there are 10 composting plants, besides the compost plants in landfills, in Latvia. Mainly green waste such as leaves, grass, and branches are treated there. One of the plants is specialized in the production of compost from sludge.

### 1.2.3.1. National goals regarding biowaste management

In accordance with Directive No. 1999/31/EC [2] on the landfill of waste, waste is regarded as biodegradable if it is capable of undergoing aerobic or anaerobic decomposition, such as food waste, park and garden waste, paper, and paperboard. In compliance with the Directive No. 1999/31/EC [2], “municipal waste” means waste from households, as well as other waste, which, because of its nature or composition, is similar to the waste from households.

In accordance with the Directive No. 1999/31/EC [2], Article 5, Paragraph 1, Member States shall set up a national strategy for the reduction of biodegradable waste going to landfills. This strategy should include measures to achieve the targets set out by the Directive. This will be accomplished by means of recycling, composting, biogas production and/or materials/energy recovery. Member States, which in 1995, or the most recent year before 1995 where standardised EUROSTAT data is available, which put more than 80% of their collected municipal waste into landfills, may postpone the attainment of the targets by a period not exceeding four years. Member States intending to make use of this provision shall inform the EC of their decision.

According to the Waste Management Law, biodegradable waste is any degradable waste from gardens and parks, households, restaurants, public catering establishments, retail premises selling food, kitchen waste, and other similar food production waste.

The Waste Management State Plan and regional plans set out measures which promote the use of environmentally friendly materials manufactured from biowaste. These include the separate collection of biodegradable waste for recovery, composting, treatment, as well as measures for biodegradable waste treatment. Biologically degradable waste is composted in waste landfills or specially equipped places for composting biodegradable waste.

To meet the requirements of the Directive No. 1999/31/EC [2], the following amount of biodegradable waste may be disposed of in waste landfills in Latvia (Table 1.2).

Table 1.2.  
Amounts of biodegradable municipal waste to be landfilled

Year	Estimated production of biodegradable municipal waste, tonnes	Amount of biodegradable municipal waste to be accepted for disposal in the landfill, tonnes	Amount of biodegradable municipal waste not acceptable to be disposed of in the landfill, tonnes
2010	607 000	345 000	262 000
2013	632 000	230 000	402 000
2020	691 000	161 000	530 000

### 1.2.3.2. Potential of biowaste energy in Latvia

During the research, an analysis of the biowaste amount and its characteristics was completed. The results show that the majority of biowaste, which can be used for energy production, is landfilled in Latvia.

From 11 landfills, only 3 have landfill gas collection systems. This leads to the situation where almost all potential waste energy is unused. The amount of landfilled municipal solid waste during the five-year period between 2008 and 2012 decreased. This

was mostly due to the economic crisis and a reduction in the number of inhabitants, and not to an increase of the recycling of waste.

From 2008 until 2012, the amount of landfilled municipal solid waste decreased by approximately 30%, from 64 688 tonnes in 2008 until 431 790 tonnes in 2012.

According to previous research [51 -53] on the composition of municipal solid waste, the percentage of biowaste is 28 – 61 % of the total municipal solid waste mass. Therefore, an average of 30% biowaste was used during the calculations.

The amount of biowaste which could be separated from municipal solid waste was 219 411 tonnes in 2008 and 151 127 tonnes in 2012.

In Figure 1.7., the amount of landfilled waste, including municipal solid waste biowaste, together with green waste and sludge is shown.

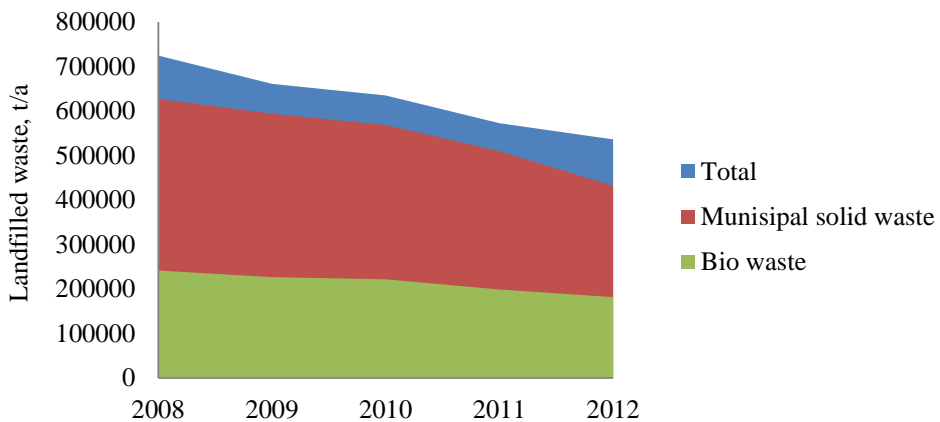


Figure 1.7. Amount of landfilled waste in Latvia, 2008 – 2012

The figure shows a decrease in the amount of landfilled municipal solid waste, but at the same time the amount of landfilled biowaste, which includes green waste, sludge, and biowaste from kitchens and enterprises, has changed only slightly during the last five years.

Figure 1.8. shows the ratio between recycled and landfilled biowaste by years

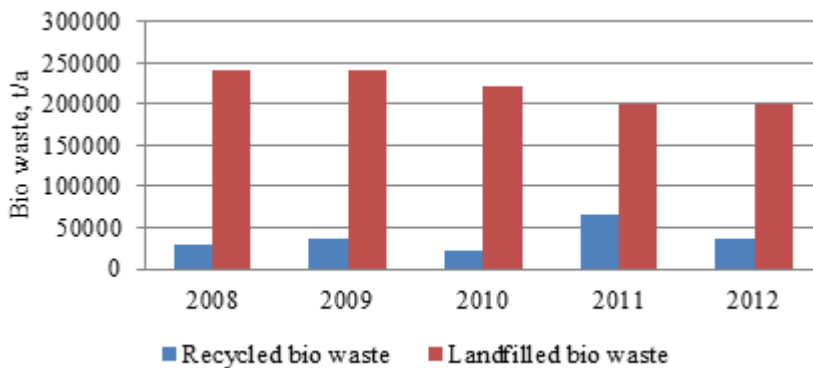


Figure 1.8. Amount of landfilled and recycled biowaste

The figure shows that the amount of recycled biowaste is increasing very slowly. Therefore, it is necessary to find better methods for biowaste management in Latvia.

Latvia does not currently have any plans for waste incineration within its borders. The Waste Management Law requires that waste should be subject to treatment before it is landfilled.

By 2014, however, equipment for mechanical pre-treatment will be installed at all landfills. Waste management companies are also planning to export refuse-derived-fuel (RDF) to waste incineration plants in Lithuania and Estonia [54].

### **1.3. Environmental Impact Assessment**

The achievement of energy efficiency in renewable energy sources from used energy resources must be ensured, and energy sources must be constructed where fossil fuels are replaced by renewable ones. As the only legislative tool in the planning phase of energy and waste projects, Environmental Impact Assessments should include a common approach which allows for the enhancement of the quality and efficiency of the Environmental Impact Assessment (EIA).

Therefore, cleaner production principles should be analyzed and implemented in the first step of the project implementation – EIA, or the preliminary screening procedure.

The aim of the screening phase is to determine if the project is subject to an EIA. During the screening, it is decided whether the EIA process for the project or activity is necessary or not. Without this verification, some actions can be evaluated very precisely while others can be forgotten or even ignored. While carrying out an effective assessment, a list with the activities planned, accompanied by the values and criteria for determining whether an action should be evaluated must be formulated [55].

The criteria of the significance of the impact include the description of the threshold value for identification. Threshold values in Latvia are environmental quality standards, emission limit values, and other limits and restrictions set in various pieces of legislation. Since the various restrictions and environmental quality standards vary in different areas, and for various types of activities, then in most cases the significance of impacts are assessed individually in each case. Often the significance of the impact is not only dependent on the type, amount, and hazard of the planned action, but also the characteristics of the selected place have an important role. In some cases, the impacts of small objects which do not exceed the allowable thresholds are potentially dangerous if they are planned in a sensitive or congested area. Therefore, these projects do in fact apply to the EIA procedure. But at the same time, relatively large objects with possible impact parameters similar to EIA application volumes may not require the application of the EIA procedure because of the optimal choice of location, and the projected technology to be used which allows for the impacts to be reduced to an insignificant amount.

So we can say that the screening stage is one of the most important and responsible steps in the process of the EIA. A faulty decision could lead to substantial financial losses for the future performance of the project, if an unreasonable decision is made to apply the full environmental impact assessment procedure, which requires substantial financial investment and time, to the project.

Of no less importance, and perhaps even greater losses are possible, if technical regulations are not fully prepared because the possible impact is not fully assessed for the proposed action. Furthermore, if the implementation of the project has already started, while not realizing the potential problem situations and risk factors resulting in damage to the environment, it is known that in most cases the consequences of the negative effects

requires more resources and time than measures that could have prevented or reduced the possibility of the caused damage.

### **1.3.1. The Role and tasks of environmental impact assessments**

Environmental impact assessment is one of the tools which may facilitate the sustainable development of a state.

EIA is focused on the implementation of preventive means, due to the fact that the aim of the environmental impact assessment is the identification of possible risks and effects as early as possible [56, 57]. Environmental impact assessment provides an opportunity to consider potential effects of the designed activity, and consider any alternatives in project implementation from different perspectives. This is performed by identifying the potential environmental, social, and health aspects of the planned activity [58].

The assessment of environmental impacts is inter-disciplinary. It aims to objectively measure the benefits and damages caused by the implementation of projects, and to provide decision makers with comprehensive information on possible effects. From this, we may conclude that the development of environment standards includes a complex set of measurements which facilitate sustainable development [59].

European and Latvian laws and regulations demand that prior to the execution of projects, which may cause a significant environmental impact, an environmental impact assessment must be carried out.

Environmental impact assessments have been performed for several decades in Latvia [60]. They have led to the reduction of the negative effects of developments within the country. In the initial years of EIA in Latvia, an elaborate system developed. In contrast to this, no significant improvements have been made during recent years.

An environmental impact assessment does not aim to prohibit polluting activities, but to reduce and eliminate adverse environmental effects incurred due to the activities of physical and legal entities. As we all know, any action can have both positive and negative consequences.

The purpose of an environmental impact assessment is to identify the possible consequences and, after a careful analysis of such consequences, to consider if the planned activity shall be implemented and, if yes, under what conditions [61].

Thus, considering the procedure of environmental impact assessments, it shall be noted that the environmental effects caused by various actions is very diverse, both in terms of the risk and the scale of such effects. As a result, not all activities require the completion of an environmental impact assessment.

Through formalizing and simplifying the assessment of various activities, one can see that they fall into three different categories:

1. Activities with insignificant effect, which in no case can cause long-term adverse effects on the environment and/or human health, and as such, they require no EIA procedure.
2. Activities which may cause adverse effects on environment and/or human health, and the risk of their impact depends on the implementation of the activity in the chosen site or the applied technology. In this case, an initial assessment of the potential impact is required and, on the basis of such an assessment, a decision is made whether a complete environmental impact assessment is required.
3. Activities with a significant effect on the environment and/or human health must complete an environmental impact assessment [59].

The aim of the environmental impact assessment procedure is not to suspend or hinder the development of the national economy and industry in the state; it aims to encourage the use of environmentally friendly technology, reasonable exploitation of resources, etc.

The environmental impact assessment procedure is an expensive, time- and work-consuming process. Thus, it is only applied in the situations of significant impacts, or the possibility of cumulative effects [62]. Shall the screening prove that the environmental impact of the planned activity is insignificant, or the proposed technological solutions and choice of site are optimal to ensure the maximum reduction of environmental impacts, and the implementation of the designed activities will not cause any social protests, the decision to not apply the complete procedure of the environmental impact assessment and issuance of technical regulations may be taken. At the same time, in some cases, instead of a complete environmental impact assessment, an assessment of possible effects on individual environmental components may be required. This may include collecting, summarizing, and assessing additional information as well as performing individual studies prior to the final project proposal and the commencement of the development. Such information allows project developers to select the best technological solutions, develop the most adequate use of technology and, if necessary, provide the basic information for the selection of impact reduction measures and environmental monitoring regulations.

### **1.3.2. Screening methods in EU Member States**

The EIA procedure is a tool used to assess the possible environmental impact of a proposed project, and its alternatives, that might be an essential factor of influence on the environment: both the natural and man-made [64]. Project screening, to decide if the project is subject to the EIA procedures (preparation of an Environmental Statement and the subsequent assessment) to support the planning application, shall be made; it is the first step to an EIA. It has two important features: firstly, many screened projects conclude that an EIA is not required - the number of projects screened is higher than the ones subject to EIA. This could lead to the situation where screening may become a routine procedure with a growing number of projects subject to it. Secondly, project screening clarifies the division between the public and the private and exerts influence on both sides of the control system.

The system requires that supervisory bodies perform suitable project screening; private developers can also benefit from the opportunity of different project arrangements to conclude if an EIA is needed before beginning the complex and costly development control process [65, 58].

The approach for the performance of an EIA in the EU member states should be harmonized, leaving a possibility for each member state to establish its own individual approach. Currently an EIA is mandatory in all member states to the projects listed in Annex I to the Directive 1997/11/EC [66]. The approaches differ for projects listed in Annex II of the Directive, even regardless of the fact that Annex III of the Directive clearly states the criteria for the assessment of projects listed in Annex II. Table 1.3 presents a classification of Member States according to the screening method and the number of distinct EIA procedures.

In Latvia, Lithuania, and Estonia the lists+listed case-by-case method is used in the screening process [67].

Table 1.3

Screening methods				
Screening method				
	List of projects		Lists+CBC analysis	
	1 list	$\geq 2$ lists	List(s) + Listed CBC	List(s) + Not Listed CBC
One type of EIA proced.	Belgium	Slovenia	Belgium (partly) Denmark Estonia Ireland Lithuania Luxemburg UK	Sweden Finland
Two or more types of EIA proced.		France Malta Portugal	Austria Cyprus Czech Republic Germany Greece Hungary Italy Latvia Netherlands Poland Slovakia Spain	

### 1.3.3. Environmental Impact Assessment in Latvia

The environmental impact assessment process in Latvia is regulated by the law “On Environmental Impact Assessment” [63] which was initiated in 1998. In compliance with the regulatory enactments of the Republic of Latvia, the institution responsible for the implementation of the environmental impact assessment procedure is the Environment State Bureau.

The Environment State Bureau makes decisions on the application or non-application of the environmental impact assessment procedure. The bureau elaborates the environmental impact assessment program as well as evaluating the work and final environmental impact reports prepared by consultants. The screening procedure is performed by the accordant regional environmental board of the State Environment Service, depending on the planned location of the project.

The main task of the environmental impact assessment is to prevent, or reduce, the possible unfavourable environmental impact created by the planned activities of physical or legal entities. However, the environmental impact of various activities differs greatly, and not always the rather expensive and time-consuming environmental impact assessment procedure should be applied in full.

The environmental impact assessment should only be performed on activities where the environmental impact is substantial, due to the type, size, or possible location of the activity.

The division of activities depending on their possible environmental impact, and the amount of activity, has been established in the legislative acts:

1. Activities for which a full environmental impact assessment procedure should always be performed are listed in Annex 1 of the law “On Environmental Impact Assessment”. These have been established as the first and main group subject to the EIA procedure;
2. The environmental impact assessment should be performed on the planned activities that might have a transboundary impact. The impact assessment should be performed in compliance with the signed international agreements of the Republic of Latvia;
3. Activities for which it is demanded by the regional environmental board which complies with the results of the initial assessment;
4. Activities the environmental impact of which is insignificant, and to which the initial assessment is not applied. The regional environmental board issues the technical regulations in compliance with the requirements of the regulatory enactments.

Figure 1.9 presents the EIA sheme in Latvia.

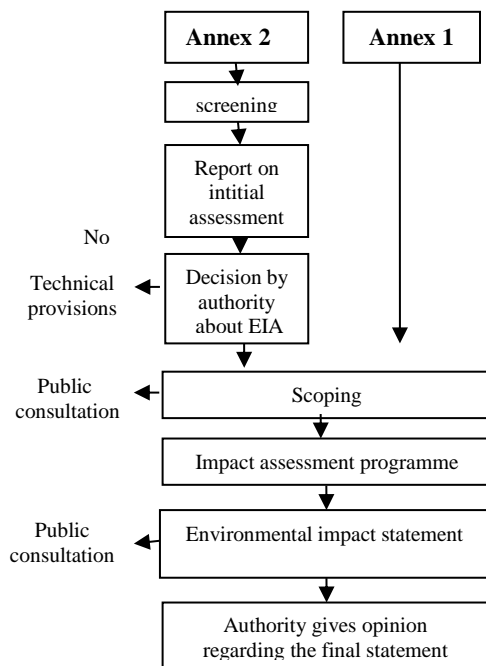


Figure 1.9. Outline of the EIA process in Latvia

It has been established in Latvia that the screening procedure should be performed to the projects listed in Annex II to the Directive 97/11/EC. On the basis of the results of the screening procedure, the decision is made on the application or non-application of the environmental impact assessment procedure. The screening procedure is carried out based upon environment quality standards, emission limiting values, and limits set by legislative

acts. The report on the screening procedure is an administrative act issued by the regional environmental board.

It should be recognized that if the regional environmental board issues a positive normative act, also all the further normative acts should be positive, as it is established by the basic principles of the Administrative Procedure Law.

Therefore, it is very important that when the initial environmental impact assessment is evaluated, also the best available technical methods are taken into account if the planned project complies with category 'A' polluting activity, and that the requirements of the regulatory enactments are taken into account if the planned project complies with another category of polluting activity.

Currently, the screening procedure is often only a formal procedure, and the assessors do the bare minimum, rather than evaluate the planned activity in detail. On one hand, formal assessment is permissible because not all submitted projects can have a substantial impact.

However, if such an approach is used, the projects where the planned technical solution is not sufficiently critiqued, and may not comply with the requirements of regulatory enactments, may still be approved.

In Latvia, the screening of more than 4000 projects has been performed. The screening has been completed for the vast majority - 96% - of projects.

During the last 5 years, on average, in 40% of cases the environmental impact assessment procedure was initiated based on the results of the screening. It attests to the significance of the screening process.

Figure 1.10. shows the distribution of projects, for which the environmental impact assessment has been performed, by areas of economic activity. Until 2010, the main spheres of the environmental impact assessment were projects in the area of infrastructure and industry, waste management projects, extraction of mineral deposits, and energy industry projects.

From an analysis of the information on the EIAs of the planned activities, it has been concluded that since the introduction of the environmental impact assessment procedure in 1997 up until the end of 2013, the environmental impact assessment procedure has been applied to 225 projects in Latvia.

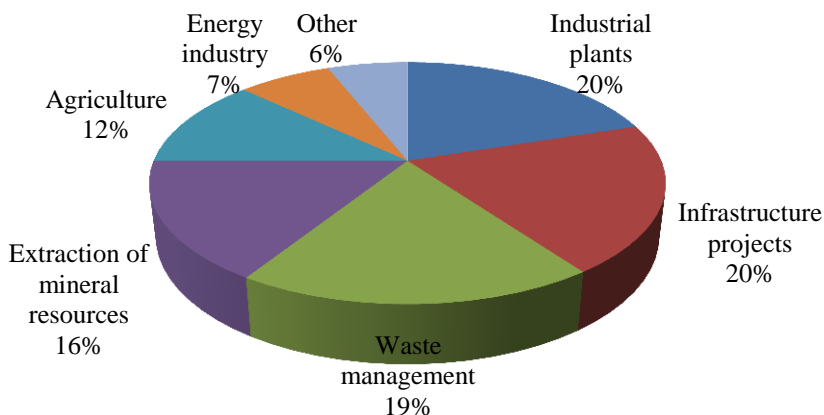


Figure 1.10. Areas of application of the environmental impact assessment in Latvia

### **1.3.4. A Comparison of EIA procedure and practice in the Baltic States**

The beginnings of the environmental impact assessment system in the Baltic States traces back to the time of the Soviet Union. The ecological examination of projects in Latvia, Lithuania, and Estonia commenced in the late 80s of the 20<sup>th</sup> century. However, it must be admitted that the assessments in this process were not coordinated. The aim of the ecological examination was to assess the ecological hazard level of economic activities, the ecological situation in specific developments and sites, and the elaboration of proposals to improve the environmental quality.

In the Baltic States, the environmental impact assessment procedure was introduced in late 90s of the 20<sup>th</sup> century. In Lithuania, the initial law on EIA, entitled the Law on Environmental Impact Assessment, was introduced in 1996, in Latvia, the law On Environmental Impact Assessment was adopted in 1998, and in Estonia, the Regulation on Conducting EIA was adopted in 1992 [68]. In 2000, the Estonian Parliament adopted the EIA and Environmental Auditing Act, which entered into force in 2001.

The Baltic States are included in the first group of post-Soviet countries to elaborate and adopt EIA laws. The law is the main normative instrument in the EIA field in each of the Baltic States. At the same time, the assessments in Slovenia were formalized in 1993, with the Slovenian act on environmental protection which introduced project and strategic environmental impact assessments [69].

One of the most substantial stages in the EIA process is screening. During which, it is determined whether the planned activity might or might not have a notable impact. The significance of the impact is determined in compliance with the selection criterion established by the directive. It should be noted that in compliance with the report from the Commission on the application and effectiveness of the EIA Directive, when establishing the border values, the EU member states often exceed the freedom of action. This is seen by either only observing some of the selection criterion of Annex III, or initially not subjecting the EIA to certain projects. Moreover, though the tendency to perform EIA is increasing, the EIAs performed in several member states differs notably (in some less than 100 and in others up to 5000), even when similar member states are compared.

In order to improve screening quality, it would be necessary to simplify and unify the verification mechanism, for example, by elaborating identical methods for screening and assessment for all Baltic States. Vital in this process is to end the practice of "salami-slicing". This occurs when the project is divided into separate parts, thus evading the border values of the EIA procedure.

It must be mentioned that many screened projects do not require EIA as a result - the number of projects screened should be higher than the number of those subject to an EIA. It means that screening might become a routine procedure, with a growing number of projects subject to it [65]. The number of screening procedures performed in Latvia and Lithuania between 2001 and 2007 is given in Figure 1.11.

The number of initial assessments performed in this period in Latvia increased from 14 cases in 2002 to 636 cases in 2007; in Lithuania from 150 cases in 2001 to 666 cases in 2007 [70].

In Lithuania, the probability of significant effects has been taken into consideration, and subsequently a full environmental impact assessment study with a report has been required in only 4.1 – 27.3% cases in different years [70]. In Latvia, the EIA procedure was applied to 4% of the assessed projects based on the results of the screening process.

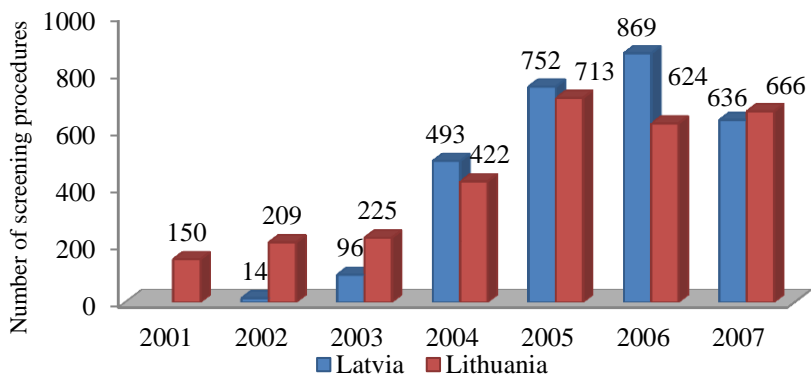


Figure 1.11 Screening procedures performed in Latvia and Lithuania

The difference between the EIA procedures in Lithuania and Latvia regarding scoping is that the programme for the completion of an EIA in Lithuania is elaborated by the submitter of the project, but in Latvia – by the competent institution – the Environment State Bureau.

The number of full EIA studies increased from 23 cases in 2001 to 56 cases in 2007 in Lithuania, and from 6 cases in 2001 to 27 cases in 2007 in Latvia (see Figure 1.12.).

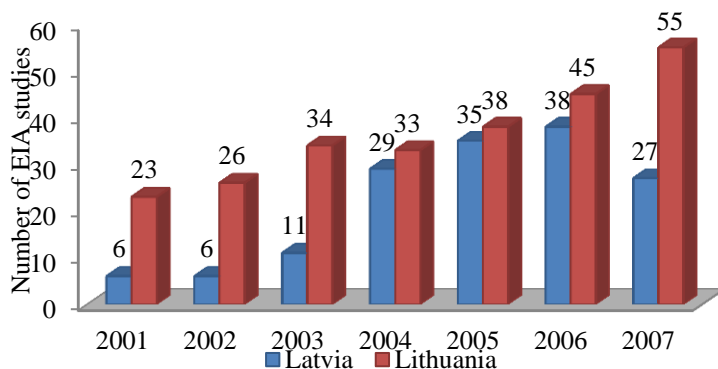


Figure 1.12. EIA studies in Latvia and Lithuania

The number of screening decisions on the EIA and Strategic Environment Assessment (SEA) performed in Estonia between 2005 and 2009 is given in Figure 1.13.

The total number of screening decisions that required EIA or SEA is slightly larger than the number of decisions that did not require EIA or SEA.

Estonian legislation establishes mandatory EIA projects for 33 activities (including dredge dumping, closure of old waste depositories, and other routine activities), compared to 22 activities stipulated by Annex I of the EU EIA Directive [71]. There is a system of licensed environmental assessment experts in Estonia [72].

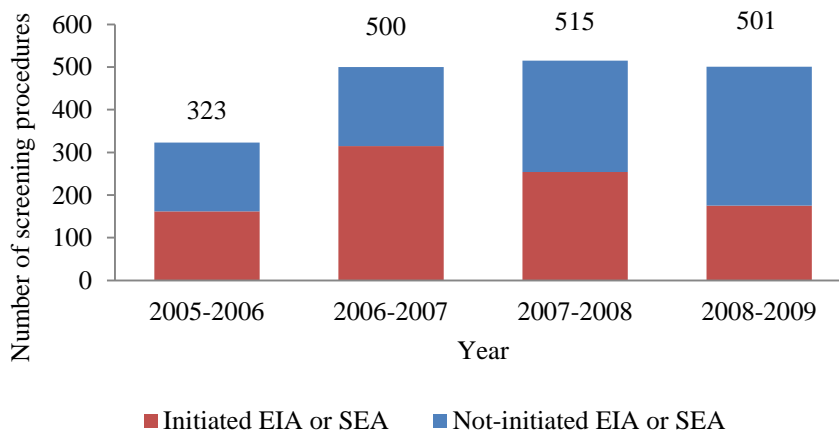


Figure 1.13. Screening procedures performed in Estonia [73]

In order to improve the quality and efficiency of EIA, a consultant should be introduced that would participate in the EIA, as well as be able to give the accordant accreditation.

The environmental impact assessment should be performed by independent consultants, assessment methods for particular types of projects that would allow objective impact assessments throughout the entire territory of the Baltic States should be elaborated.

The concepts of sustainability need methods and tools to evaluate (comparing and measuring) the impacts of human activities for the provision of goods and services (generally defined as products).

Environmental impacts range from emissions into the environment through to the consumption of resources associated with the entire life of a certain product from extracting resources till the end-of-life. These emissions and consumptions (energy and materials) contribute to several types of impacts (e.g. climate change, stratospheric ozone depletion, tropospheric ozone creation, eutrophication, acidification, toxicological stress on human health and ecosystems, the depletion of resources, water use, land use, and noise). A clear need to decrease this amount, with the help of regulatory practices, is needed: the life cycle assessment is exactly one of those practices [74].

An EIA was carried out for 10 out of 11 landfills before the implementation of the MSW landfill project. For one site, an EIA was not carried out since it was made in an existing waste dumping site. In order to evaluate whether predicted impacts were assessed in a sufficiently objective manner, an analysis comparing the current situation with the planned design is carried out.

Annual environment reports were used for the performance evaluation of the landfills. Annual environment reports are developed according to the waste management legislation in Latvia.

#### 1.4. The concept of cleaner production in waste management

The concept of cleaner production was introduced by the United Nations Environment Programme (UNEP) in 1989 in response to the logic of sustainable production and consumption [75].

This concept became a program of action with two specific objectives:

1. Improving eco-efficiency of production in the short- and medium- term;
2. Long-term dematerialization.

Globally, the process of adopting cleaner technologies is part of the sustainable development policy defined in Agenda 21, adopted in Rio de Janeiro in 1992 [76], in that it promotes and encourages the adoption of new manufacturing processes that make scale economies of both raw materials and energy, and are cleaner with regard to environmental protection and adjacent populations.

The concept of cleaner production is well-known in industrial environmental management.

The key principles of cleaner production are:

1. The Precautionary Principle;
2. The Preventive Principle;
3. The Public Participation Principle;
4. The Holistic Principle.

Clean production is an integrated approach to production, constantly asking what happens throughout the life cycle of the chemical or product. It is necessary to think in terms of integrated systems, which is how the living world functions (see Figure 1.14.).

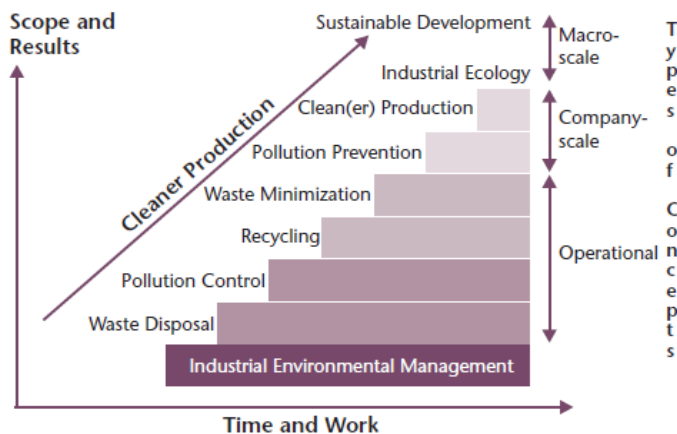


Figure 1.14. Cleaner production scheme [77]

### 1.4.1. Cleaner production in waste management

Nowadays, different methods for municipal solid waste treatment are used:

1. MBT;
2. Mechanical Biological Stabilisation (MBS);
3. Mechanical Physical Stabilisation.

As well, the energetic utilization of wastes has started to become more popular in Europe. A lot of waste incinerators (WIP), facilities for waste and refused derived fuels (RDF) were built and often controversially discussed. Since the price of primary energy carries increased in the last few years, waste as an energy resource becomes more and more attractive. Therefore, the energetic utilization of high calorific fraction from municipal solid waste and commercial waste is processed in power stations for refuse derived fuels.

Furthermore, high calorific solid recovery fuels (SBS) are used with high energy efficiency as quality assured co-firing material in power plants and cement kilns.

The situation in Europe is very different with waste treatment technology, for example, in Latvia the biowaste sector is underdeveloped, but in Germany, due to overcapacities, the plant operators are ready to import waste for treatment from other European Countries.

Taking into account European targets regarding the reduction of biowaste landfilling, the future consequence will be that suitable biowaste will be used more for the production of energy. In Germany for example, if electricity is generated by facilities using biogas produced by anaerobic digestion of biowaste, this electricity attracts a higher subsidy rate than if the biogas is produced by digesting other types of biomass. Sustainable management of biowaste combines material and energy recovery paths with the aim of optimising the integration of nutrients and carbon recycling, energy production, and CO<sub>2</sub> reduction by replacing fossil fuels.

To achieve the maximum result, principles of cleaner production should be implemented in all four steps of biowaste management (see Figure 1.15).

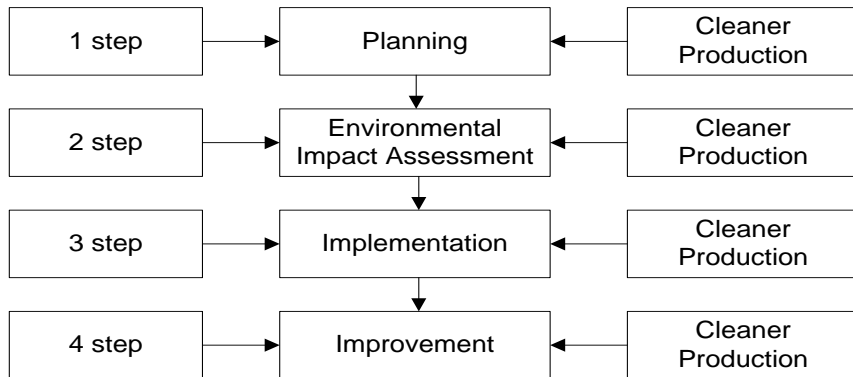


Figure 1.15. Biowaste management scheme

### 1.5. Indicators for waste management

Indicators are used in all areas of management. The use of indicators especially helps during the evaluation of the operational performance. Benchmarking practises help to evaluate the performance of different scenarios, existing and planned activities. Information given by indicators is used by stockholders for decision-making. Therefore, due to the importance of this issue, it is important to use the correct indicators for each area.

Environmental indicators are a management tool for making performance-based decisions about strategies, and can drive innovative policy development and technological design [81]. Indicators have become an integral component of environmental policies for 30 years [82], and are considered an essential tool for tracking environmental progress, informing the public, and supporting policy evaluation [79].

Indicators can be classified depending on purpose, scale, aggregation level and temporal scale [78, 79, 80].

Classification of indicators is shown in Table 1.4.

Table 1.4.

Classification of indicators		
Classification	Indicator	Description
Purpose and framework	Core Environmental indicators	Designed to help track environmental progress and the factors involved in it, and analyse environmental policies
	Key Environmental indicators	Reduced set of the core indicators that serve wider communication purposes. They inform the general public and provide key signals to policy makers
	Sectorial Environmental Indicators	Designed to help integrate environmental concerns into sectoral policies. Each set focuses on a specific sector
	Indicators derived from Environmental accounting	Designed to help integrate environmental concerns into economic and resource management policies
	Decoupling Environmental Indicators	Measure the decoupling of environmental pressure from economic growth. They are valuable for determining whether countries are on track towards sustainable development
Aggregation level	Simple Indicators	Resulting from the estimation or measurement of an indicative variable
	Composite Indicators	Obtained by the aggregation of several variables or simple indicators
Spatial scale	Global scale	
	Local scale	
Temporal scale	Short-term indicator	
	Long-term indicator	

Waste indicators are important for programmatic purposes or comparisons, communication regarding the systems, and for guiding progress towards an improved waste system policy and design [83]. Waste indicators identify needed measurements to determine whether the system objectives are being met [84].

Since the objective of most waste systems in the developed world is to provide environmental benefit, indicators are used to indicate progress towards this objective.

The main steps to be followed during the definition of waste indicators are:

1. Clear definition of the objectives of the set of indicators;
2. Definition of cleaner production principles in biowaste management to be applied;
3. Selection of the indicators;
4. Indicators' validation.

Waste indicators used in literature are summarized in Table 1.5.

Table 1.5.

Waste indicators		
Study	Key domains and indicators	No. of indic.
Arendse and Godfrey [85]	Indicators were developed in the area of generation, types, recycling, disposal, time scale, cost, capacity.	37
Armijo et al. [86]	Service coverage, cost, service satisfaction, composition, separation, recycling, recovery, disposal	18
Coelho et al. [87]	Cleaner waste treatment based on water, air, soil, material and energy used by the waste treatment technology	14
DEA [88]	Waste indicators were proposed focusing on ecology, avoidance, reuse, recycle, safe treatment and disposal based on the socio-economic, environmental contexts	50
EPA [89]	Indicators were developed in 7 broad areas in planning, financial viability, management, staffing, operations, coordination, and compliance	32
Euro Consultants [90]	Legislation, waste generation, recycling infrastructure, efficiency	49
European Commission [91]	Waste quantity, hazardous waste, prevention, recycling, disposal, non-energetic recovery, energetic recovery, environmental benefits, impacts, data	19
European Commission [92]	Indicators on waste prevention based on consumption, housing types, waste generation, reuse, incentives, etc.	10
Klundert [93]	Technical, environmental, financial, socio-economic, institutional and policy sectors	84
Passarini et al. [94]	Geography, density, waste generation, composting, sorting, recycling	6
PRIF [95]	Collection, frequency, recycling, sorting, environmental standard, landfill and cost efficiency	7
United Nations [96]	Comprehensive waste management performance indicators were developed based on geographic, quantity, composition, management, treatment, socio-economic, environmental benefit or burdens	152
United Nations [97]	Key waste management performance indicators were developed based on geography, quantity, composition, management, treatment, socio-economic, environmental benefit or burdens	26
Viguri et al. [98]	Quantity, eco-efficiency, recycling, treatment and carbon footprint	8
Vivanco et al. [99]	Quantity, waste types, sorting, distance covered, treatment technology, net recovery, transport intensity	28
Wilts [100]	Prevention, reuse, extension of product lifespan, environmental cost, human health	7
Kondili et.al. [101]	Electrical energy recovery, thermal energy recovery, fossil fuel substitution, 2010 RES contribution, land occupation, economic gains, operational cost, initial cost	9
Zaman [102]	Environmental emissions, environmental savings, net. Environmental benefit, economic cost, audition and monitoring	56

## 1.6. MCA methodology: an overview

Multi-criteria analysis tools are tools that support a comparison of different policy options on the basis of a set of criteria. They are very effectively in supporting the assessment of, and decision-making on, complex sustainability issues because they can integrate a diverse set of criteria in a multidimensional guise and they can be adapted to a large variety of contexts. The procedures and results obtained from the MCA can be improved with the participation of stakeholders [103].

A multi-criteria analysis establishes preferences between options by reference to an explicit set of objectives that the decision-making body has identified, and for which it has established measurable criteria to assess the extent to which the objectives have been achieved. In simple circumstances, the process of identifying objectives and criteria may alone provide enough information for decision-makers [104]. The MCA has many advantages over informal judgement unsupported by analysis:

1. It is open and explicit;
2. The choice of objectives and criteria that any decision-making group may make are open to analysis and to change if they are felt to be inappropriate;
3. Scores and weights, when used, are also explicit and are developed according to established techniques. They can also be cross-referenced to other sources of information on relative values, and amended if necessary;
4. Performance measurement can be sub-contracted to experts, so they need not be left in the hands of the decision making body itself;
5. It can provide an important means of communication, within the decision-making body, and later between that body and the wider community;
6. Scores and weights are used, providing an audit trail [104].

There are many MCA techniques, and their number is still rising. A large number of MCA methods exist to rank, compare and/or select the most suitable policy options according to the chosen criteria. These methods distinguish themselves through the decision rule used, and through the type of data they can handle (quantitative, qualitative or mixed). So the method to choose to apply an MCA depends of the decision rule preferred, and the type of data available. Criteria used in this manual for the selection of techniques are: internal consistency and logical soundness; transparency; ease of use; data requirements not consistent with the importance of the issue being considered; realistic time and manpower resource requirements for the analysis process; ability to provide an audit trail; software availability [104].

The following eleven methods were identified throughout the literature review:

1. Multi-Attribute Utility Theory (MAUT);
2. Analytic Hierarchy Process (AHP);
3. Fuzzy Set Theory (Fuzzy);
4. Case-based Reasoning (CBR);
5. Data Envelopment Analysis (DEA);
6. Simple Multi-Attribute Rating Technique (SMART),
7. Goal Programming (GP),
8. ELECTRE;
9. PROMETHEE;
10. Simple Additive Weighting (SAW),
11. Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS).

The main advantages, disadvantages, and areas of application are described in the following table.

Table 1.6.

Summary of Techniques [105]			
Method	Advantages	Disadvantages	Areas of Application
MAUT	Takes uncertainty into account; can incorporate preferences.	Needs a lot of input; preferences need to be precise.	Economics, finance, actuarial, water management, energy management, agriculture
AHP	Easy to use; scalable; hierarchy structure can easily adjust to fit many sized problems; not data intensive.	Problems due to interdependence between criteria and alternatives; can lead to inconsistencies between judgment and ranking criteria; rank reversal.	Performance-type problems, resource management, corporate policy and strategy, public policy, political strategy, and planning.
CBR	Not data intensive; requires little maintenance; can improve over time; can adapt to changes in environment.	Sensitive to inconsistent data; requires many cases.	Businesses, vehicle insurance, medicine, and engineering design.
DEA	Capable of handling multiple inputs and outputs; efficiency can be analyzed and quantified.	Does not deal with imprecise data; assumes that all input and output are exactly known.	Economics, medicine, utilities, road safety, agriculture, retail, and business problems.
Fuzzy	Allows for imprecise input; takes into account insufficient information.	Difficult to develop; can require numerous simulations before use.	Engineering, economics, environmental, social, medical, and management.
SMART	Simple; allows for any type of weight assignment technique; less effort by decision-makers.	Procedure may not be convenient considering the framework.	Environmental, construction, transportation and logistics, military, manufacturing and assembly problems.
GP	Capable of handling large-scale problems; can produce infinite alternatives.	Its ability to weigh coefficients; typically needs to be used in combination with other MCDM methods to weigh coefficients.	Production planning, scheduling, health care, portfolio selection, distribution systems, energy planning, water reservoir management, scheduling, wildlife management
ELECT.	Takes uncertainty and vagueness into account.	Its process and outcome can be difficult to explain in layman's terms; outranking causes the strengths and weaknesses of the alternatives to not be directly identified.	Energy, economics, environmental, water management, and transportation problems.
PROMET	Easy to use; does not require the assumption that criteria are proportionate.	Does not provide a clear method by which to assign weights.	Environmental, hydrology, water management, business and finance, chemistry, logistics and transportation, manufacturing and assembly, energy, agriculture.

SAW	Ability to compensate among criteria; intuitive to decision-makers; calculation is simple, does not require complex computer programs.	Estimates revealed do not always reflect the real situation; result obtained may not be logical.	Water management, business, and financial management.
TOPSIS	Has a simple process; easy to use and program; the number of steps remains the same regardless of the number of attributes.	Its use of Euclidean Distance does not consider the correlation of attributes; difficult to weigh and keep consistency of judgment.	Supply chain management and logistics, engineering, manufacturing systems, business and marketing, environmental, human resources, and water resources management.

Multi-Criteria Decision Analysis (MCDA) is a process that allows complex qualitative and quantitative information to be evaluated and assessed in a systematic and consistent way while taking account of subjective views of the data and their relative importance [106].

The key features of an MCDA are (Diakoulaki and Grafakos, 2004):

1. It involves the stakeholders in the decision-making process;
2. It acts as an interactive learning process allowing stakeholders to take account of the points of view of other stakeholders;
3. It takes a multidisciplinary approach, allowing full account to be taken of the complexity of natural systems;
4. It allows many criteria to be taken into account, both quantitative and qualitative [106].

The main steps of MCDA are showed in Figure 1.16.

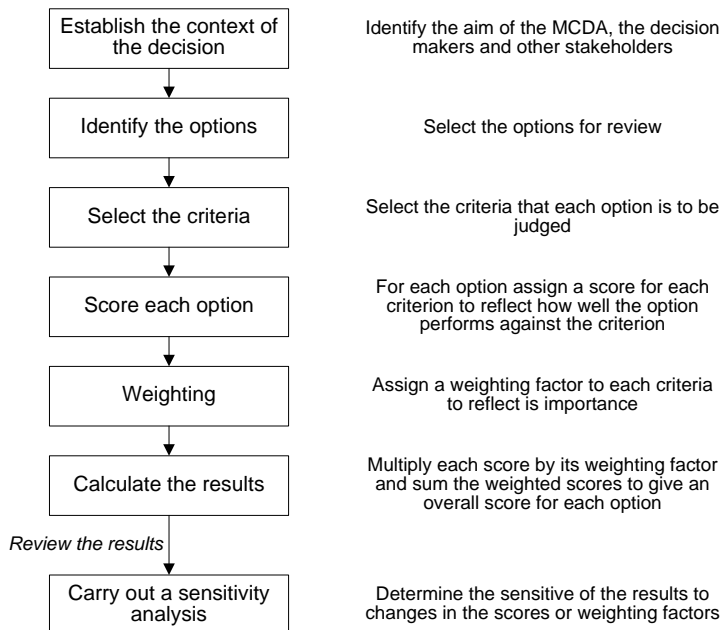


Figure 1.16. MCDA process [104, 106]

## **1.7. CRA methodology: an overview**

Regression analysis involves identifying the relationship between a dependent variable and one or more independent variables. A model of the relationship is hypothesized, and estimates of the parameter values are used to develop an estimated regression equation. If the model is deemed satisfactory, the estimated regression equation can be used to predict the value of the dependent variable given values for the independent variables.

Correlation and regression analysis are related in the sense that both deal with relationships among variables. The correlation coefficient is a measure of linear association between two variables. Values of the correlation coefficient are always between -1 and +1. A correlation coefficient of +1 indicates that two variables are perfectly related in a positive linear sense; a correlation coefficient of -1 indicates that two variables are perfectly related in a negative linear sense; and a correlation coefficient of 0 indicates that there is no linear relationship between the two variables. For simple linear regression, the sample correlation coefficient is the square root of the coefficient of determination, with the sign of the correlation coefficient being the same as the sign of  $b_1$ , the coefficient of  $x_1$  in the estimated regression equation.

Neither regression nor correlation analyses can be interpreted as establishing cause-and-effect relationships. They can indicate only how, or to what extent, variables are associated with each other. The correlation coefficient measures only the degree of linear association between two variables. Any conclusions about a cause-and-effect relationship must be based on the judgment of the analyst [107].

## **1.8. SD methodology: an overview**

System dynamics processing helps to conceptualize and rationally analyze the structure, interactions and mode of behaviour of complex systems and sub-systems to explore, assess, and prognosticate their impacts in an integrated and holistic manner. It facilitates a more sophisticated, quantitative simulation than simple spreadsheet programs, and is capable of more robust and reliable outcomes [108].

The use of System Dynamics SD in waste management planning can help predict future trends and analyse system characteristics. SD has been applied in fields related to waste management over the past several years. In the literature, research using SD modelling to analyse solid waste, demolition waste, construction waste and hospital waste has been completed.

Since the first studies using the SD approach in the waste sector [109, 110], a large number of studies have used the SD approach to simulate scenarios in different applications of MSW management and treatment [111, 112]. Sliwa (1994), Dyson and Chang (2005), Kollikkathara et.al. (2010), Cai and Liu (2013) applied SD modelling to MSW management in a case study of a specific place [113 – 116]. Escalante (2013), Lang et.al. (2002) analysed the behaviour of households adopting biowaste separation and biowaste recovery [117 – 119].

## **1.9. Integration of MCA with other methodologies**

A limited amount of research has also been carried out on the integration of the SD method with other methods used in the waste sector. Karavezyris et.al. (2002) have developed a combined SD and fuzzy logic model to forecast the amount and kinds of MSW

[120]. The integration of these methods has allowed for the creation of a supplementary tool to manage and forecast MSW amounts using a combination of SD and fuzzy logic.

Brans et.al. (1998) and Santos et.al. (2001) proposed to integrate the MCA and SD methodologies [121, 122]. Brans et.al. (1998) proposed to use a combination of MCA and SD as a control measure for socio-economic processes [121]. Santos et.al. (2001) proposed to use it for organisational performance measurement and management [122].

Brans et.al. (1998) proposed a new methodology to control socio-economic structures by combining the principles of SD, Control Theory, and Multi-Criteria Decision Analysis (MCDA) [121]. The methodology consists of three key steps: development and calibration of the model, definition of long-term strategies, and short-term control. The authors demonstrated the proper control of socio-economic systems through a combination of SD, Control Theory and MCDA. Santos et.al. (2001) argued that the integration between SD and MCDA can be predicted if the measurement system is effective in supporting the decision-making process and encourages improvements in organizational performance [122]. SD and MCDA can help with a detailed analysis of the structure and problems and consequently determine the proper action plan for performance improvement. In addition, using SD together with MCDA can reflect the multiple interests involved. As well, the preferred course of action to assist decision-makers in conflicted environments can be identified. The MCDA methodology helps decision makers understand the problem, and can help them make more appropriate decisions. At the same time, the use of SD modelling is able to provide a greater understanding of the system of interest.

The proposed literature review highlights evident lacks on the integration of MCA and SD approaches into waste management. The interests of multiple stakeholders need to be taken into account. MCA and SD individually proved their potential for handling waste management issues. Each method has its advantages and its shortcomings. Biowaste management has been stressed as a key component of managing waste. An effective tool to evaluate different biowaste scenarios and assist stakeholders in decision-making is imperative. This would lead to continuous improvement in methods of managing waste.

In light of the previous outcomes mentioned in the literature review, the main goal of this study is to propose an effective tool to assess, compare, and screen biowaste management alternatives based on a combination of both MCA and SD modelling. MCA modelling aims to identify the optimal solution based on a set of specific, identified criteria. While SD modelling is an effective tool to deal with dynamic and complex problems [123] where the physical processes, information flows, management strategies, and the potential policy measure must be clearly identified to be able to effectively define the interaction between, and among, the aforementioned problems. Thus, a combination of MCA and SD modelling provides a method that gives an holistic approach while taking into account environmental, economic, technical, and social aspects which need to be integrated in a time scale reference.

## 2. 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 CRA analysis 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.

### 2.1. An 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.

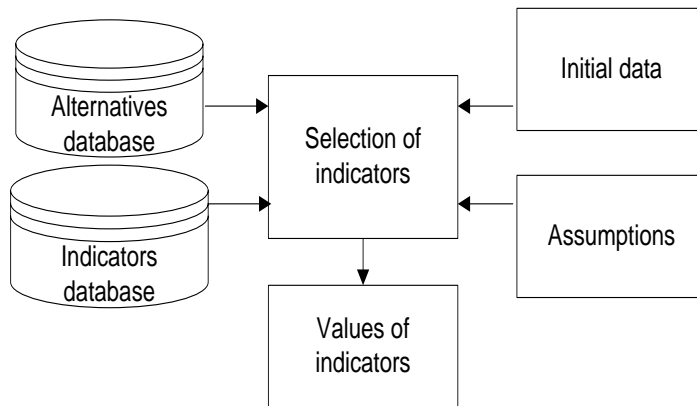


Figure 2.1. Inventory phase

### 2.2. 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.

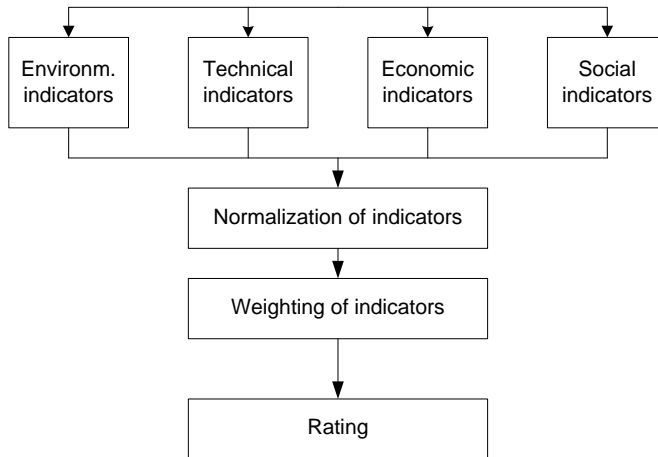


Figure 2.2. Multi-Criteria Analysis scheme

### 2.3. 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 [124].

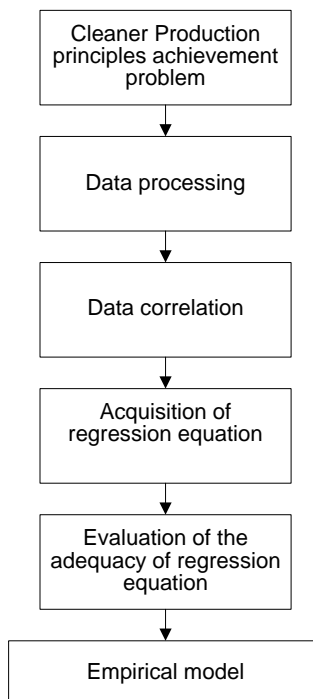


Figure 2.3. Empirical model

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

## 2.4. 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 [125].

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.

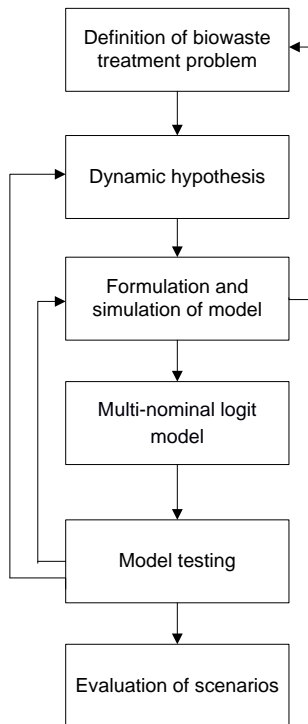


Figure 2.4. System Dynamics algorithm

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 2.5.

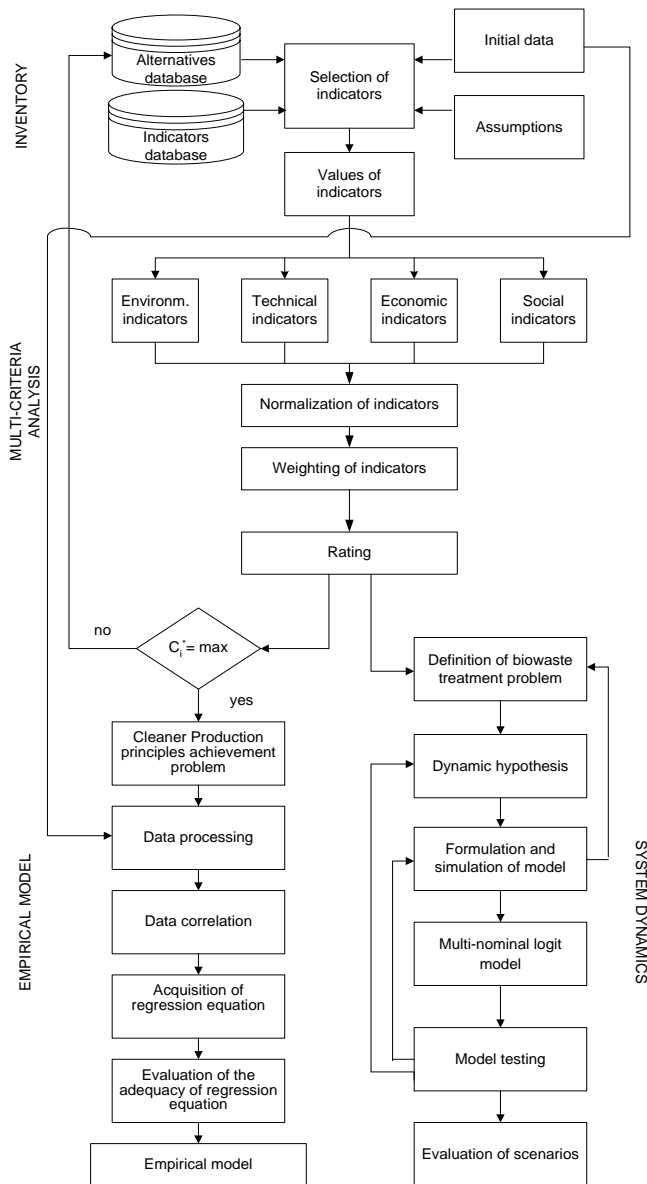


Figure 2.5. Methodological algorithm

### **3. IDENTIFICATION AND ANALYSIS OF CLEANER PRODUCTION INDICATORS**

#### **3.1. Biowaste management scenarios**

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 [126], incineration [127 – 129], biogasification [130], biodegradation of waste in reactors [131], anaerobic digestion [132], composting and pyrolysis [133].

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. 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.

##### **3.1.1. Separate collection with anaerobic digestion**

Anaerobic digestion (AD) of the organic fraction of municipal solid waste and catering/food waste is one of the best options for biowaste treatment [134]. Anaerobic digestion has important advantages in comparison with other techniques. In contrast to composting, the anaerobic digestion of biowaste has a simultaneous energetic output [135]. In contrast to landfilling and the utilization of landfill gas, anaerobic digestion provides a closed nutrient cycle. Anaerobic digestion is one of the best options for biowaste management in Latvia. In comparison to waste incineration plants, AD plants need lower investments. The distances for feedstock transport to AD plants are shorter than in the case of waste export to existing waste incineration plants in other countries. Nutrients can be recovered more easily for agricultural production. Furthermore, wet feedstock does not have to be dried, which is required for incineration.

There are differences in the operation of anaerobic digestion processes. There are continuous and discontinuous anaerobic digestion processes. In the continuous process, biowaste is automatically fed at regular intervals into the anaerobic digestion reactor. This process promotes continuous biogas production of consistent quality.

In the discontinuous process, the digesters are filled by a wheel loader, then after several weeks they are emptied and refilled. Biogas production is not continuous, but parallel connection of several digesters working on a staggered system can largely compensate for this. Discontinuous processes have advantages over continuous methods because of their simpler mechanical reactor systems. On the other hand, the latter require a

smaller reactor volume because of their higher space-time yield and can usually be automated more effectively than discontinuous processes

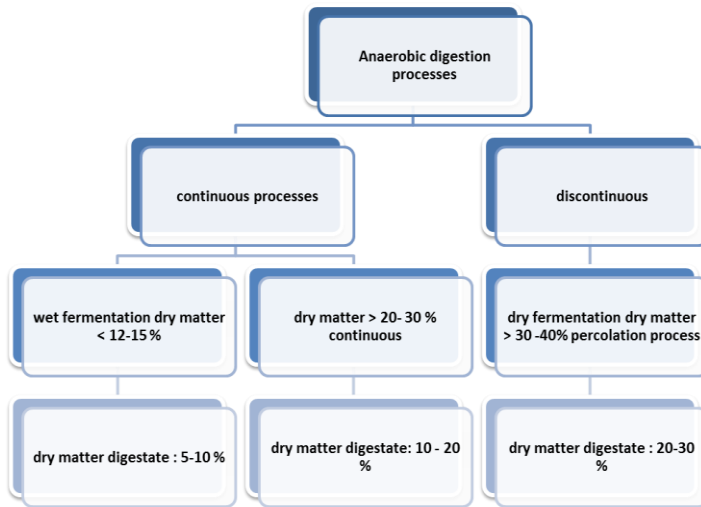


Figure 3.1. Anaerobic digestion of biowaste [136]

Anaerobic digestion of separately collected biowaste is an option with a lot of advantages thanks to the high energetic output [137]; closed energetic cycle [138], lower emissions [139], as well as the positive impact on the social environment and employment.

In the case of this scenario, a separate biowaste collection system must be introduced. For the treatment of biowaste, some existing biogas stations can be used, and there is a necessity for new plants close to urban areas to be constructed. Anaerobic digestion plants should be constructed close to the main organic waste producers to optimize feedstock transportation. As well, plants can be located in the territory of existing MSW treatment facilities. The location of the biogas plants close to urban areas might be economically feasible in the case of source separated organic waste being collected and delivered to a biogas plant near the closest city. This would allow for savings on transportation costs compared to the scenario if the biogas plant is located in landfills.

### 3.1.2. Separate collection with composting

The composting scenario provides for the composting of biowaste with a high content of lignocellulose. This scenario could be applicable for green waste or small facilities (further use of compost for greening, recultivation of lands, pits, scuffles, organic farming, decorative improvement, sport areas, fields).

Composting is a common practice in many cases, as well, this occurs in Latvia and all over Europe. The environmental benefit for this scenario is a high-value end-product [140] and a closed nutrient cycle.

Composting is one of the cheapest biowaste treatment options, but in the case of composting, the energy content of the biomass is not utilized.

The mechanical composting processes applied can be divided into various categories:

1. composting in heaps (triangular, trapezium-shaped, or flat stacks);
2. composting in bunkers/containers;

3. row/tunnel composting;
4. composting as briquettes;
5. other systems.

The processes differ in the way the heaps are constructed (open, covered, in containers), the type of ventilation, and also the duration of the intensive rotting stage and the maturity of compost desired. If the intensive rotting system is set up for mature compost, the main and subsequent rotting phases are integrated. If the intensive rotting results in sanitized fresh compost, a second rotting stage can follow to achieve a higher degree of decomposition. In composting facilities, the second stage is carried out predominantly in flat or triangular heaps.

The following diagram provides an overview of possible processes.

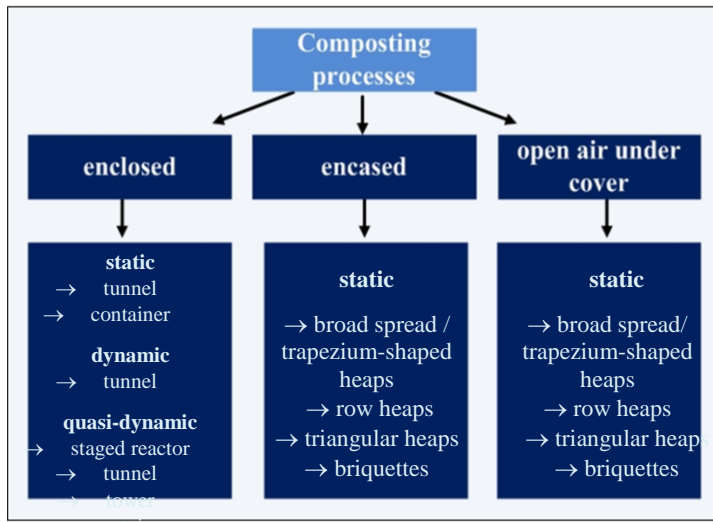


Figure 3.2. Composting of biowaste [136]

The amount of green waste which can be composted using this method is shown in Figure 3.3. The amount of green waste is about 15 000 tonnes a year. It is recommended to use this scenario only for green waste since compost produced in Latvia is currently not required, and this scenario has no energetic output.

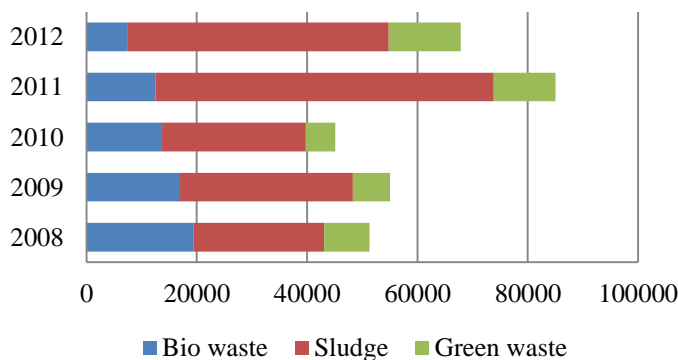


Figure 3.3. Composition of waste from 2008 till 2012

In accordance to an EC report on the assessment of the options to improve the management of biowaste in the European Union [141], the best method for biowaste treatment is composting. Composting is the only method mentioned in Latvian legislation for minimizing the amount of biowaste and biowaste treatment. During the development process of the waste management system, several solid waste disposal landfills in Latvia established composting facilities. The aim of the composting facilities was to minimize the amount of biowaste to be deposited in the country; however, practical experience shows that these composting areas are not being used to their full potential.

### 3.1.3. Mechanical Biological Treatment

During these years, equipment for mechanical waste preparation and separation [142, 143] will be installed in Latvian landfills. Waste preparation and separation equipment will be installed for the production of RDF and the minimization of the amount of the landfilled biodegradable part of MSW. Questions concerning the biological treatment of the prepared and separated MSW are still unresolved. There are 3 options which are the most suitable for biological treatment in Europe [126, 144]:

1. Aerobic - Bio-drying/ Biostabilisation: partial composting of the whole waste;
2. Aerobic - In-Vessel Composting: may be used to either biostabilise the waste or process a segregated organic rich fraction;
3. Anaerobic Digestion: used to process a segregated organic rich fraction (see Figure 3.4).

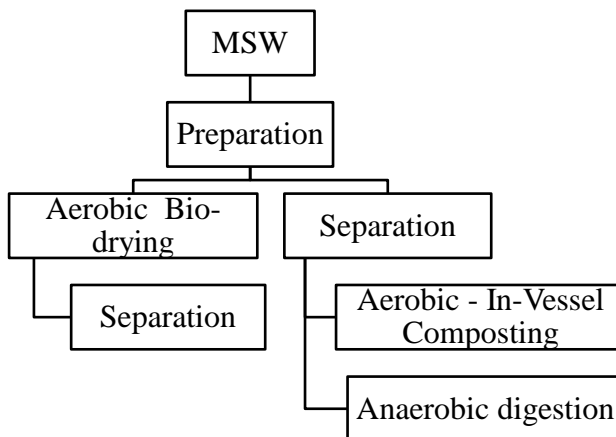


Figure 3.4. Biological treatment of MSW

The first MSW plants with MBT in Latvia use aerobic treatment, since the amount of waste is small and composting can be done in existing composting facilities in landfills. In landfills with bigger amounts of biodegradable waste, anaerobic digestion should be introduced for the treatment of waste after the mechanical treatment. In the case of MBT, only dry fermentation technologies can be used, since waste contains impurities. In the case of MBT, the energetic output will be lower.

MBT scenarios can be applied for collected MSW. At the same time, the separate collection of biowaste should be supported and promoted.

### 3.1.3.1. MBT with mechanical biological pre-treatment and anaerobic digestion

The treatment option of biowaste depends on the quality of collected materials. If biowaste is separated from the MSW stream, biowaste contains impurities which can negatively affect the operation of the biowaste treatment plant.

Anaerobic digestion of separately collected biowaste leads to a larger energy output compared to the MBT of biowaste. Mechanical biological treatment of MSW has become more popular in recent years. MBT is a waste treatment process that involves both mechanical and biological treatment. The first MBT plants were developed with the aim of reducing the environmental impact of landfilling residual waste. The steps of an MBT are shown in Figure 3.5.

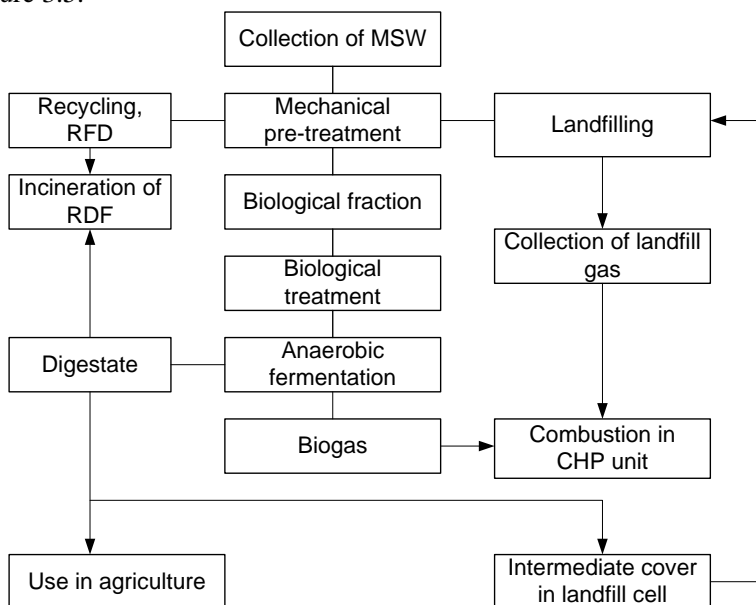


Figure 3.5. MBT with anaerobic digestion

This scenario, as well as the biowaste composting scenario, provides full mechanical–biological treatment of MSW. As a result of biowaste anaerobic fermentation, the amount of waste organic dry matter decreases and, as a by-product, biogas is generated. Initially, the generated biogas may be used in biogas co-generation facilities for energy and heat recovery, or for transportation purposes after biogas purification and compression.

This scenario ensures a high energetic output from one side, and a high-value end product and closed nutrient cycle (digested material) from the other side.

### 3.1.3.2. MBT with mechanical biological pre-treatment and composting

In MBT with mechanical biological pre-treatment and composting scenario, biological treatment can be applied in two ways:

1. Bio-drying or Bio-stabilization. All waste steam is partially composted through bio-drying.

2. In-Vessel Composting. This method may be used to either bio-stabilise the waste or process a segregated organic rich fraction. This scenario has no energetic output.

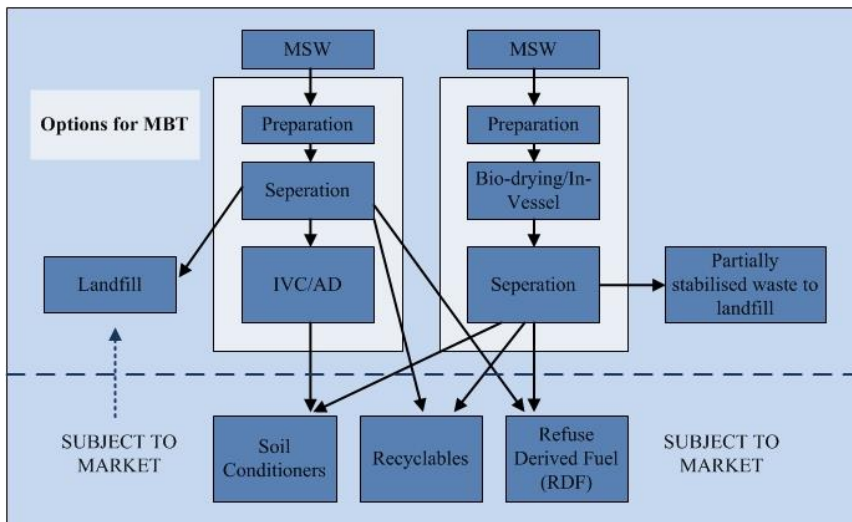


Figure 3.6. Mechanical Biological Treatment options [142]

### 3.1.4. Incineration of MSW

Waste incineration, with or without energy recovery, is a well-known technique in Europe. There are no incineration plants in Latvia, and a small amount of RDF is co-combusted in cement kilns. The construction of incineration plants was accompanied with substantial investments and public protests. Therefore, the realistic option is waste export to incineration plants in neighbouring countries coupled with existing incineration plants.

#### 3.1.4.1. Incineration with energy recovery

In the upcoming years in the Baltic States Lithuania and Estonia, 7 waste incineration plants will start to operate with a total capacity of 815 000 tonnes of RDF a year [41]. Therefore, a portion of waste produced in Latvia could be burned in waste incineration plants in Estonia or Lithuania. A part of the biowaste, after anaerobic digestion, could be incinerated to produce electricity in the case that it will not be necessary to use digested biowaste to cover landfills. The standard approach for the recovery of energy from the incineration of MSW is to utilise the combustion heat through a boiler to generate steam. CHP Plant is the most efficient option overall for utilising recovered energy from waste via a steam boiler [145].

There are three combustion technologies that can be employed to burn MSW or RDF:

1. rotary Kiln;
2. fluidised Bed;
3. moving grate;
4. fixing grate.

### **3.1.4.2. Incineration without energy recovery**

The given biowaste treatment process does not provide for the efficient minimisation of greenhouse gas emissions [146], energy is not recovered, and the treatment process does not provide maximum economic added value. No use of nutrients is possible. Incineration without energy recovery has no energetic output.

### **3.1.5. Landfilling with the collection and utilization of landfill gas**

Landfilling is the current practice in Latvia. Landfilling is the cheapest option and no investments are needed for this scenario. Waste landfill operators are still making loan payments. Since the income of landfills depends on the amount of landfilled waste, and the amount of landfill gas produced, landfill operators are uncertain about the introduction of biowaste treatment scenarios. At the same time, landfilling has the biggest impact on the environment [127, 147], the energetic output is low [129], and the EU targets regarding landfilling cannot be achieved.

Landfill gas could be energetically used, but energy output is low.

## **3.2. Impact assessment of anaerobic digestion projects in Latvia**

Biogas production has many benefits. The first, and the main benefit, is related to new job creation and rapid rural development. Therefore, the development of the biogas sector stimulates the establishment of other enterprises and indirectly increases the income level and job opportunities in a given region. At the same time, the production of biogas has negative aspects as well: soil erosion, food/energy conflict, and a substantial impact from the transportation of feedstock and digestate.

The first time the production and collection of biogas from biological processes was described was in 1895 in Great Britain. The process has developed considerably since those initial days.

Today, it is possible to produce biogas from different sources including wastewater sludge, manure, biowaste, and algae as well. The energy crisis of the 1970s led to a new understanding of renewable energy sources, including the use of biogas energy produced through anaerobic fermentation.

Latvia, along with other countries, is intrigued by the use of biogas. This interest is related to the need to replace fossil fuels with renewable resources. In addition, there is a need to find environmentally sustainable solutions for the treatment and recycling of manure and organic waste.

In Europe, the production of biogas has increased dramatically over the last ten years due to the growing demand for renewable energy as a substitute for energy carriers. Most biogas plants in Europe use biogas for electricity production in CHP plants [147].

In Figure 3.7. the main processes of biogas plant are shown.

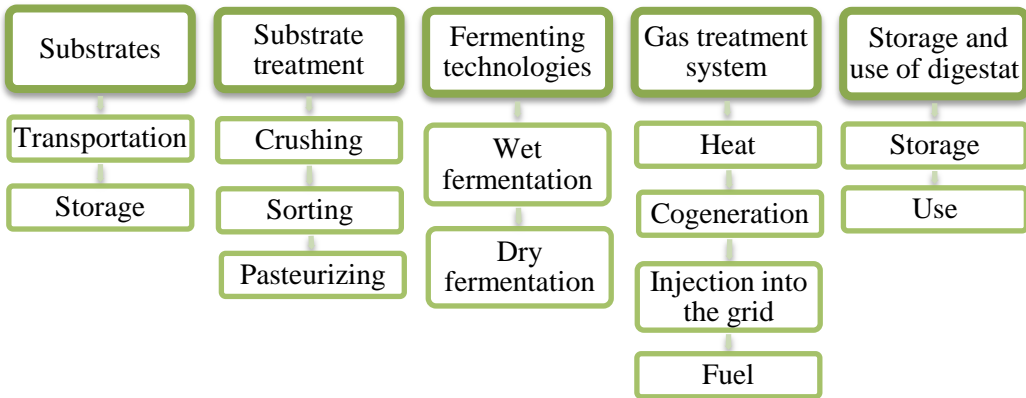


Figure 3.7. Biogas technologies process steps [13]

Until 2007, only three biogas plants had been operating in Latvia with a total installed electricity generating capacity of 7,5 MW<sub>el</sub>. Since 2009, the number of biogas plants has rapidly increased in Latvia.

Currently, 58 businesses have received a quota for biogas production with a total installed electrical capacity of nearly 54 MW<sub>el</sub>.

In April 2011, there were 15 functioning biogas plants in Latvia with a total electrical capacity close to 19 MW<sub>el</sub>. In 2012, the total capacity of installed biogas plants in Latvia was 22,922 MW<sub>el</sub>. 35 biogas plants were operational in 2012 in Latvia [148, 149].

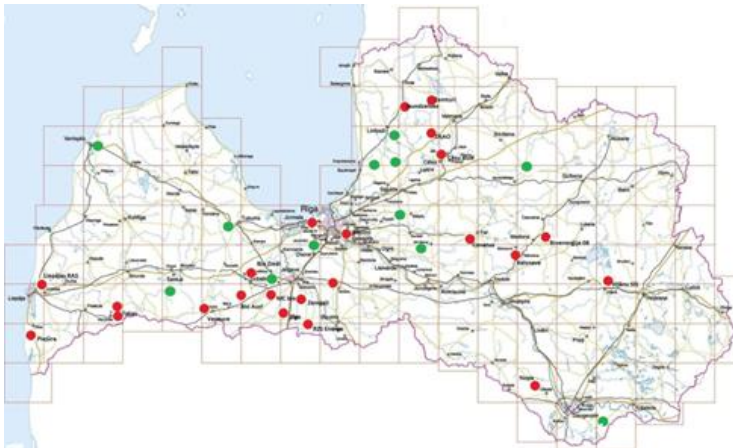


Figure 3.8. Biogas plants in Latvia [148]

The EIA screening of 39 biogas plants had been completed in Latvia by the end of 2012. So far, a full EIA procedure has not yet been applied or performed for any biogas plants.

In Figure 3.8. the biogas plant network in Latvia is shown. The figure shows that the largest amount of biogas plants is located in the central part of Latvia, and a limited amount in the eastern and western parts of the country.

The aim of the screening phase of EIA is to determine if the project must be subject to an EIA. Without this verification some actions can be evaluated very precisely while others can be forgotten or ignored. While carrying out an effective assessment a list with the activities planned, accompanied by the values and criteria for determining whether action should be evaluated, are formed [55, 150].

Categories of activities which are compulsorily required to carry out an EIA are defined in annex 1 of the EIA directive. In annex 2 of the directive, the operations that need to be undertaken in the EIA procedure on a case by case basis are defined. There may also be activities that are not included in these annexes, but the responsible organization of government after the screening has to decide to grant the EIA procedure to the activity. The state may also establish stricter limits, allowing certain projects to be subject to EIA procedure. The EIA procedure can also be made on a voluntary basis as an important step in developing the project [64].

Despite the fact that the EIA directive defines a uniform screening process, each country has implemented the EIA directive differently. Together with significant differences in regulations and practices of the initial inspection, the main shortcomings which have emerged are: doubts on the effectiveness of certain criteria and limits of systems for projects in annex 1, non-systematic approach for verification of projects in Annex 2, large differences in the initial test criteria between member states, the lack of clear definitions of the types of projects leading to possible misinterpretation of daily practice. Criteria that define the level of significance of the project vary depending on the quantitative or qualitative assessment. Predestined criteria are based on thresholds or previously taken measurements and specified restrictions and limits existing in laws, rules and other guidelines. Criteria based on judgment are applied, if the project is unlikely to have a significant impact, but in the context the need to take precautions is justified.

In Latvian legislation, activities that must be carried out in environmental impact assessment are clearly defined, as well as the scope of the work, which is carried out in accordance with international treaties, is also clearly defined. At the same time groups of activities subject to screening are not well-defined in the Latvian legislation, as well as the screening thresholds and criteria for evaluating the potential impact of the activity are not clearly defined. This leads to a very wide field of subjective judgments and indecisive approaches. By unreasonably reducing the number of projects which are subject to EIA procedure, the public's right to engage in discussion becomes limited and it is not possible for the public to comment on a project. The lack of laws, regulations and guidance complicates the decision-making, and leads to conflict and makes it possible to use the lack of structure within the laws for selfish purposes.

According to the legislation, the application of the initial planned actions is filed at the regional environmental administration of the State Environmental Service, depending on the location of the planned activity. The regional environmental administration evaluates the material concerning the proposed project and decides whether it is necessary to perform a screening. By evaluating the laws and regulations, it was found that The Cabinet of Ministers of the Republic of Latvia has determined the order in which the screening of the environment is completed for the proposed action. The application procedures and application content is defined in the legislation.

According to Latvian laws and regulations on screening, the regional environmental administration is entitled to invite experts to evaluate, request and receive information from

state and local government institutions, as well as to request and receive additional information from the project proposer. However, given the current economic situation, the government is not able to invite experts because there are no resources for the remuneration of said experts.

### **3.2.1. The screening of biogas projects in Latvia**

It is not possible to precisely define what is considered to be a significant impact on the environment. In the majority of developed countries, where the EIA procedure has been introduced, various methodological tools are developed to aid this process, so uniform potential of environmental impact evaluation in the screening process of proposed action could be made, and a decision as to whether the activity should complete an environmental impact assessment procedure could be taken. In most cases, such aids are made as questionnaires or a matrix.

The criteria of the significance of the impact include the description of the threshold value for identification [64]. The threshold values in Latvia are environmental quality standards, emission limit values and other limits and restrictions set in various legislation. Since the various restrictions and environmental quality standards vary in different areas and for various types of activities, then in most cases the significance of impacts are assessed individually in each case. Often the significance of the impact is not only dependent on the type and amount of hazard of the planned action, but also the characteristics of the selected place have an important role. In some cases, the impacts of small objects which do not exceed the allowable thresholds are potentially dangerous if they are planned in a sensitive or congested area; therefore, these projects are applied to the EIA procedure. But at the same time, the relatively large objects with possible impact parameters similar to EIA application volumes may not require the application of the EIA procedure because of the optimal choice of location and the projected technology that allows the impacts to be reduced to insignificant levels.

So we can say that the screening stage is one of the most important and responsible steps in the process of the EIA. A faulty decision could lead to substantial financial loss for the future performance of the project, if an unreasonable decision is made to apply the full environmental impact assessment procedure, which requires substantial investments in both time and finances for the project.

Perhaps even greater losses are possible if technical regulations are not fully prepared because the possible impact is not fully assessed for the proposed action, and the implementation of the project has already started, while not realizing the potential problem situations and risk factors resulting in damage to the environment. It is known that in most cases, the consequences of the negative effects requires more resources and time than measures that could have prevented or reduced the possibility of the damage caused.

The EIA procedure in Latvia has been used for more than 10 years. A lot of projects were analysed during these years.

If a classification of Latvia's biogas plants is needed, then they can be classified into 3 groups according to the used substrate:

- Stations which produces biogas from wastewater treatment;
- Stations where biogas is produced from the deposited waste of landfills;
- Stations where livestock and agricultural waste is used for biogas production.

What kind of biogas plants will be built in the future depends on several related factors. State support for electricity production from renewable energy resources (including biogas) is provided by the regulations of the Cabinet of Ministers. The regulations include

a number of criteria for electricity producers from biogas to qualify for the mandatory purchase of electricity and ensure that the power producer will be able to sell electricity at a fixed price. When the situation is viewed from this perspective, it would be best for producers to build small plants, as this will provide more profit for each kilowatt hour produced. However, it should be kept in mind that the main criteria that the producer has to use while choosing what kind of station to install remains the availability of the used substrate and possibilities for the usage of produced energy [151].

As for the possible biogas plants in the future, there is a great potential for bird and pig farms, as well as regional landfills. Latvia is divided into 11 waste management regions. Despite the development of new landfills, the organic fraction is not yet sorted from the stream of municipal solid waste in Latvia. In theory, all regional landfills are potential biogas producers, if the gas is obtained from sorted organic waste [152].

There are many landfill sites in Latvia where biogas production is possible, but the collection system of biogas is not yet built; however, the construction of such a system is planned for the future. During the period from 2008 to December 2012 the screening step was performed for 39 projects that have been classified as a biogas plant or a biogas cogeneration plant in Latvia. These projects are summarized and shown in Figure 3.9.

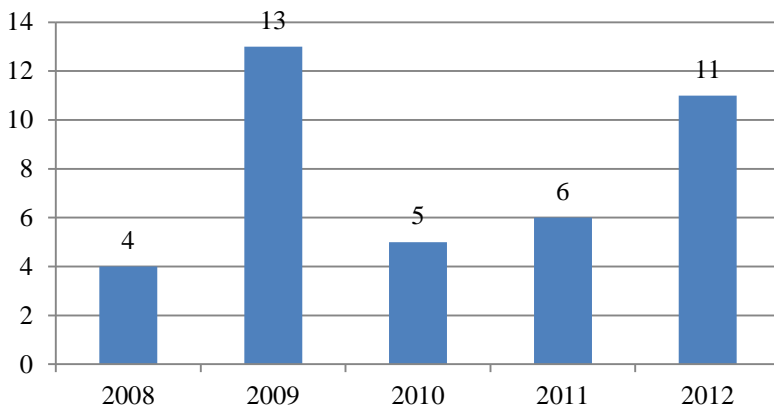


Figure 3.9. Biogas production projects for which the screening step has been made from 2008 to 2012

As shown in Figure 3.9., most of the procedures of the screening step for biogas projects in the given period were completed in 2009, when the estimated number of projects was 13.

So far, a full EIA procedure has not been applied or performed for any biogas plants. By contrast, an A or B permit of polluting activities has been issued for 30 projects of biogas cogeneration facilities up until now. From these 30, the screening step has been completed for only 8 projects of biogas cogeneration plants. This means that the total amount of biogas planned plants is about 70.

Not always can the successfulness of a particular biogas plant be assessed according to its individual technical specifications. Therefore, it is worthwhile to compare technical parameters of planned and already constructed plants. To compare the effectiveness of biogas plants in Latvia, the amount of biogas produced from one tonne of waste can be compared. Also, a good way to measure the yield of biogas is to compare the amount of

biogas produced with the power of cogeneration plants where the produced biogas will be burnt.

### 3.2.2. Feedstock for anaerobic digestion plants in Latvia

The total amount of substrates used for the production of biogas at the end of 2012 was approximately 1,000,000 tonnes per year. The substrates used for biogas production are corn, manure, green fodder, biowaste, sludge, distillery refuses, and landfill gas. The percentages of substrates used for the production of biogas are shown in Figure 3.10.

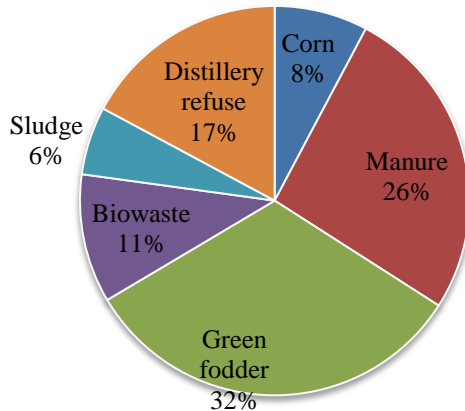


Figure 3.10. Substrates used for the production of biogas in Latvia (without landfill gas)

Almost all biogas plants use different substrates for the production of biogas. The exceptions are only one landfill gas and one biogas plant producing biogas from wastewater sludge in the city of Riga. The total installed capacity (electrical and heat power) is approximately 40 MW, but at the same time heat is only used - in a few cases.

This means that in many cases the heat from the Cogeneration Heat Plant unit is not used, but wasted. New solutions must be found for the sustainable use of the biogas produced.

Twenty five stations where livestock and agricultural waste is used for biogas production and one station, which produces biogas from wastewater treatment, were analysed during the research.

The substrates used in these plots are shown in Figure 3.11.

The type of substrate used for biogas production affects the amount of produced biogas, therefore the amount of substrate and capacity of the plant varies greatly. For example, from one tonne of corn it is possible to produce 202 m<sup>3</sup>/t of biogas, and at the same time from the same amount of manure it is possible to produce only 25 m<sup>3</sup>/t of biogas.

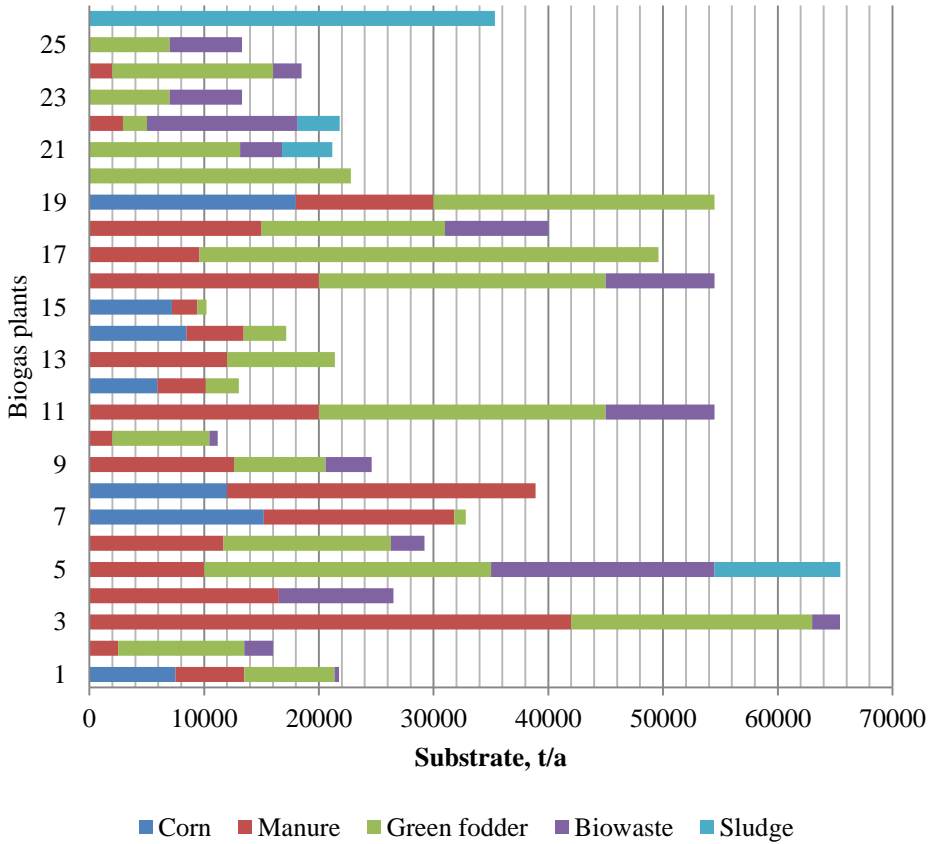


Figure 3.11. Use of substrates in biogas plants

As well, the amount of biogas produced depends on the plant system, temperature, and retention time. The organic load can influence the composition of the biogas substantially.

The division of anaerobic fermentation into wet and dry fermentation is only theoretical, microbiological processes take place in a wet environment. The difference is in the pumping characteristics of the substrate.

The composition of biogas varies. Mainly, the biogas composition depends on the type of substrate that has been used for biogas production. Mainly carbon monoxide (CO), which is a product of incomplete combustion, and nitrogen oxide compounds (NO<sub>x</sub>) is emitted while burning biogas. Both of the above-mentioned gases are considered greenhouse gases.

Methane yields of selected feedstock are shown in Table 3.1.

Table 3.1.

Methane and biogas yields [13]

Substrate/Feedstock	Methane yield, %	Biogas yield, m <sup>3</sup> /t
Wet cattle manure	60	25
Wet pig manure	65	28
Distillery refuse	61	40
Cattle manure	60	45
Pig manure	60	60
Poultry manure	60	80
Biowaste	61	100
Green fodder	54	172
Corn fodder	52	202

This table shows that corn fodder is one of the best substrates, because of the high biogas yield. In spite of this, only 7 of 35 biogas plants use corn fodder as a substrate for the production of biogas in Latvia.

In Figure 3.12., the most commonly used feedstock for biogas production in Latvia is shown. The most popular feedstocks are green fodder, manure, and biowaste.

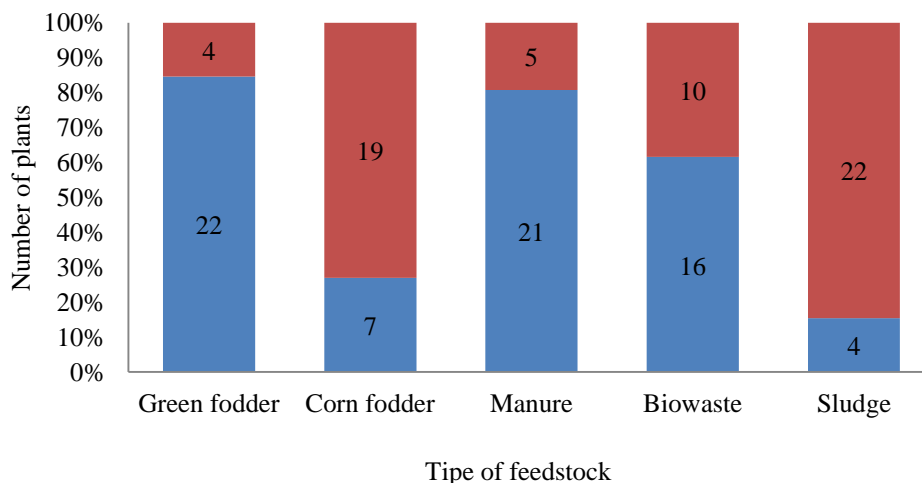


Figure 3.12. Substrates used for biogas production in Latvia

### 3.3. Impact assessment of anaerobic digestion plants

Special attention during the evaluation of biogas plants should be paid to these essential criteria: sustainability of the biogas plant; impact on air quality; occurrence of odours; occurrence of noise; impact on soil; impact on water; and safety aspects of the station.

### **3.3.1. Sustainability of biogas plants**

The sustainability of a biogas plant is one of the most important aspects of a biogas plants' EIA. The first biogas plants in Europe, as well as the largest part of the existing biogas plants in Latvia, operate inefficiently, because the heat from the CHP unit is unused or not maximised. Therefore, it is very important at the first stages of a project assessment to select projects for future development with an effective use of electricity and heat. In the future, it is necessary to develop biomethane projects, as well as projects where state-of-the-art technologies are used.

The operation of a biogas plant is related to different types of emissions going into the environment. If not treated properly, these emissions may leave an important impact on the environment as well as human health.

### **3.3.2. Impact on air quality**

According to Latvian law, while modelling air emissions, any available and accepted methods in the world can be used for calculating emissions. That leads to a situation where different companies use different emissions modelling methods and different emission factors. As a result, it is not possible to objectively evaluate the estimated emissions from various plants. In addition, at the moment companies often use the emission factors of natural gas during the modelling process, which should be unacceptable because biogas composition differs from natural gas composition.

It is therefore necessary to develop a uniform methodology for the calculation and modelling of air emissions of biogas plants.

### **3.3.3. Occurrence of odours**

Substrates used for the production of biogas' volatile organic compounds (e.g. isobutyric acid, butyric acid, iso-valeric acid, and valeric acid, along with at least 80 other compounds) produce unpleasant odours.

Anaerobic digestion significantly reduced the concentration of many of these compounds, such that their potential for giving rise to offensive and lingering odours during storage and distribution has been significantly reduced. Thereafter, the use of appropriate distribution methods can prevent the release of any residual odour. Therefore, it is important to minimize the disturbance of the excrement during its transfer from the storage tank [153].

In the case of biogas projects, public awareness and participation is an important factor for successful project implementation. It is very important to inform the public about the project in the very first stage of the development of the project.

### **3.3.4. Occurrence of noise**

The Combined Heat and Power station has to comply with European noise regulations. Noise emissions during the biogas production derive mainly from the production machines – air and exhaust fans, the cooler of the mixer, and the flue. Similarly, noise also arises from the transport which delivers the raw material to the biogas plant. If most of the noise from the production installations is unavoidable, then in relation to noise arising from transport, it can be optimized by planning the transportation of raw materials during the day.

### 3.3.5. Impact on soil

In accordance with Latvian legislation, territories where pollution may have an increased effect on human health or the environment and its biological diversity, or the territories that are highly sensitive to pollution load shall be known as highly sensitive territories [154]. The largest portion of biogas plants in Latvia is located in highly sensitive territories (see Figure 3.13.).

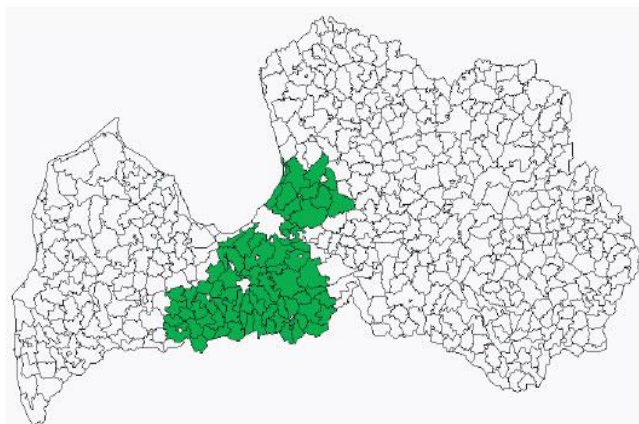


Figure 3.13. Highly sensitive territories [155]

During the evaluation of environmental impacts in highly sensitive territories, special attention must be paid to the use of excrement and protection against leakage during the running of a biogas plant.

Emissions to water bodies have to be avoided during the operation of a biogas plant [156].

### 3.3.6. Impact on water

As well, all related water regulations have to be considered. In accordance with Latvian regulation, the minimum distance between watercourses needs to be between 10 and 500 m depending on the size of the water source [157].

### 3.3.7. Safety aspects of the station

In the permit required for a biogas plant to run, it is necessary to include an assessment of various preventive and damage control measures. In such cases these include: explosion prevention; fire prevention; mechanical hazards; sound-proof design; electrical safety; lightning protection; thermal safety; asphyxiation and poisoning prevention; hygiene; and health and safety.

## 3.4. Analysis of energy efficiency of the anaerobic digestion plants

During the energy efficiency research, 33 biogas cogeneration plants were analysed. The installed capacity of these plants varies from 0.25 to 6,28 MW. Figure 3.14 shows the installed capacities of biogas cogeneration plants.

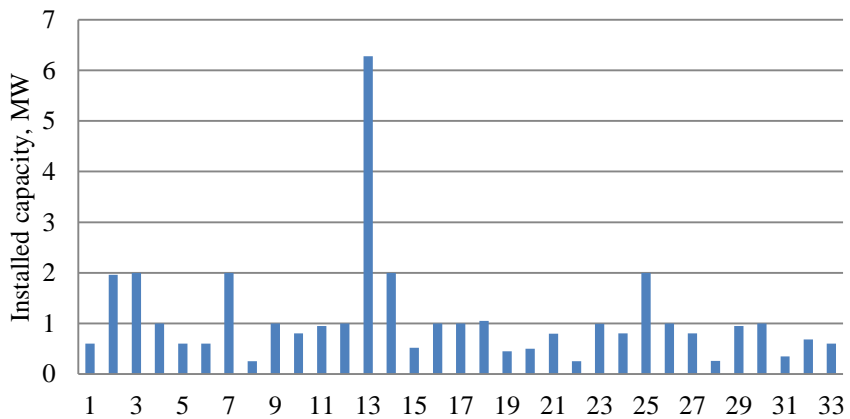


Figure 3.14. Installed capacity of biogas cogeneration plants

Biogas cogeneration plants operate with varying capacity, and only a few plants are currently operating at full capacity throughout the whole year. This leads to an additional load to the environment. The operation ratio (10) is written as follows:

$$K = E_{\text{actual}} / P * \tag{3.1.}$$

where

K - operation ratio;

E - actual electricity generation, MWh/year

P - installed capacity, MW;

□ - operation h/year (assumption 8000 h/year).

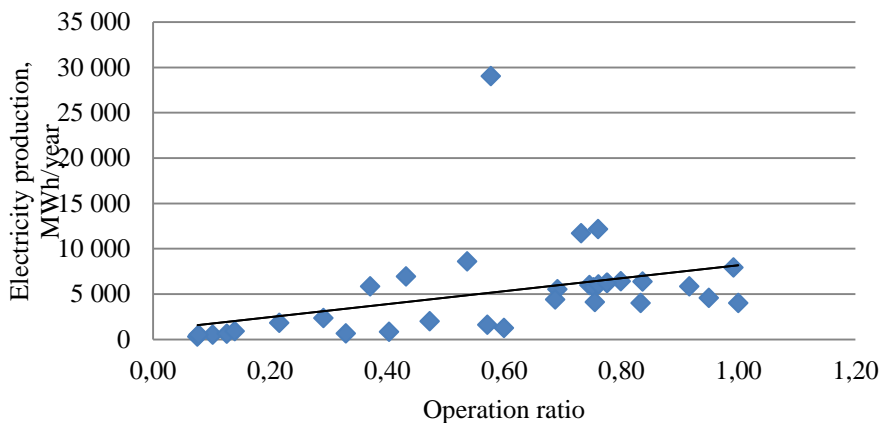


Figure 3.15. Production of electricity depending on operation ratio

The Figure 3.15 shows that the majority of the biogas cogeneration plants operate part-time, with partial capacity. Only four stations operate with an optimal load in accordance with the projected capacity. These plants have feed-in tariffs, and the production of electricity is economically feasible. As well, there is a tendency that demonstrates that the production of electricity is higher when a power station operates with

a full load throughout the year. Therefore, an analysis and impact assessment of biogas plants must be done during a period of operation.

### 3.5. 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 3.2.

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 <sup>3</sup> /t of biowaste	Min
	Water usage	m <sup>3</sup> /t of biowaste	Min
Technical	Fossil fuel substitution	%	Max
	Biogas production	m <sup>3</sup> /t of biowaste	Max
	Energy consumption	kWh/t of biowaste	Min
	Energy production	kWh/t of biowaste	Max
Economic	Heat production	kWh/t biowaste	Max
	Operational costs	€/t of biowaste	Min
	Capital costs	€/t of biowaste	Min
Social	External environmental damage costs	€/t of biowaste	Min
	Public participation and acceptance	%	Max

Values for the environmental dimension included greenhouse gas emissions [141], leakage [157], water usage [157], and fossil fuel substitution [159]. Indicators were taken both from the literature and from Latvian waste management companies.

Values for the technical dimension included biogas production [136], energy consumption [136, 157], energy production [136, 158], and heat production [136]. Again, indicators were taken from both the literature and from Latvian waste companies.

For the economic value, data from the European Commission [159] 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 3.3.).

Table 3.3.

Designation of biowaste treatment scenarios	
Designation	Biowaste handling practice
A <sub>1</sub>	Separate collection - Anaerobic Digestion
A <sub>2</sub>	Separate collection – Composting
A <sub>3</sub>	MBT - mechanical biological pre-treatment – Anaerobic Digestion
A <sub>4</sub>	MBT - mechanical biological pre-treatment – composting
A <sub>5</sub>	Incineration with energy recovery
A <sub>6</sub>	Incineration without energy recovery
A <sub>7</sub>	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 (see Figure 3.16.).

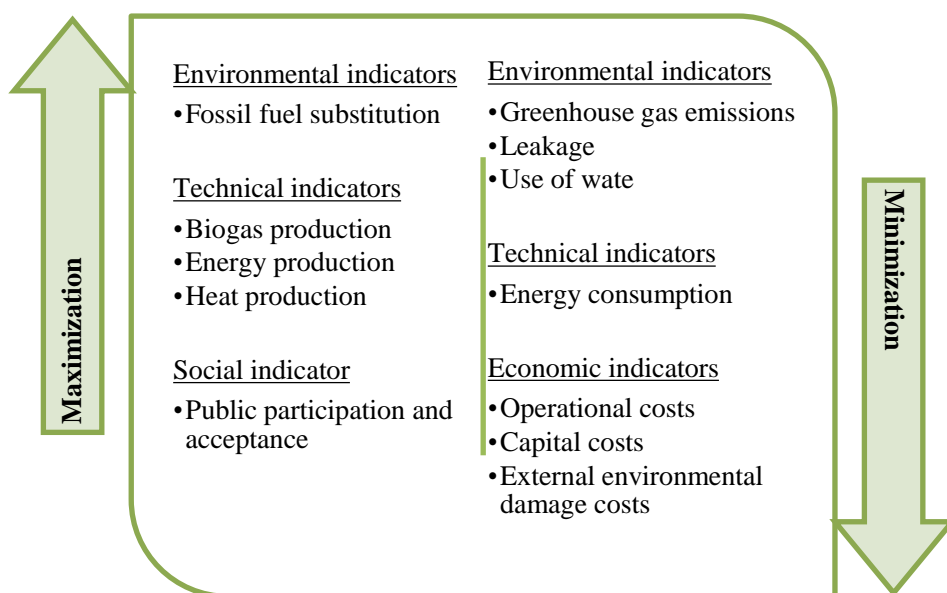


Figure 3.16. Cleaner production indicators in biowaste management

## **4. TESTING OF METHODOLOGY FOR THE INTEGRATION OF CLEANER PRODUCTION INTO BIOWASTE MANAGEMENT**

### **4.1. Multi-Criteria Analysis of biowaste management scenarios**

Multi-Criteria Analysis is used to identify compromises for resolving complex policy planning problems like waste management [160].

The advantage of the MCA method is that it allows the preferred alternative among several to be determined. Maimone (1985) [161] was one of the first to use MCA to evaluate different solid waste treatment systems. MCA studies on landfills [162, 163] and waste incinerators [164, 165] have also been completed.

A number of tools have been used to do MCA studies. The most commonly applied method is Elimination and Choice Expressing Reality (ELECTRE III) [166 -168], as well as Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE) [169], The Analytic Hierarchy Process (AHP) [170] and Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) [171] have also been used.

However, there is still a lack of research which has been carried out on combining complementary environmental evaluation tools in waste management. Herva and Roca [172] ranked MSW treatment alternatives based on footprint methodology and MCA. Dong et.al. [171] used the combination of life cycle assessment (LCA), life cycle costing (LCC), and MCA to evaluate municipal waste management systems.

In both studies, the results of additional methodologies were used to implement the MCA in addition to the ecological footprint indicator expressed as a single measure, Herva and Roca [172] included the use of five criteria in carrying out the MCA. These were water consumption, air emissions from organic compounds, air emissions from dust, suspended solids in water, and occupied landfill volume. Dong et.al. [171] used LCA and LCC calculations to implement the MCA and evaluate MSW using factors weighted for energy, the environment, and the economy.

#### **4.1.1. Methodology of Multi-Criteria Analysis**

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 [158], and the assessment of the sustainability within different renewable energy systems [173]. 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 [163].

Within this study, the adoption of a multi-criteria analysis is proposed as a suitable solution for the evaluation of the multi-faceted benefits and/or impacts of different biowaste scenarios. The evaluation of the level of sustainability is one of the key factors to be evaluated.

Within a multi-criteria analysis, this is illustrated by considering different spheres of interests. These spheres cover the environmental, financial, socio-economic [174], and technical perspectives [163]. Earlier tools highlighted the importance of the Life Cycle

Assessment. Where shifting the burden is avoided by incorporating an holistic approach, the LCA methodology was found to be a valid and useful tool. However, a lack of a clear and adequate indicator for the social aspect has proven to be a shortcoming of the method and a potential bottleneck [175].

In light of the aforementioned reasons, the multi-criteria analysis provides a good tool for decision-making, when selecting the optimal solution among the available alternatives.

The multi-criteria analysis is useful in terms of providing quantitative solutions to qualitative problems, which can help decision-makers make justifiable choices. Several papers provide guidelines on how to finalize a multi-criteria analysis [176] a brief description follows:

1. definition of the problem (base scenario);
2. definition of an evaluation matrix (i.e. main actors in process, alternative strategies);
3. definition of the potential tools to be implemented;
4. criteria evaluation;
5. criteria weights;
6. aggregation of weighted results;
7. ranking of the scenarios;
8. results of the discussion and recommendations.

The most obvious bottleneck in the whole system is the socio-economic aspect. Its complexity makes evaluation difficult. Representation using quantitative models increases the inaccuracy and, consequently, obscures the significance of the structural elements of the full model.

A simple choice for the evaluation of the sustainability assessment of a system among impact criteria is proposed by Nzila et al. [175] who defined a set of measurable criteria for a reliable and valid quantitative judgement in relation to the environmental, technical, and economic dimensions. In this way it is shown that the sustainability indicators can be used as a benchmark, thereby aiding the decision-making process.

Coming to a “single-score”, final result of sustainability through the multi-criteria analysis is a complex task. In fact, most of the time is spent on developing an articulated system in which the majority of indicators offer a holistic view of a final, simplified way on how to provide information about the level of sustainability to decision-makers and the general public.

For the evaluation and finding of the optimal treatment scenario, TOPSIS (the Technique for Order of Preference by Similarity to Ideal Solution) was applied. TOPSIS was developed by Hwang and Yoon [177].

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 [178].

The basic element of TOPSIS analysis is a data matrix, where evaluation criteria are represented by  $x_1, x_2, \dots, x_j, \dots, x_n$  (see Figure 4.1.).

$$\begin{matrix}
& & x_1 & x_2 & \cdots & x_j & \cdots & x_n \\
A_1 & \left[ \begin{array}{cccccc}
x_{11}^k & x_{12}^k & \cdots & x_{1j}^k & \cdots & x_{1n}^k \\
x_{21}^k & x_{22}^k & \cdots & x_{2j}^k & \cdots & x_{2n}^k \\
\vdots & \vdots & \cdots & \vdots & \cdots & \vdots \\
x_{i1}^k & x_{i2}^k & \cdots & x_{ij}^k & \cdots & x_{in}^k \\
\vdots & \vdots & \cdots & \vdots & \cdots & \vdots \\
x_{n1}^k & x_{n2}^k & \cdots & x_{nj}^k & \cdots & x_{nn}^k
\end{array} \right.
\end{matrix}$$

Figure 4.1. TOPSIS decision-making matrix

Different criteria used in analysis have different dimensions. Value normalization shall be carried out in order to make these data comparable and, afterwards, to rank alternatives in accordance to how closely they resembled the Positive Ideal Solution. In this case, normalized values ( $b_{ij}$ ) were obtained using Jüttler's -Körth's [179] linear normalization method.

$$b_{ij} = \frac{\max x_{ij} - x_{ij}}{\max x_{ij} - \min x_{ij}} \quad (4.1)$$

if max  $x_{ij}$  is preferable;

$$b_{ij} = \frac{x_{ij} - \min x_{ij}}{\max x_{ij} - \min x_{ij}} \quad (4.2)$$

if min  $x_{ij}$  is preferable.

Normalized data were also arranged in a matrix and then weighted by multiplying them with the weights given to the criteria ( $w_j$ ) (see Figure 4.2.)

$$\begin{matrix}
& & w_1 b_1 & w_2 b_2 & \cdots & w_j b_j & \cdots & w_n b_n \\
A_1 & \left[ \begin{array}{cccccc}
w_1 b_{11}^k & w_2 b_{12}^k & \cdots & w_j b_{1j}^k & \cdots & w_n b_{1n}^k \\
w_1 b_{21}^k & w_2 b_{22}^k & \cdots & w_j b_{2j}^k & \cdots & w_n b_{2n}^k \\
\vdots & \vdots & \cdots & \vdots & \cdots & \vdots \\
w_1 b_{i1}^k & w_2 b_{i2}^k & \cdots & w_j b_{ij}^k & \cdots & w_n b_{in}^k \\
\vdots & \vdots & \cdots & \vdots & \cdots & \vdots \\
w_1 b_{n1}^k & w_2 b_{n2}^k & \cdots & w_j b_{nj}^k & \cdots & w_n b_{nn}^k
\end{array} \right.
\end{matrix}$$

Figure 4.2. Normalized and weighted data matrix

The next step of the TOPSIS analysis is the determination of the Positive and Negative Ideal solution.

Positive Ideal solution

$$A^+ = \text{Max}_i w_j b_{ij} \quad (4.3)$$

Negative Ideal solution

$$A^- = \text{min}_i w_j b_{ij} \quad (4.4)$$

Separation from Positive Ideal solution ( $S^+$ ) is calculated by the following formula:

$$S^+ = \sqrt{\sum_{j=1}^n (v_{ij} - v_j^+)^2}, \quad i=1,2,\dots,m \quad (4.5)$$

Separation from the Negative Ideal solution:

$$S^- = \sqrt{\sum_{j=1}^n (v_{ij} - v_j^-)^2}, \quad i=1,2,\dots,m \quad (4.6)$$

The last step is the calculation of alternatives Relative Closeness to the Ideal Solution:

$$C_i^* = \frac{S_i^-}{(S_i^+ - S_i^-)}, \quad i=1,2,\dots,m \quad (4.7)$$

The obtained number is in the range [0;1] and shows the alternative rating. If  $C_i^* = 1$ , the alternative is equal to the Ideal solution, if  $C_i^* = 0$  it is the opposite of the Ideal solution. The closer the rating is to 1, the better the alternative.

The input data for a TOPSIS biowaste treatment alternative analysis are shown in Table 4.1.

Table 4.1.

Input data for a TOPSIS biowaste treatment alternative analysis

Criterion Altern.	Environmental dimension				Technical dimension			
	GHG emissions	Leakage	Fossil fuel substitution	Water usage	Biogas production	Energy consumption	Energy production	Heat production
A <sub>1</sub>	0,49	0	0,63	0,14	110	20	250	250
A <sub>2</sub>	0,49	0	0	0	0	52,5	0	0
A <sub>3</sub>	0,7	0	0,355	0,05	75	40	145	140
A <sub>4</sub>	0,7	0	0	0	0	20	0	0
A <sub>5</sub>	0,36	0	1,44	0	0	142	450	1000
A <sub>6</sub>	0,36	0	0	0	0	142	0	0
A <sub>7</sub>	1,47	0,145	0,22	0,052	20	2,8	23	20

Criterion	Economical dimension							Social dimension		
	Operational costs $w_9b_{i9}$			Capital costs $w_{10}b_{i10}$			External environ. damage costs	Social participation and acceptance $w_{12}b_{i12}$		
	LV	LT	EE	LV	LT	EE		LV	LT	EE
Altern.										
A <sub>1</sub>	28,00	28,00	29,00	376	376	381	22,24	5	5	5
A <sub>2</sub>	8,00	8,00	8,00	124,5	125,5	127,5	8,66	6	6	3
A <sub>3</sub>	28,00	28,00	29,00	372	376	381	22,24	2	2	6
A <sub>4</sub>	14,00	14,00	14,50	176	178,5	181,5	8,66	3	3	4
A <sub>5</sub>	20,00	20,00	21,00	651	635	640	12,63	4	4	4
A <sub>6</sub>	22,00	22,00	22,00	631	655	661	19,95	7	7	1
A <sub>7</sub>	5,00	5,00	5,00	119	120	122	62,09	1	1	2

#### 4.1.2. Normalized and weighted decision-making matrix

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 are displayed in Table 4.2.

Table 4.2.

Normalized and weighted decision-making matrix for Latvia

Criterion	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 $w_8b_{i8}$	
Altern.									
A <sub>1</sub>	0.0234	0	0.0563	0.07	0	0.0124	0.0444	0.075	
A <sub>2</sub>	0.0234	0	0.1	0	0.1	0.0357	0.1	0.1	
A <sub>3</sub>	0.0613	0	0.0753	0.025	0.0318	0.0267	0.0678	0.086	
A <sub>4</sub>	0.0613	0	0.1	0	0.1	0.01236	0.1	0.1	
A <sub>5</sub>	0	0	0	0	0.1	0.1	0	0	
A <sub>6</sub>	0	0	0.1	0	0.1	0.1	0.1	0.1	
A <sub>7</sub>	0.2	0.07	0.0847	0.026	0.0818	0	0.0949	0.098	

Criterion	Economical dimension							Social dimension		
	Operational costs $w_9b_{i9}$			Capital costs $w_{10}b_{i10}$			Exter. environ. dam. costs $w_{11}b_{i11}$	Social participation and acceptance $w_{12}b_{i12}$		
	LV	LT	EE	LV	LT	EE		LV	LT	EE
Altern.										
A <sub>1</sub>	0.1	0.1	0.1	0.0476	0.0479	0.0481	0.0305	0.0333	0.0333	0.02
A <sub>2</sub>	0.013	0.013	0.0125	0.001	0.001	0.001	0	0.0167	0.0167	0.06
A <sub>3</sub>	0.1	0.1	0.1	0.0476	0.0479	0.0481	0.0305	0.0833	0.0833	0
A <sub>4</sub>	0.0391	0.0391	0.0396	0.0107	0.0109	0.011	0	0.0667	0.0667	0.04
A <sub>5</sub>	0.0652	0.0652	0.0667	0.1	0.0963	0.0961	0.0089	0.05	0.05	0.04
A <sub>6</sub>	0.0696	0.0739	0.0708	0.0962	0.1	0.1	0.0254	0	0	0.1
A <sub>7</sub>	0	0	0	0	0	0	0.12	0.1	0.1	0.08

### 4.1.3. Results of MCA

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 ( $C_i$ ). 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 4.3). 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.

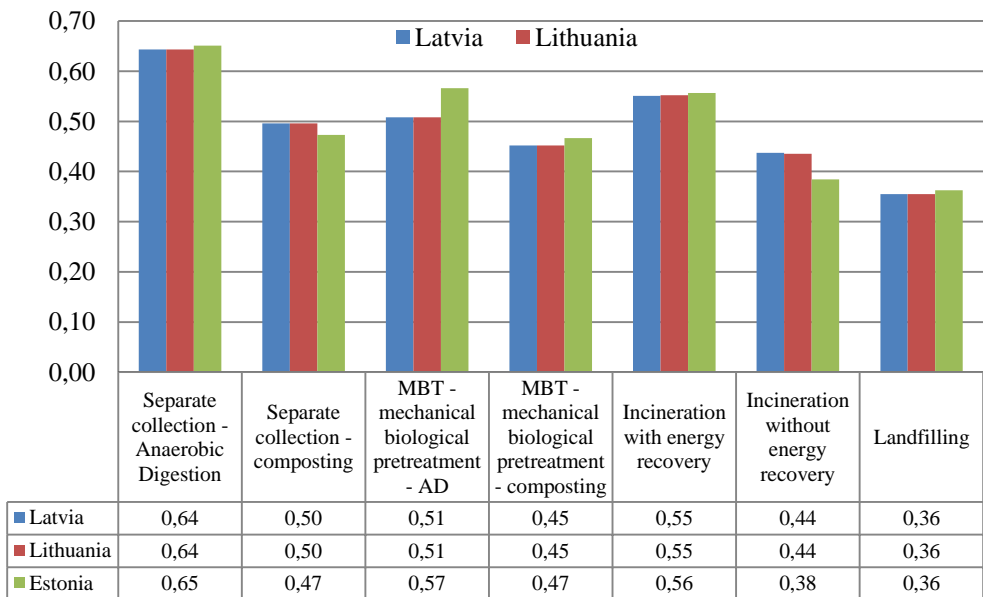


Figure 4.3. Comparison of ratings

## 4.2. 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 [180, 181]. 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.

#### 4.2.1. Data correlation analysis of the reduction of GHG emissions

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,

$$r = \frac{\sum_{i=1}^m (x_i - x)(y_i - y)}{(m-1)S_x * S_y}, \quad (4.8.)$$

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 4.4.

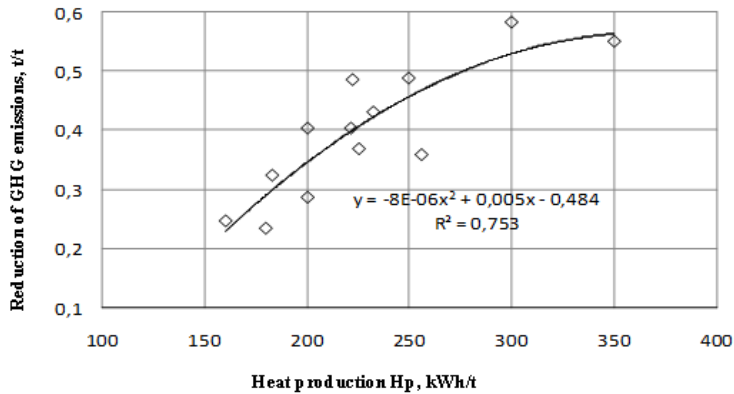


Figure 4.4. Decrease in GHG emissions depending on heat production

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:

$$GHG = -8E - 06.Hp^2 + 0,005.Hp - 0,484 \quad (4.9)$$

Equation (4.9) 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 4.5.

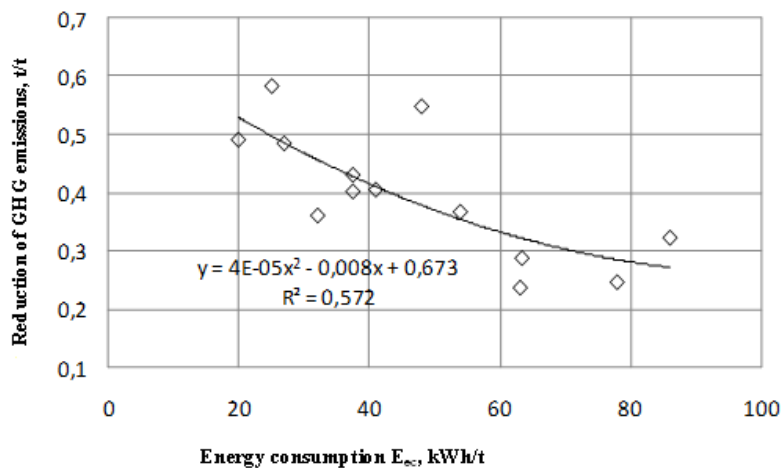


Figure 4.5. Reduction of GHG emissions depending on energy consumption

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:

$$GHG = 4E - 05.Eec^2 + 0,008Eec + 0,673 \quad (4.10)$$

As the mutual correlation of magnitudes is worse, the equation (4.10) 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.

$$GHG = f(Eec; Eep; Hp) \quad (4.11)$$

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.

#### 4.2.2. Regression analysis of data from the reduction of GHG emissions

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 [182]. 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 4.6. On a logarithmic graph, a normal distribution is graphed as a straight line. In Figure 4.6, 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.

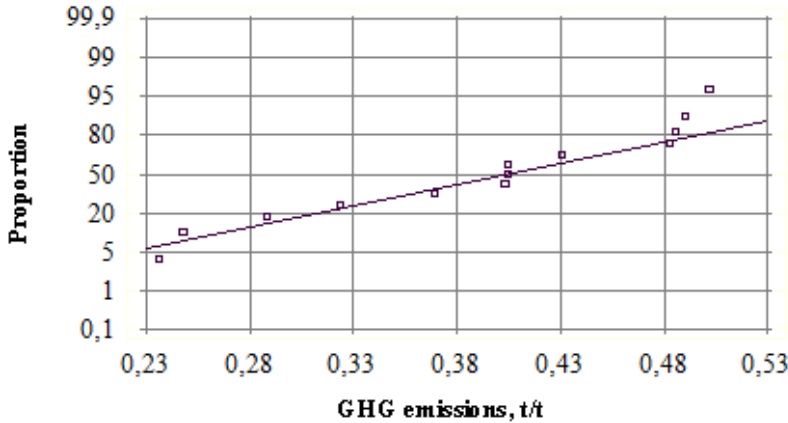


Figure 4.6. Distribution of GHG emission values

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 [182].

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

$$y = b_0 + b_1x_1 + b_2x_2 + \dots + bx = b_0 + \sum_{i=1}^n b_i x_i, \quad (4.12)$$

where

- y – dependent variable magnitude;
- $b_0$  – free agent of the regression;
- $b_1 \dots b_n$  – regression coefficients;
- $x_1 \dots x_n$  – independent variable magnitudes.

The regression equation obtained as a result of the statistical analysis corresponding to expression (4.8) includes statistically significant independent variables

$$GHG = b_0 + b_1 \cdot E_{ec} + b_2 \cdot E_{ep} + b_3 \cdot H_p \quad (4.13)$$

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 4.3.

Table 4.3.

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  $b_0 \dots b_n$  of the regression equation (4.13), criterion t is used, which has a Student distribution with f degrees of freedom

$$f = m - (n + 1), \quad (4.14)$$

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 Student distribution tables is  $t_{tab} = 1.9$ . As shown in Table 5.1, the relationship in all cases is  $t > t_{tab}$ .

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:

$$GHG = 0,2874 - 0,00241 \cdot E_{ec} + 0,000257 \cdot E_{ep} + 0,000653 \cdot H_p \quad (4.15)$$

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 (4.15) 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.

### 4.2.3. Evaluating the adequacy of the regression equation

The assessment of the adequacy of the equation (4.15) 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:

$$F(f_1, f_2) = \frac{S_y^2(f_1)}{S_{rem}^2(f_2)}, \quad (4.16)$$

where

$S_y^2(f_1)$  – dependent variable magnitude y dispersion;  
 $S_{rem}^2(f_2)$  – 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 (4.15) 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.

#### 4.2.4. Verifying the proper applicability conditions of a regression analysis

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, multi-colinearity 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 4.4.

Table 4.4.

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 4.3. The values observed in Table 4.3 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 4.7.

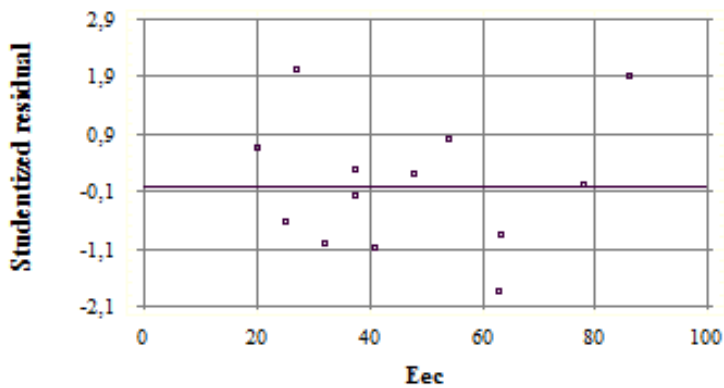


Figure 4.7. Remainder distribution depending on the energy consumption of a biogas plant

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 (4.15) 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 4.8 shows this data comparison as a graph.

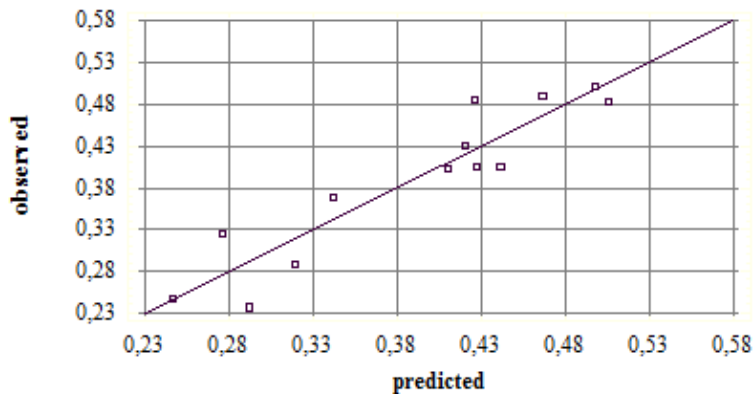


Figure 4.8. A comparison of analysable and calculated data showing a reduction of GHG emissions

As shown in Figure 4.8., 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.

### 4.3. System Dynamics model

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 Figure 4.9. This diagram is used to analyse the structure and behaviour of the biodegradable waste market.

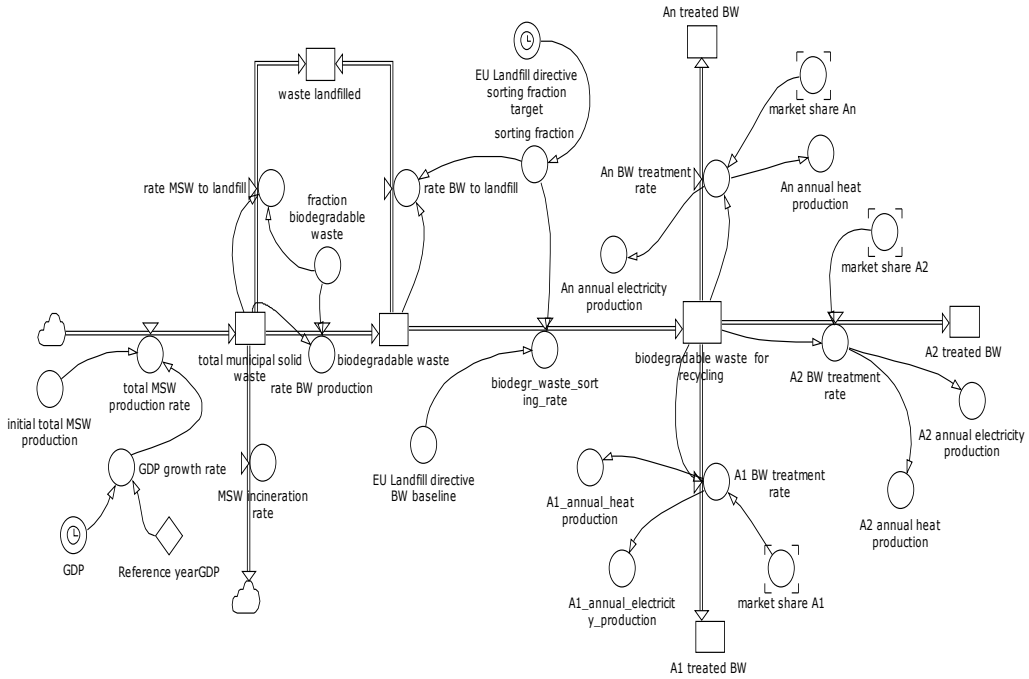


Figure 4.9. General stock and flow diagram

The results obtained in the TOPSIS analysis for each market share of alternative technological option are integrated into the system dynamics model using the multinomial logit model [183]:

$$MS_i = \frac{\exp^{-\alpha C_i}}{\sum_j \exp^{-\alpha C_j}} \quad (4.17)$$

where

$MS_i$  – market share of alternative;

$\alpha$  - 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:

$$Q_{BWR} = \int_{t=0}^{t=1} (BL_{BW} \times SF - \sum_{i=1}^n MS_i \times Q_{BWR})(t) \times dt + Q_{BWR}^{init} \quad (4.18)$$

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, %;

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

The total municipal solid waste generated annually depends on the GDP growth rate [136]. 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 [2] 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 [2] 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.

#### 4.3.1. System Dynamics modelling

TOPSIS results, shown in Figure 4.3 for each country, were entered into the dynamic system model shown in Figure 4.9. 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 analysed 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 Figure 4.10.

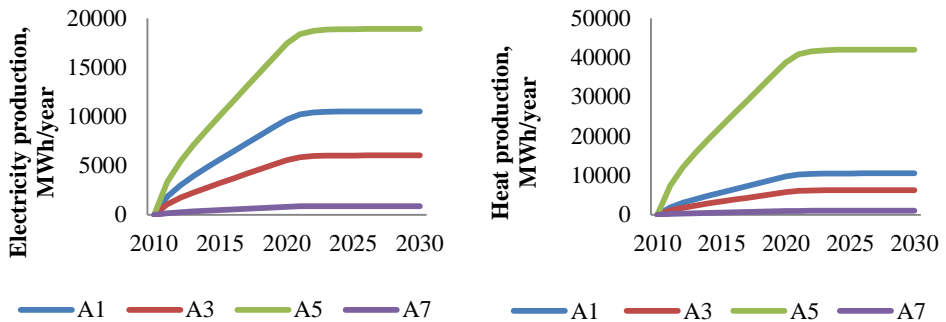


Figure 4.10. Simulated annual heat and electricity production rates for different biowaste treatment technological alternatives in Latvia

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.

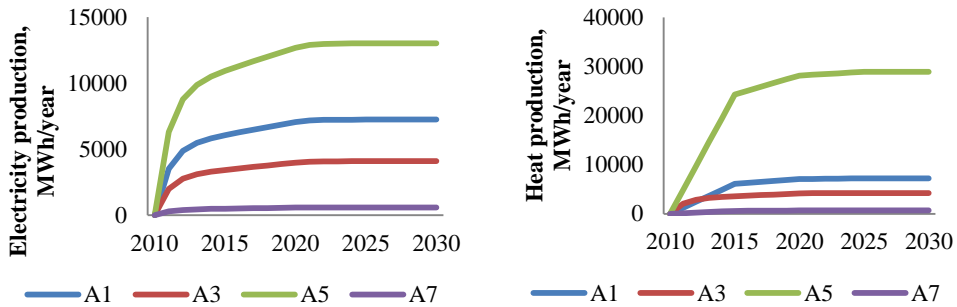


Figure 4.11. Simulated annual heat and electricity production rates for different biowaste treatment technological alternatives in Estonia

In Estonia, alternative A5 could be used to produce 29 GWh of heat energy and 13 GWh of electrical energy in 2030. Seven GWh/year each of heat energy and electrical energy could be produced using alternative A1, and, using alternative A3, four GWh of each type of energy could be produced annually (see Figure 4.11.). In Lithuania, by 2030, alternative A5 could produce 70GWh of heat energy and 31 GWh of electrical energy (see Figure 4.12.). Using alternative A1: 17 GWh of each could be produced, and using alternative A3, ten GWh of each type of energy could be produced.

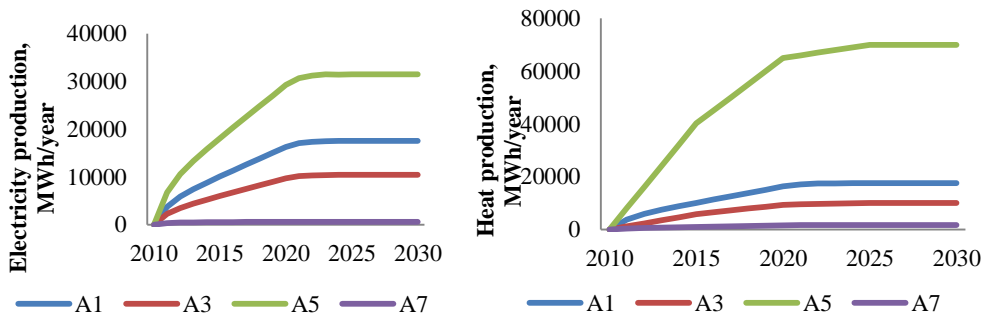


Figure 4.12. Simulated annual heat and electricity production rates for different biowaste treatment technological alternatives in Lithuania

## 5. DISCUSSIONS

The ultimate goal of this research was to develop an effective framework to assess, compare, and screen biowaste management alternatives that stakeholders can apply to their specific situations. For this purpose, a modelling framework for the assessment of biowaste management alternatives based on a combination of MCA and CRA and MCA and SD modelling have been created. The aim of the proposed method implemented in the modelling tool is mainly 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.

The results obtained in the MCA analysis for each market share of the alternative technological option are integrated into the SD model using the multi-nominal logit model.

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.

However, the modelling framework for the combination of both MCA and SD approaches may provide an instrument for decision-making support which can then envision future developments, rather than for exact predictions of the future. The application of the proposed modelling framework has to be an iterative process since many factors used in this study may change over time. For this reason, the SD model has been consciously created in a simplified fashion to illustrate the combination of both MCA and SD approaches in the field of waste management. Yet if required, it can be supplemented with waste sorting, environmental taxes, technological learning processes, etc. Future research based on the results of this study should take into account national borders, and the level of detail available. The SD model depends on the specific problems of the subject area under review. The structure of the SD model has been developed from interviews with experts in the field, for this reason a more accurate sensitivity analysis and consistent model validation should be carried out. A sensitivity analysis should also be devoted to the weighing used within the TOPSIS analysis. A Life Cycle perspective in terms of environmental and costs assessment should be integrated in order to increase the quality of the data used within the MCA analysis.

A set of extended criteria should also be evaluated in order to evaluate the real effect on the outcomes in respect to the first set of criteria selected.

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.

The completed analysis shows that:

- the reduction of GHG emissions is determined by three statistically significant parameters:

- energy consumption;
- energy production;
- heat production.
- 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.

## CONCLUSIONS

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:

1. Separate collection with anaerobic digestion;
2. Separate collection with composting;
3. 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.

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.

Some slowdown in respect to this preliminary view could be represented by a higher willingness from the EU to decrease the level of incineration, since too much incineration negatively affects the environmental and human health dimensions in favour of other alternatives where final energy production from biological waste is foreseen. On the other hand, some currently underdeveloped concepts in terms of technology (i.e. pyrolysis, gasification) can be promising for the future even though, nowadays, their environmental and economic performance is not feasible and not comparable to incineration [171]. The author leaves this particular analysis as a further step in the development of this model.

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.

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.

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