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CARBON FARMING TOWARDS CLIMATE NEUTRALITY

Summary of the Doctoral Thesis

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

To be granted the scientific degree of Doctor of Engineering Science, the present Doctoral Thesis has been submitted for defence at the open meeting of RTU Promotion Council on Month 23, 20124 at the Faculty of Natural Sciences and Technology of Riga Technical University, 12 k-1 Āzenes Street, Room 116.

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DECLARATION OF ACADEMIC INTEGRITY

I hereby declare that the Doctoral Thesis submitted for review to Riga Technical University for promotion to the scientific degree of Doctor of Engineering Sciences is my own. I confirm that this Doctoral Thesis has not been submitted to any other university for promotion to a scientific degree.

Ketija Bumbiere …………………….. (signature)
Date: ……………………..

The Thesis has been written in English. It contains an introduction, 4 chapters, conclusions, a list of references, 33 figures, and 27 tables; the total number of pages is 227, including appendices. The bibliography contains 283 titles.

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INTRODUCTION

Relevance of the Topic

Europe has already experienced an average surface air temperature rise of 0.8 °C during the 20th century, and simulations show that the future expected rate of temperature rise per decade will be between 0.1 °C and 0.4 °C, caused by anthropogenic greenhouse gases (GHG). The global mean temperature in 2021 was already about 1.1 °C above the 1850–1900 average temperature. On 12 December 2015, Parties to the UNFCCC ratified the Paris Agreement and have committed to reducing emissions by at least 55 % by 2030 compared to 1990 levels and being climate-neutral by 2050.

The energy sector is responsible for 64.0 % of the total GHG emissions in Latvia in 2016, of which the transport sector is responsible for 44.2 %, while the agricultural sector is responsible for 23.6 % of the total Latvian GHG. Agriculture is in the most direct contact with natural resources – water, land, plants, animals, natural minerals, energy – and is directly and indirectly linked to all other sectors, including energy and transport sector. Not only its connection with other sectors and all kinds of resources but also the diversity of its activity makes it a very complex, difficult sector to organize, but it is a very important investment both in terms of environmental and also in economic development. The direction of the transformation is influenced by different strategies. Climate Neutrality Strategy 2050 measures to achieve the goal planned in the strategy are to achieve resource-efficient agriculture that produces products with high added value and high productivity, and to increase agricultural investment in bioenergy, for example, biogas production. Efficient management of the agricultural sector and the use of biogas could have a positive effect on reducing emissions from not only the agricultural sector, but the development of biogas production alone will also not allow to decarbonize the entire agricultural sector. That is why the EU aims to find new ways to decrease GHG emissions through a new approach for Europe – the EU Carbon Farming initiative – stating that farming practices that remove CO_2 from the atmosphere should be rewarded in line with the development of new EU business models. However, the European Commission acknowledges that carbon farming is in its infancy and there is a lot to be addressed, and it is crucial and challenging to implement energy efficiency and resource efficiency measures without simultaneously reducing productivity because one of the main challenges facing the agricultural industry is to provide food for the increasing population while reducing its influence on the climate and environment.

Inclusive, sustainable, growth-promoting and equitable development of all sub-sectors of agriculture could not only have a large impact on the agricultural sector itself but also other sectors in which it is necessary to reduce GHG emissions. However, unprofessionally adopted policies that focus only on specific agricultural sub-sectors or groups of companies may not only prevent these goals but may even delay them. It should be taken into account that agriculture is a very complex system in which simple saving measures and knowledge are not enough to achieve both these savings and productivity.

The Proposed Theses

The following theses were proposed in the research:

- Resource management is an essential prerequisite, which would make it possible to sustainably ensure the progress of the agricultural sector towards climate neutrality.
- The efficiency of resources is an essential prerequisite, which it would allow to sustainably ensure the progress of the agricultural sector towards climate neutrality.
- Carbon farming is an essential prerequisite, which would make it possible to sustainably ensure the agricultural sector moves towards climate neutrality.
- The production of products with higher added value is an important factor in the agricultural sector's progress towards climate neutrality in order to maintain the economic sustainability of companies and the industry.
- Biogas has great potential in Latvia and in the movement towards climate neutrality of the agricultural sector.

The Aim of the Research

The purpose of this research is to examine the impact of climate neutrality measures on the agricultural sector and to define the main prerequisites for the development of the sector on the way towards carbon-restricted, sustainable and viable agriculture. To achieve the goal, the following tasks have been set:

- To analyze the biogas sector and propose the most sustainable solutions.
- To research and clarify the best carbon farming methods for the case of Latvia, where the main emphasis is on the subsector of field crop cultivation.
- To study the management of energy efficiency and resource efficiency and determine the importance of their implementation in agricultural enterprises.
- To study how to increase the economic contribution to the agricultural sector by producing products with higher added value from livestock residual products.
- To conduct a case study to assess the importance of introducing innovations in the second largest sub-sector of agriculture – animal husbandry.

The Novelty of the Research

The novelty of the research is the cross-cutting analysis for the transition to climate-neutral agriculture and the implementation of resource management, energy efficiency, and carbon farming at two different but interrelated levels: state (first level) and farm (second level), including a comprehensive emphasis on the agriculture sector.

The first level of novelty is related to the level of the agricultural sector of Latvia:

- The scientific idea of carbon farming using the multicriteria analysis method was tested.
- Biogas potential was determined and SWOT analysis of sustainability was performed.
- The TIMES model was developed to evaluate the production of products with a higher added value from residual livestock products
- Sustainable biogas was used in the energy sector using multicriteria analysis.

The second level is related to the analysis, modelling, simulation, and forecasting of the operations of companies in various subsectors of the agricultural sector, using traditional and non-traditional methods and models.

To develop an integrative decision-making methodology for the transition of the agriculture sector to climate neutrality, a different distribution of research methods, both quantitative and qualitative, was used. The novelty of the research also is the use of several academic methodologies to determine the direction towards a result-based agriculture sector and climate neutrality. The following methods were used and models were created:

1) carbon balance to assess the sustainability of biogas raw materials;
2) sustainability SWOT analysis to assess the current situation and future perspective of the biogas sector;
3) multi-criteria analysis to evaluate the most suitable raw materials for biogas production in Latvian conditions, the sustainable way of using biogas in the energy sector, as well as the most suitable carbon farming methods for local companies;
4) energy efficiency analysis to assess the importance of energy and resource management and implementation opportunities in any agricultural enterprise;
5) the TIMES model to assess the production of products with higher added value from residual products in the livestock sector.

Hypothesis

Effective movement towards climate neutrality in the agricultural sector is sustainable and viable if there is simultaneously:

- effective use and management of resources;
- production of products with high added value;
- principles of carbon farming.

Practical Relevance

The Thesis has a high practical significance in the national and European context. The findings and conclusions of this research are useful in the process of improving Latvia’s agricultural policy towards climate neutrality. This research can be used by any agricultural company in the development of decision-making in various state documents, in studies, and in other learning processes.

Structure of the Research

The Thesis is based on eight interconnected scientific publications, mainly paying attention to the solutions suitable for Latvia, as well as the development of methods that would help in the development of sustainable policies in the context of the Green Deal. The Thesis contains a literature review, which presents a discussion of the objectives of the Green Deal in the context of agriculture, an analysis of the literature that provides the background knowledge that is critically needed in conducting such research, as well as an outline of the methodologies used, research results and conclusions. Overall, the structure of the research follows the path of the agricultural sector to climate neutrality (see Fig. 1).

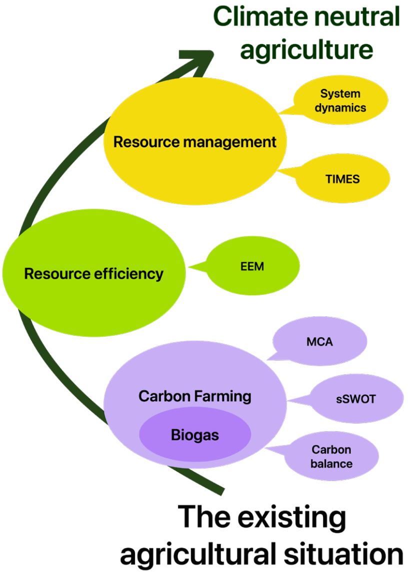


Fig. 1. Structure of the research.

The Thesis structure and the role of publications are shown in Table 1.

Table 1

Thesis Structure and the Role of Publications

Method	**Publication number**	**Publication title**	**Management level**
Carbon balance method	1	Development of a carbon balance methodology for biogas produced from specially grown substrates: A Latvian case study	Farm level
Sustainability SWOT analysis	2	What will be the future of the biogas sector?	State level Farm level
MCA	3	Ranking of bioresources for biogas production	Farm level
MCA	4	Sustainable biogas application in the energy sector	State level Farm level
MCA	5	Development and assessment of carbon farming solutions	State level Farm level
EEM method	6	The role of energy management in the agricultural sector: Key prerequisites and impacts	Farm level
TIMES method	7	Application of TIMES for bioresource flow optimization – case study of animal husbandry in Latvia, Europe	State level Farm level
System dynamics	8	Progress of the agricultural sector towards climate neutrality: Identification of essential stages	Farm level State level

The research is starting from the simplest basic stage, which examines biogas from such different aspects as:

- sustainable production of biogas, where carbon balance was carried out to objectively quantify naturally or anthropogenically added or removed carbon dioxide from the atmosphere to determine the environmental impact of biogas production from specially grown maize silage, which can be used in the calculation of its environmental impact for any other substrate too;
- the future of biogas in Latvia, where an understanding of the recent evaluation of Latvia's biogas sector is provided through the analysis of literature, reports, legislation and scientific articles through a sustainability SWOT analysis;
- bioresources for sustainable biogas production, where multi-criteria analysis was carried out to determine Latvia's biogas sector potential to predict the best feedstock depending on resources available in the country, which of the substrates for biogas production has the highest potential and sustainability;
- sustainable use of biogas, where multi-criteria analysis was carried out to determine the potentially best use for biogas in the energy sector.

Although biogas undoubtedly plays an important role in the climate neutrality of agriculture, it will also be an important part of carbon farming policy in the future, therefore a multi-criteria analysis of carbon farming was done, to identify the most suitable carbon farming solutions for Latvian conditions and determine their importance in reducing GHG emissions.

Although carbon sequestration is an important aspect of agriculture's progress towards climate neutrality, it is not possible without economic justification, therefore the following studies were done on:

- energy efficiency, with the aim to see if there would be a potential energy and emission savings from implementing energy management actions and proposed framework for the energy management system in the agricultural sector at a company level;
- products with higher added value, where the study presents a novel model based on the TIMES modelling approach, which helps to investigate the application of new technologies in the agriculture sector and evaluate contribution to the agriculture sector in terms of the production of new competitive products, in addition, developing of biorefinery that has a significant impact on both agriculture and other sectors by increasing overall resource efficiency.

To achieve the goal of the Thesis, the final research was done:

- climate neutral agriculture, where a system dynamics model using Latvian dairy farming as a case study was made, so it would not only provide an insight into the system's structure but also identify the system's weak links and allow for the calculations and development of recommendations.

The discussion of the research results is presented in Chapter 3, where the main statements are in bold highlighting the findings of the Doctoral Thesis with the value of future sustainability.

SCIENTIFIC APPROBATION

1. Bumbiere, K., Pubule, J., Blumberga, D. What Will Be the Future of Biogas Sector? Environmental and Climate Technologies, 2021, Vol. 25, No. 1, pp. 295–305. Available: https://doi.org/10.2478/rtuect-2021-0021.
2. Bumbiere, K., Gancone, A., Vasarevičius, S., Blumberga, D. Ranking of Bioresources for Biogas Production. Environmental and Climate Technologies, 2020, Vol. 24, No. 1, pp. 368–377. Available: https://doi.org/10.2478/rtuect-2020-0021.
3. Gancone, A., Bumbiere, K., Pubule, J., Blumberga, D. Sustainable biogas application in energy sector. Conference paper. 2020 IEEE 61st Annual International Scientific Conference on Power and Electrical Engineering of Riga Technical University, RTUCON 2020 – Proceedings, 9316593. Available: 10.1109/RTUCON51174.2020.9316593.
4. Bumbiere, K., Pubule, J., Gancone, A., Blumberga, D. Carbon balance of biogas production from maize in Latvian conditions. Agronomy Research, 2021, Vol. 19, Special issue 1. Available: https://doi.org/10.15159/ar.21.085.
5. Bumbiere, K., Diaz Sanchez, F. A., Pubule, J., Blumberga, D. Development and assessment of carbon farming solutions. Environmental and Climate Technologies, 2022, Vol. 26, No. 1, pp. 898–916. Available: https://doi.org/10.2478/rtuect-2022-0068.
6. Bumbiere, K., Sereda, S., Pubule, J., Blumberga, D. The Role of Energy Management in the Agricultural Sector: Key Prerequisites and Impacts. Agronomy Research, 2023, Vol. 21, Special issue 2, pp. 439–450. Available: https://doi.org/10.15159/AR.23.034.
7. Bumbiere, K., Feofilovs, M., Asaris, P., Blumberga, D. Application of TIMES for Bioresource Flow Optimization – Case study of Animal Husbandry in Latvia, Europe. Recycling, 2023, Vol. 8, No. 5, p. 70. Available: https://doi.org/10.3390/recycling8050070.
8. Bumbiere, K., Meikulane, E., Gravelsins, A., Pubule, J., Blumberga, D. Progress of the agricultural sector towards climate neutrality: identification of essential stages. Sustainability, 2023, Vol. 15, No. 14, 11136. Available: https://doi.org/10.3390/su151411136.

The research results have been discussed and presented at the following conferences

1. Bumbiere, K., Pubule, J., Blumberga, D. What Will Be the Future of Biogas Sector? International Scientific Conference of Environmental and Climate Technologies, CONECT, May 12–14, 2021, Riga, Latvia.
2. Bumbiere, K., Gancone, A., Vasarevičius, S., Blumberga, D. Ranking of Bioresources for Biogas Production. International Scientific Conference of Environmental and Climate Technologies, CONECT, May 13–15, 2020, Riga, Latvia.
3. Bumbiere, K., Gancone, A., Pubule, J., Blumberga, D. Sustainable biogas application in energy sector. 2020 IEEE 61st Annual International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON 2020): Proceedings, Latvia, Riga, 5–7 November 2020.

4. Bumbiere, K., Pubule, J., Gancone, A., Blumberga, D. Development of a carbon balance methodology for biogas produced from specially grown substrates: A Latvian case study. Biosystems Engineering May 5–6, 2021, Tartu, Estonia.
5. Bumbiere, K., Diaz Sanchez, F. A., Pubule, J., Blumberga, D. Development and assessment of carbon farming solutions. International Scientific Conference of Environmental and Climate Technologies, CONECT, May 11–13, 2022, Riga, Latvia.
6. Bumbiere, K., Sereda, S., Pubule, J., Blumberga, D. The Role of Energy Management in the Agricultural Sector: Key Prerequisites and Impacts. 13th International Conference on Biosystems Engineering 2023 May 10–12., Estonia, Tartu.
7. Bumbiere, K., Meikulane, E., Gravelsins, A., Pubule, J., Blumberga, D. Progress of the agricultural sector towards climate neutrality: identification of essential stages. International Scientific Conference of Environmental and Climate Technologies, CONECT, May 10–12, 2023, Riga, Latvia.

Other publications

1. Bumbiere, K., Barisa, A., Pubule, J., Blumberga, D., Gomez-Navarro, T. Transition to climate neutrality at University Campus. Case study in Europe, Latvia. Environmental and Climate Technologies, 2022, Vol. 26, No. 1, pp. 941–954. Available: https://doi.org/10.2478/rtuect-2022-0071. Published by Sciendo. International Scientific Conference of Environmental and Climate Technologies, CONECT, May 11–13, 2022, Riga, Latvia.
2. Vistarte, L., Pubule, J., Balode, L., Kaleja, D., Bumbiere, K. An Assessment of the Impact of Latvian New Common Agriculture Policy: Transition to Climate Neutrality. Environmental and Climate Technologies, 2023, Vol. 27, No. 1, pp. 683–695. Available: https://doi.org/10.2478/rtuect-2023-0050. Published by Sciendo. International Scientific Conference of Environmental and Climate Technologies, CONECT, May 10–12, 2023, Riga, Latvia.

1. METHODOLOGY

To achieve the research objectives, several methods were used – carbon balance, sustainability SWOT analysis, multi-criteria analysis, TIMES model and system dynamics model. The methodology and results sections are reviewed sequentially.

1.1. Carbon balance method

A carbon balance was carried out to objectively quantify naturally or anthropogenically added or removed carbon dioxide from the atmosphere to determine the environmental impact of biogas production from a substrate – in this case from specially grown maize. Although the carbon balance method has been used so far, for example, to model the change of land use or of forestry under various effects of forestry management methods, there are no studies that have developed carbon balances to determine the environmental impact of substrate selection in biogas production. The methodology was based on life cycle analysis, which included calculations of:

- emissions of maize silage cultivation due to tillage, mineral nitrogen fertilizers and fuel use in heavy machinery;
- emissions collected due to the photosynthesis process;
- emission leaks from the biogas production process;
- emissions from the use of maize digestate fertilizer;
- emissions saved from the mineral fertilizer replacement with digestate.

To calculate fuel emissions, data were collected from an agricultural farm in Latvia. By finding out the lowest combustion heat of diesel fuel, it is possible to obtain consumed energy for field treatment. However, knowing the energy consumed in the process of field cultivation as well as using the emission factors of the 2006 Intergovernmental Panel on Climate Change (IPCC) guidelines, it is possible to obtain the result in terms of tons of emissions from the use of fuel. By determining the annual emissions, indicators – emissions from the processing of 1 ha of maize used for biogas production – are calculated.

During the special cultivation of maize, fuel is not the only source of emissions; it is also caused by the incorporation of crop residues into the soil, as well as the use of nitrogen. Therefore the Tier 1 methodology from the 2006 IPCC guidelines was used to calculate nitrous oxide emissions from managed soils. For direct nitrous oxide emissions from agricultural soils, the following equation was used:

$$N_2O\text{–}N = [(F_{SN} + F_{CR}) \times EF], \tag{1.1}$$

where

N_2O – N–N_2O emissions in units of nitrogen (direct N_2O emissions from treated soils, kg N_2O–N year–^{1});

F_{SN} – the amount of nitrogen in the fertilizer applied to the soil (kgN/year);

F_{CR} – N amount of maize residues entering the soil on an annual basis (above and below ground);

EF – N_2O emission factor from N input, kg N_2O–N kg^{-1} N (input = 0.01).

The following equation was used to report kg N_2O–N emissions to N_2O emissions:

$$N_2O = N_2O - N \times 44/28 \tag{1.2}$$

One of the calculation parameters for estimating the direct nitrogen oxide emissions from the use of N in managed soils is the amount of pure nitrogen fertilizers per year. Data on the required inorganic fertilizers used in soils are taken from A. Kārkliņš' book "Calculation methods and standards for the use of soil treatment and fertilizers", which states that a maize yield of 31.8 t/ha requires 0.1 t/ha N fertilizer.

Yield N per year is calculated using the Tier 1 methodology of the 2006 IPCC Guidelines:

$$F_{CR} = Yield \times DRY \times Frac_{Renew} \times Area \times R_{AG} \times N_{AG} \times Area \times R_{BG} \times N_{BG}\,, \tag{1.3}$$

where

$Yield$ – the harvested maize yield (kg fresh maize yield/ha);

DRY – the dry matter part of harvested maize (kg dry matter / kg fresh matter);

$Frac_{Renew}$ – total area of maize;

$Area$ – the total part of the area harvested for maize (ha/year);

RAG – terrestrial, surface residue solids (AGDM), and maize harvest (Crop), kg dry matter (kg dry matter)$^{-1}$;

N_{AG} – N surface plant residue content in maize (kg N / kg dry matter);

R_{BG} – ratio of underground residues to maize yield (kg dry fraction / kg dry fraction);

R_{BG} can be calculated by multiplying RBG-BIO by the total aboveground biomass to cereal yield ratio ($R_{BG} = [(AG_{DM} \times 1000 + Crop / Crop)]$;

N_{BG} – the N content of underground residues of maize (kg N / kg dry matter) (0.007).

To calculate the annual production of crop residues F_{CR}, the following calculation is required:

$$R_{AG} = AGDM \times 1000/Crop, \tag{1.4}$$

as well as an additional equation to estimate terrestrial surface solids AGDM (Mg/ha):

$$AGDM = (Crop/1000) \times slope + intercept. \tag{1.5}$$

The correction factor for estimating the dry matter yield is determined as:

$$Crop = Yield\ Fresh \times DRY, \tag{1.6}$$

where

$Crop$ – harvested dry yield fraction T, kg dry matter ha^{-1};

Yield Fresh – part of fresh harvest T, kg fresh fraction ha^{-1};
DRY – dry matter fraction of harvested crop T, kg dry fraction (kg dry fraction)$^{-1}$.

Although the use of digestate in field fertilization reduces emissions compared to synthetic fertilizers, digesting soil with digestate also generates greenhouse gas emissions. The results of analyses obtained from the farm "X" producing biogas from maize indicate that the N content of the digestate fertilizer is, on average, 3.8 kg/t. By knowing the N content of the digestate and the tons of digestate obtained, the digestate fertilization emissions were calculated by the 2006 IPCC guidelines.

When looking at emissions from the biogas production process, it should be considered that although biogas is produced from maize, which is a renewable resource and recovers the carbon emissions that the plant has absorbed during its growth process, emissions from the biogas production process are considered. According to the scientific article, emission leakages account for 1 % of biogas losses in biogas production, which includes both the 52 % methane in it and the remaining 48 %, which is assumed to be carbon dioxide.

Although GHG emissions result from field cultivation during maize cultivation, maize growth involves photosynthetic processes that sequester CO_2 from the atmosphere. To calculate the amount of CO_2 captured in a year in a certain area of biogas maize, the amount of dry matter is multiplied by the CO_2 sequestration factor.

All variations in the amplitude of losses are summarized and presented as an average.

1.2. Sustainability SWOT analysis

The sustainability SWOT analysis, where strengths, weaknesses, opportunities, and threats are analyzed, is a new twist of the familiar SWOT, where much more can be incorporated than environmental issues. It is a very simple method to be effectively used not only for companies and resource planning but also for strategy prioritization at the industrial and policy levels. It is meant to drive collaboration on environmental challenges, possible risks, and opportunities, which otherwise may go unnoticed.

This part of the research is the result of a literature review, mainly analyzing reports, legislation, and scientific articles that were identified as relevant material to provide an understanding of the recent evaluation of Latvia's biogas sector. When selecting sources of information, priority was given to the most recent articles. Special attention was given to

- papers on, for example, national plans, technological and economic reports on Latvia's energy, and biogas sector and journal articles to look objectively at the most pressing issues and developments of the last 20 years;
- scientific papers published in peer-reviewed journals in English.

It studies the development of Latvia's biogas industry, which is especially relevant and interesting due to its instability and rapid variability. The analysis sheds light on the economic, environmental, political, and social dynamics through the application of the sustainability SWOT (sSWOT) method. Based on the obtained literature review, a table was created (presented in the results section) in which the strengths, weaknesses, opportunities and threats are defined.

1.3. Multi-Criteria Analysis

The TOPSIS method is one of the methods that allows to determine the exact value of criteria to compare different units with great success. The TOPSIS method used in this work to make a decision was “the classical TOPSIS method for a single decision-maker”. The TOPSIS method is chosen for this research because it allows compromises between criteria, where a poor result on one criterion can be offset by a good result on another criterion, thus providing more realistic modelling than methods that include or exclude alternative solutions due to strict constraints. Unlike other methods, in the TOPSIS method, the optimization (max or min) for the desired outcome is determined for each criterion and it assigns a value to each alternative.

During the first step of the research, data collection and analysis, including the review of scientific literature, initial data and regulations were done. Based on the results of the first step of the study, indicators (technical, environmental, and economic) used for the multicriteria decision-making process were identified and selected. During the next step, values of indicators were set, and after the normalization and weighting of indicators, rating and evaluation were conducted. MCA was done to find the best bioresources for biogas production. The TOPSIS method is based on 7 main steps:

- demonstrate a performance matrix;
- normalize the decision matrix;
- calculate the weighted normalized decision matrix;
- determine the positive ideal and negative ideal solutions;
- calculate the separation measures;
- calculate the relative closeness to the ideal solution;
- rank the preference order.

MCA was carried out to determine Latvia’s biogas sector potential – to predict the best feedstock depending on resources available in the country, which of the substrates for biogas production has the highest potential and sustainability. The following raw materials were analyzed in this multi-criteria analysis: cattle manure, swine manure, poultry manure, sewage sludge, organic waste, wood, straw, and maize silage. The year 2017 was used for data collection, and this multi-criteria analysis does not consider the size of the farms, which is related to the actual number of livestock, manure collection technology, and the transportation distance from the raw material extraction site to the biogas plant.

The efficiency of different feedstocks in terms of yield and how many cubic meters of biogas can be obtained from a ton of a given feedstock was analyzed. The efficiency of these raw materials was determined as an average value and summarized. To determine the importance of using a particular substrate in the production of biogas, data was collected on how much emissions it could eliminate, thus approximating the proportion of their availability and importance, and environmental impact depending on how much this material is produced in one year and its emission factor. To calculate objectively the amount of emissions that could potentially be avoided (both nitrous oxide and methane), emissions were compared to carbon dioxide equivalents and added up. 1 kg of nitrous oxide was calculated as 298 kg of carbon dioxide, while 1 kg of methane was calculated as 25 kg of carbon dioxide.

In total, 3 main criteria were considered. Experts voted that the most important criteria were climate friendliness (35 %), economic justification (35 %), and technological aspect (30%).

To determine the potential of manure for biogas production, a calculation was done to sum up the amount of specific raw material emissions in Latvia in one year. To determine which feedstock is the most economically advantageous for biogas production, information on feedstock prices was collected. To obtain the cost of producing 1 m^3 of biogas from a given substrate, the substrate price was divided by the substrate efficiency. As a result, the 3 main criteria identified as determinants of biogas substrate selection were summarized in Table 1.1 for comparison.

Table 1.1

Multi-Criteria Analysis Values

	Efficiency (yield of biogas), m^3/t	**Environmentally friendly (emissions to be collected in Latvia), kt CO_2eq/year**	**Economic factor, €/m^3 biogas**
Cattle manure	35.0	115.47	0.09
Pig manure	44.0	25.71	0.02
Poultry manure	80.0	4.73	0.03
Sewage sludge	218.0	113.53	0.01
Organic waste	100.0	403.50	–0.74
Wood	35.5	0.00	1.18
Straw	190.0	0.00	0.08
Maize silage	202.0	–6.56	0.25

1.3.1. MCA to find a sustainable way for the use of biogas

Although biogas production is particularly suitable for Latvia, since 2016 when 56 biogas plants were in operation, 7 plants have ceased their operations by 2020; moreover, more biogas plants are planned to stop operating. At the same time, the transport sector is the biggest GHG emitting sector in Latvia, and although EU member states must ensure 10 % of renewable energy consumption in the transport sector by 2020, its share in 2018 was only 4.7 %; biogas is not used in the transport sector at all. Given that the largest consumption sector in final energy consumption is transport, as well as the fact that the transport sector is the largest source of GHG emissions, it would be important to set the lowest possible excise tax rate for biomethane and biofuels from 2022, evaluating the possibility to differentiate the reduced rates for first-generation biogas.

That is why the focus of this research is on agricultural biogas, which can be used for two purposes in the energy sector: (a) combusted in CHP systems, as well as electricity used for auto transport; (b) purified to biomethane and used for auto transport. The methodology is demonstrated in Latvia as a case study. Six indicators were used to analyse biogas application options in the energy sector (see Table 1.2).

Table 1.2

Indicators Used for the Assessment of Biogas Application Scenarios

Dimension	Indicator	Unit	Preferable outcome	Weight of the indicator, %
Technical	Efficiency of the whole system	%	Max	10
	Efficiency gains for the transport sector	%	Max	20
	Energy produced for the transport sector	MWh	Max	10
Environmental	Reduced GHG emissions	$ktCO_2eq$	Max	30
Economic	Costs	€/MW	Min	25
Economic	External Costs	€/MW	Min	5

These six criteria from three dimensions were used to assess the analysed scenarios. Criteria weights were determined by experts in the field. Values for indicators were obtained from the literature and the Latvian Biogas Association. The Multicriteria analysis method TOPSIS was used to determine the best scenario for biogas application in energy transport. The normalized and weighted decision-making matrix is shown in Table 1.3.

Table 1.3

Normalized and Weighted Decision-Making Matrix

Indicators	**Technical indicators**			**Environmental indicator**	**Economic indicator**
	Efficiency of the whole system	Efficiency gains for the transport sector	Energy produced for the transport sector	Reduced GHG emissions	Costs, €/MW
Scenario 1	0.076	0.093	0.098	0.291	0.260
Scenario 2	0.065	0.177	0.021	0.073	0.150

1.3.2. MCA to find the most suitable carbon farming solutions

The goal of this research is to identify carbon farming solutions for Latvian conditions and determine their importance in reducing GHG emissions. It compares six carbon farming options with five different parameters that were considered (one for economic feasibility, two for environmental friendliness, and two for technological aspects – opportunities for the amplitude of methods implementation in real life) and weighted equally by industry experts. The methodological algorithm was applied to the case study of Latvia, but it can be used for a variety of studies that need to find the best solution depending on these criteria.

As one of the criteria for the TOPSIS analysis, the area allocated for this process already in Latvia without making any improvements or expansions was accepted. Also, the potential area was determined to find out the possible potential of the carbon farming methods not only in existing territories for these processes but also in the future, expanding the management of wider territories with sustainable practices. Since agricultural data in Latvia is relatively rarely updated, the used areas in 2016, indicated in the statistical databases, were accepted. Since the data on the extent of capture by soil application in the territory in Latvia is not known, the area allocated for it is currently accepted as the entire area used for farming, since the scope of application of this practice is very wide, but it has a huge potential for improvement at the same time. The areas required to produce biogas and biomethane were calculated if biogas was 100 % produced from the manure of agricultural animals currently present in Latvia, considering the area needed for pastures and the area needed to produce the necessary food for these animals. Expansion of biogas and biomethane areas is not accepted because biogas and biomethane are products produced from a waste product and not as a primary product, therefore the development of this method will not be a determining factor to increase the number of farm animals in enterprises. To roughly determine the currently used area for biogas/biomethane production, the amount of energy produced in 2016 from biogas obtained in Latvia was determined and considering how much yield can be obtained from 1 t of the respective type of manure, it was calculated that only 16.2 % of the manure resource available in Latvia is used. Accordingly, the currently theoretically used territory has been equated to the amount of biogas production. The potential expansion site for such practices as agroforestry and perennial plants is assumed to be the unmanaged Latvian scrubland.

To determine the available budget, the information was taken from the Latvian Common Agriculture Policy (CAP) Strategic Plan 2023–2027 and information on Cohesion funds for Biomethane development.

The amount of GHG emission sequestration in kilotons within one year of each method in the currently allocated areas was adopted. Since there is no exact data on how much emission occurs in these processes/sectors, the calculations were made based on assumptions from scientific publications.

Since zero tillage predicts a 41 % emission reduction, while minimal tillage is 26 % compared to conventional, data from conventional maize cultivation were used to calculate the estimated annual CO_2eq reduction. The current potential of biogas and biomethane is calculated by considering IPCC Default GHG emission factors and average N excretion per head of animal per year. However, it should be taken into account that the real emission reduction would be much higher because this calculation takes into account only those emissions that are prevented by managing agricultural animal manure, while if the calculation were done differently – not according to the usable area, where the reduction of GHG emissions depends in the most direct way on the territory to be used but on the possible consumption of biogas/biomethane in Latvia if the use of natural gas and fossils were completely replaced by biogas and/or biomethane (according to the potential amount that can be obtained, it is possible to make sure that this is a realistically achievable goal in the case of Latvia). Using Central Statistical Bureau data, which indicates that in 2016, natural gas consumption was 1371 m^3, and the EPA calculator it is calculated that in 2016, 29 397 t of CO_2eq were generated due to the consumption of natural gas, which means that if biogas were used, emissions would not only be prevented by 100 % but they would still be negative, as the use of biogas achieves a 240 % reduction in emissions compared to fossil resources and 64 % compared to the natural gas in energy, while for biomethane 202 % to fossil fuel use in transport.

Accepting the application of willow biochar in the entire area of agricultural arable land in the current territories, as well as knowing that Willow biochar could compensate for 7.7 % of annual agricultural greenhouse gas emissions; however, in 2018, soil cultivation in Latvia generated 1547.4 ktCO_2eq emissions, which was the largest sub-sector of GHG emissions in the agricultural sector in terms of emissions. The possibilities of sequestration could be as much as 119 ktCO_2eq per year, but it should be noted that this calculation is idealized without in-depth research on those areas where such application of willow biochar would not be desirable. However, considering the wide range of capture by soil methods, we accept it as an example calculation for all agricultural lands, which would be possible to achieve in the entire territory. Perennial plants can sequester about 3.6 tCO_2/ha/y, and knowing the currently used territory, the positive impact of the perennial plant on the environment can be calculated.

By calculating how much it would be possible to potentially sequester GHG emissions using all the resources available for the specific method, it is possible to see how big the opportunities for reducing emissions are provided by the implementation of positive agricultural practices. In this calculation, only those emissions that can be prevented because of manure management are considered in the biogas and biomethane potential. It does not include the emission reductions that would result from using digestate as fertilizer, so it should be noted that the true benefit would be much higher. All values for TOPSIS indicators are shown in Table 1.4.

Table 1.4

Values for TOPSIS indicators

CF method	Area in 2020, ha	Potential area, ha	Budget, €	GHG emission sequestration in the existing areas allocated for this measure, ktCO_2eq/year	Potential GHG emission sequestration, ktCO_2eq/year
Zero tillage	12 818	370 000	5 550 000	8.2	595.0
Minimal tillage	68 388	370 000	5 550 000	27.9	377.3
Biogas	180 216.1	1 112 445	0	61.6	380.1
Capture by soils	2 285 477	2 285 477	16 688 447	119.2	119.2
Perennial plants	28 827	103 829	15 520 000	103.8	373.8
Biomethane	180 216.1	1 112 445	61 000 000	61.6	380.1
Agroforestry	0	103 829	4 055 000	0	37.4

1.4. Energy efficiency measurements

The methodology was based on the IPCC guidelines, written in 2017–2018. The year 2005 was compared to 2015 to see the increase in emissions in the agricultural sector. The following methods, guidelines, and manuals were used in this research: IPCC Guidelines, Latvian Inventory Report on GHG Emissions, and manual "Guide for Farmers to calculate GHG at farm level and measures to reduce it". Analysis of indicators and comparison of agricultural enterprises will be carried out, and a methodology that can be applied at a certain level will be developed.

To achieve the goal of this research, an algorithm of methodology has been developed (Fig. 1.1). It is divided into eight stages, showing the advisable actions at each level – (1) evaluation of data on GHG emissions, (2) analysis of data at the national, (3) sectoral, or (4) company level, (5) analysis of the data on energy consumption, (6) comparison of the companies, (7) improvement measures proposed, and (8) energy efficiency measures defined. The algorithm's first part is oriented toward identifying and analyzing the current situation. Still, the second part is identifying future perspectives, searching for possibilities, and implementing practical solutions to promote development.

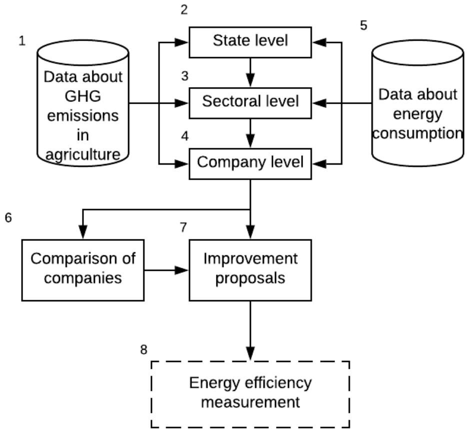


Fig. 1.1. Scheme of the methodology.

As is seen in the scheme, the methodology includes eight modules, of which three are the main ones: state level (2), sectoral level (3), and company level (4). From stages 1 to 5, data collection and publicly available data are analyzed using data analysis methods. Data are compared in stages 6 to 8, and GHG emissions and energy reduction measures are proposed. These measures are also called energy efficiency measures.

The agricultural sector emissions are calculated in the following categories: agricultural lands, intestinal fermentation, manure, land liming, and urea utilization (National Inventory Submissions 2022 | UNFCCC, n.d.).

This research aimed to see if there would be potential energy and emission savings from implementing energy management actions and propose a framework for an energy management system in the agricultural sector at a company level.

1.5. TIMES model

The TIMES bioeconomy value model (TIMES-BVM) is designed to model bioresource flows and technologies for the development of the animal husbandry sector; however, it can be modelled to research other subsectors in agriculture, such as cereal farming, field plant production, greenhouse horticulture, and others. The aim of the model is to help understand how the agricultural subsector can contribute to meeting the higher value-added goal for bioresource growth for 2030. The model addresses the development of biorefineries from the perspective of natural limits (the capacity of resource application), economic viability (technology, maintenance, and operation), and socio-economic aspects (increased salaries, etc.). The model created in the research is used to find the most economically viable scenario for increasing the value of bioresources. It is achieved through an optimization-type simulation, which uses historical data from 2015 to 2019 and a forecast of future industry development trends as well as opportunities to use new bioresource technologies to produce higher-added-value products starting in 2023.

The model structure is created based on the general TIMES-BVM structure, including resources (in this case, primary livestock resources such as eggs, meat, milk, wool, and honey), technologies (pre-processing and preparation of raw products; production of food, feed, and other products; and processing of by-products), product flow (import, export, and domestic production) and demand. Processes used in the structure are divided into primary production, import and export processes, transformation activities like those in biorefineries, and product demand. These elements are defined based on data from statistical databases, such as the Central Statistics Bureau (CSB) of Latvia, Eurostat and Faostat databases, those from the literature, interviews of companies, and approximations.

The model includes four bioresource stages: primary and processed resources, final product, and demand. Various technological processes are integrated for primary resource supply in terms of local and imported resources, costs, efficiency, capacity, availability, and limitations of processing technologies for primary and secondary resources. Each conversion path in the simulation of the model is calculated through an optimization approach, and the results show the best solution to satisfy the demand at the lowest cost. The results include the technical and economic characteristics of the pathways based on the model inventory. The model output is produced as a quantitative result for biomass flows and new capacity additions for technologies used in the production of products to meet the demand, the overall costs, and the overall added value of the products supplied.

Table 1.5

TIMES-BVM Model Input Data

Constituent	Variable	Measure of Unit
Primary resource supply	Type	Domestic harvest/import
	Stock Cumulative Value	Thousand tons, kt
	Cost	EUR/kt
	Yearly production	Thousand tons, kTt
	Limitations	Upper/lower
	Flow	Input/output items
Conversion (existing and new technologies)	Flow	Input/output items
	Efficiency	%
	Existing Installed Capacity	Thousand tons yearly, kta
	Utilization	%
	Investments	EUR/kta
	Lifespan	Years
	Fixed costs (maintenance and operating)	EUR/kt
	Added value	EUR/kt
	Limitations	Upper/lower
Demand	Demand value	Tkt

The structure of TIMES-BVM requires defining product demand for the selected target year of simulation, which is carried out by applying a forecast based on regression analysis according to methods introduced in the literature. Input data (see Table 1.5) for the request of finished products are fixed on prediction based on regression analysis for the years up to 2030. Regression analysis is performed prior to running the model. The demand for the finished product is a dependent variable in regression analysis.

The data input for resource import, export, and domestic production values is based on the extrapolation of statistical trends from 2015 to 2019 with the help of regression analysis. These values have upper and lower boundaries entered the model in the range of ±10 %, except for meat, which has a range of ±25 %. These ranges allow tradeoffs among other processes to fulfil the demand within the given set of limited capacities of technologies and resources. The selected boundaries allow production to match the demand and the avoidance of model instabilities due to poor statistical data availability and quality. This assumption allows the avoidance of shortages or surpluses that are neither consumed nor exported.

The new technologies to produce higher-added-value products included in the model structure are dietary supplement production from processed eggshells, gelatin production from meat-processing by-products, protein powder production from milk-processing by-products, production of wool pellets from wool-processing by-products, and production of honey-derived products from honey by-products.

The limit for the availability of new technologies in the model is set to 2023, signifying the current possible implementation of these technologies. The production amounts are limited by the available by-products and waste products from existing processes. Therefore, the production of new products with higher added value depends on the demand and, thus, also the local production of the conventional products. The demand was defined based on the historical average market data for these segments: calcium carbonate, gelatin, and its derivatives (excluding casein glues, bone glues, and isinglass), protein concentrates and flavored or colored sugar syrups, pellets and briquettes of pressed and agglomerated wood and of vegetable waste and scraps.

The added value of the item is recognized as factor costs and is established as the gross earnings of biorefineries (salaries included) for operating activities. It is estimated based on the official CSB available data on the market-added value and produced volume of goods.

Other factors limiting the use of by-products within the model were assumptions about technologies – process efficiencies, resource and product prices and costs, and upper and lower limits on the import, export, and local production of raw resources and final products – as they influence the commodity balance and thus indirectly influence the need for resource processing, resulting in different amounts of by-products and, consequently, different amounts of new products.

Mass balance validation is used as a crucial element in the TIMES model to guarantee the robustness of the findings. The mass balance calculation is adopted from the EN 16785-2 standard "*Bio-based products – Bio-based content – Part 2: Determination of the biobased content using the material balance method*". When discrepancies in mass balance are found, additional research is conducted to determine the precise causes and probable sources of errors in the model assumptions. These could be typographical errors in data entry, insufficiency of data sources, or unrealistic modelling assumptions. Once the differences are identified, the necessary corrections can be made to guarantee a more accurate depiction of the model simulation outputs.

1.6. System dynamics

The Stella Architect modelling tool was used to create a simulation model to present in a simplified mathematical way an agricultural sub sector – dairy farming. It was chosen because it not only shows the structure visually but also includes numbers, equations, and mutual interactions of various influences. It includes economic, environmental, and technological aspects. A literature analysis was carried out, in which scientific articles and policy documents were analyzed, while later connecting practical and theoretical knowledge by making calculations with data obtained from a real company to draw the most objective conclusions and avoid any blind spots.

The purpose of the model is to create the operation model of the dairy farm, which reflects the importance of investment implementation both in an economic and environmental context, where it is possible to observe the amount of emission reduction. It is possible to predict the importance of the implementation of investments and changes in emissions considering several interrelated influencing factors in the dairy farm model. To identify the main drivers and weak links, it was necessary to model the importance of investment implementation and the change in emissions. In general, the model was divided into four sectors: dairy cows, investment in dairy farming, economic factors, and emissions. Each sector was modelled so it could be used for each emission scenario. Once the boundaries of the model study were defined, it was determined that the emissions generated would be viewed in two ways: generated emissions, which will be measured in ktCO_2eq per year and generated emissions per product, which will be measured in ktCO_2eq to the annual production volume. It was further determined that the change in emissions in the model would be determined in 3 scenarios:

1. The dairy farmer does not invest in any of the dairy farm performance improvement measures.
2. The dairy farmer invests only in improving manure management.
3. The dairy farmer invests in all farm improvement measures.

So that the data obtained by the model could be compared with real-life situations and conclusions could be drawn, it was chosen to simulate the model in the period from 2012 to 2022.

Dairy cows are the most important element in a dairy farm, as the obtained raw milk is the main product that brings profit to the company. Dairy cows are mostly at least two years old and have reached their first lactation. The cow sector in the model consists of two main stocks: dairy cows and sick cows (Fig. 1.2). Dairy cow stock has both outgoing and incoming flow. To increase the number of cows, the owner buys new dairy cows or grows heifers. If a cow's milk production drops, it is sold. Sick cows are treated, but when the treatment is unsuccessful and requires a lot of resources that would affect not only the costs but also the yield, they are usually sent to the slaughterhouse or die naturally. Livestock health is particularly affected by the availability of high-quality feed, living conditions, and thermoregulation.

The incoming flow of the stock of dairy cows was determined considering the maximum number of beds for cows in the barn. However, the outflow of the stock, "sales", is determined by multiplying the sales ratio by the number of milking cows.

A similar principle applies to the cure and mortality flows of the sick cow stock, but the inflow of sick cows is affected by the level of feed quality. The effect of feed quality on morbidity is derived from a non-linear relationship in which the feed quality rating is used as an argument. The effect on morbidity ranges from 0 to 1.

Cows also produce manure from their digestive systems. Manure can be divided into liquid and litter (solid). Litter manure is cow excrement with/without litter and fodder remains, and liquid manure – with urine and/or water admixture. The total amount of manure produced was calculated as tons/year.

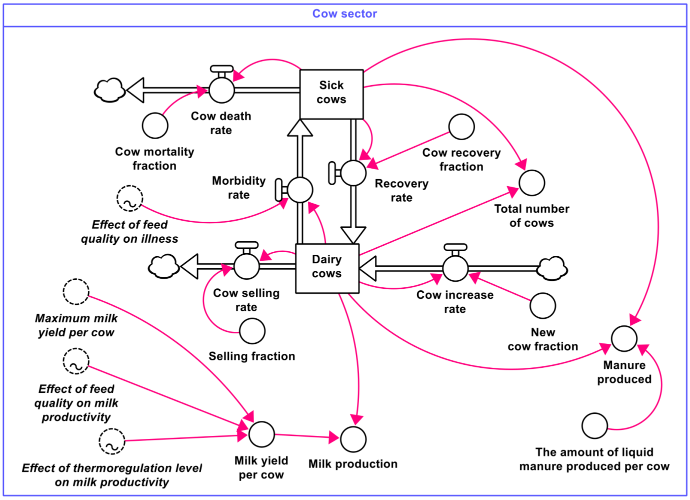


Fig. 1.2. Structure of the cow model.

The quantity of milk produced and sold (t) depends on the number of cows and the average yield of one cow. In general, milk yield per cow is influenced by several parameters, including the effect of thermoregulation level and feed quality on milk yield. Both the effect of feed quality and the effect of thermoregulation on hunger are characterized by a non-linear relationship that varies in the range from approximately 0 to 1, in which the rating of feed quality or thermoregulation level is used as an argument. In the model, the average milk yield at the beginning of 2012 is taken from the data of the reviewed dairy farm, to then be able to compare how investing in thermoregulation and feed quality improvement technologies increases milk yield.

The emission sector in the model represents emissions from the company as well as emissions per unit of production. It is necessary to calculate the emissions to be able to evaluate the progress towards climate neutrality. In dairy farming, the main GHG emissions come from intestinal fermentation and manure management. Although in the documentation, the calculation of emissions from fuel consumption, electricity, and heat production is below the energy and transport sector, it is important to include it. In the model, the emission sector has two main stocks and two main flows (Fig. 1.3).

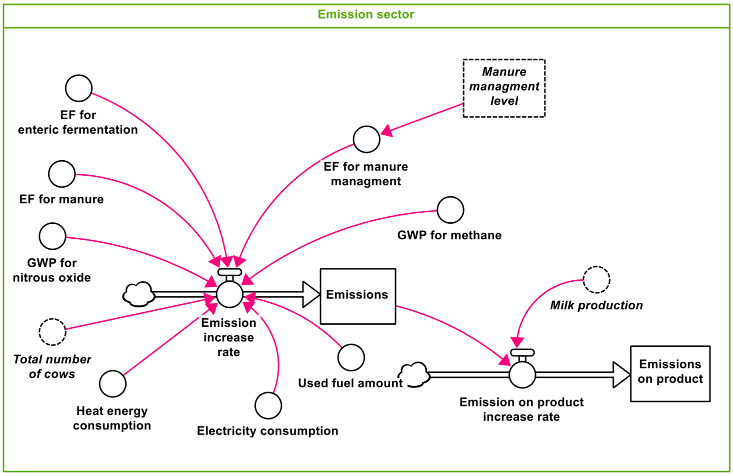


Fig. 1.3. Structure of the emission model.

Methane emissions from intestinal fermentation processes, GHG emissions generated to produce the consumed electricity and heat energy, as well as GHG emissions generated due to fuel consumption were calculated. Manure emissions were also calculated; however, several parameters must be considered when calculating manure. Organic matter and water make up most of the composition of manure. Manure emits both methane and nitrogen oxide emissions. How much methane is released from manure depends on its oxygenation, water content, pH level, and feed digestibility. How much nitrous oxide is produced depends on climate, pH, and manure management. To be able to perform a unified accounting of emissions, it is necessary to switch to CO_2eq. In general, both dairy farm data and predetermined constants were taken for the calculation.

It is important to investigate the economic sector as it is one of the determinants of investment and savings, providing a safety net and a sense of security for a farmer that the company will have a better chance of getting out of financial difficulties after taking risks on new investments. In dairy farming, the biggest expenses come from electricity consumption charges, dairy cow treatment costs, and capital costs, while income comes from milk production and sales, which are affected by the amount of milk sold, which depends on the yield obtained from the cow. Cow and milk prices are determined by the cooperative, additional income also comes from the sale of culled cows, where the price per cow depends on the market. Income is the factor that contributes to the accumulation of profit, because even if the expenses are very high, if there is a large income, the accumulated profit will also be within the norm. A feedback loop is also created from the amount of accumulated profit because investment decisions are made based on the amount of accumulated profit and own available financing. If a decision is made to make investments, then the reduction in retained earnings is determined by the channeling of funding to investments and the self-financed part (Fig. 1.4).

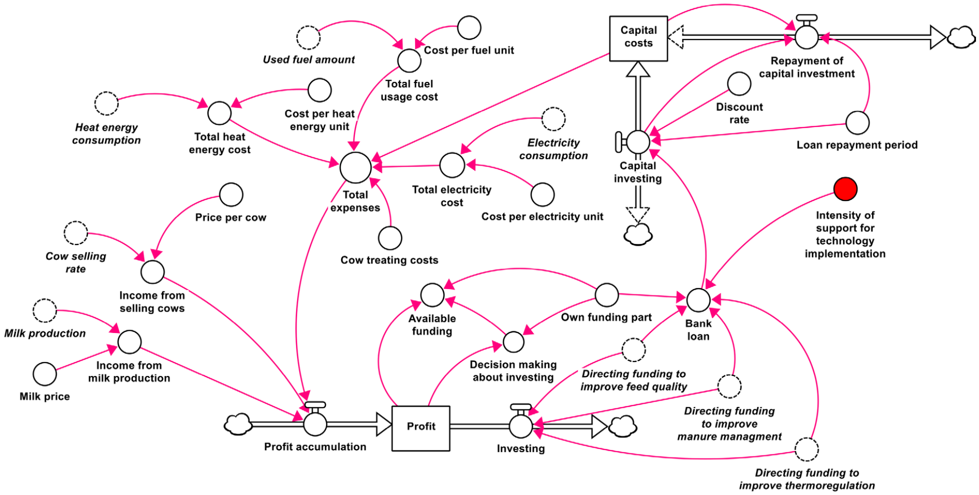


Fig. 1.4. Structure of the economic model.

The capital cost sector consists of one main stock – capital cost, the increase of which is determined by making capital investments, which is affected by the discount rate, bank loan, and the loan repayment period, while the reduction of the stock is affected by the repayment period, the capital investor, and the capital costs themselves. A dairy company needs to take a loan from a bank to cover the costs needed to make improvements on the farm, which are not compensated for by the support offered by the state.

To manage dairy cow manure, it is possible to use different management methods. Each type of manure management in the model is evaluated in points, which determine the level of management on the farm.

The model considers the time required to implement improvements at the management level (Fig. 1.5). The improvement of the level is also influenced by the ratio between the funding diverted for improvement and the investment required to improve manure management by one point. The necessary investment for improvement per cow is determined by the necessary investment for raising the quality indicator by one point, the difference between the maximum and management level in the farm, as well as the available support measures. To determine whether it is worth investing in the improvement of manure management, the implementation time of improvement measures is determined by whether the improvement of manure management contributes to an increase in income. If the manure is used to produce biogas, it is possible for the dairy farmer to receive payment for the manure sold to the biogas plant, unless the farmer himself has invested in the biogas plant.

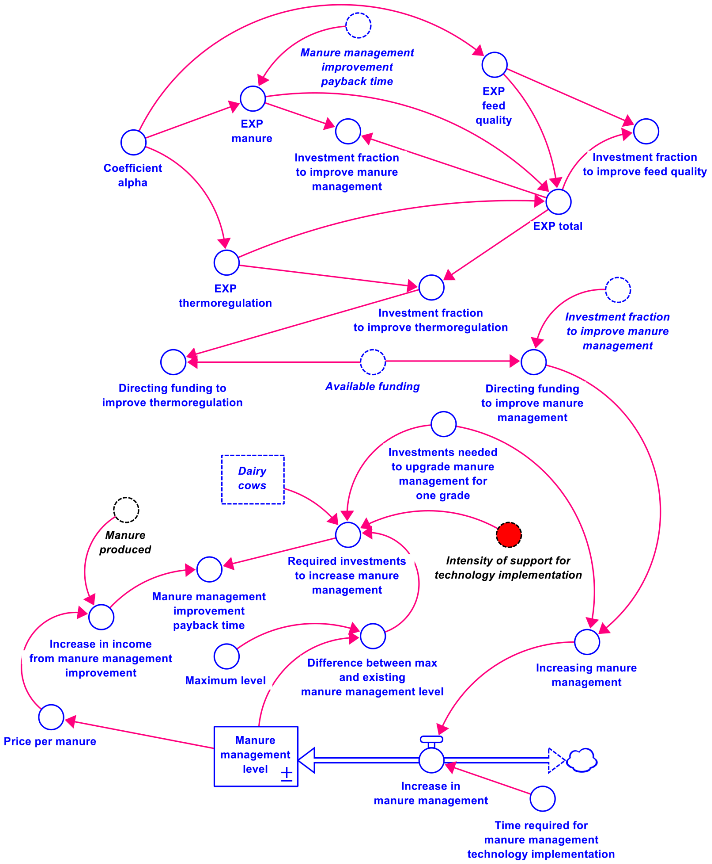


Fig. 1.5. Structure of the investment in manure management model.

Feed quality is included because it affects milk yield, the health of cows, generated emissions, and the farm's profit (Fig. 1.6). The most important indicator by which feed quality is determined is feed digestibility (%). In the model, feed quality is measured on a scale of 1 to 10, where 1 is the worst feed quality indicator and 10 is the best. However, to achieve high feed quality, it is necessary to invest in technologies to achieve the set goal. The effect of feed quality on milk yield varies between approximately 0.1 and 1 and is derived from a non-linear relationship using the feed quality score as the argument. The model also examines how income could increase as feed quality increases to determine the payback period. The increase in feed quality is affected by the time it takes to introduce new technology, as well as the ratio between the funding diverted to improve quality and the investment needed to improve quality by one point. The necessary investment for improvement per cow is determined by the necessary investment for raising the quality indicator by one point, the difference between the maximum and the existing level of feed quality on the farm, as well as the available support measures.

It is crucial to make improvements in thermoregulation to improve the well-being of livestock, which would also affect the milk yield significantly and reduce diseases. In the model, the level of thermoregulation is evaluated on a scale from 1 to 10, where 1 is the worst thermoregulation and 10 is the best. The effect of thermoregulatory level on yield varies between 0.1 and 1 and is derived from a non-linear relationship using the thermoregulatory level score as an argument. The model also explores how earnings could increase if the level of thermoregulation is increased to determine the payback period (Fig. 1.6).

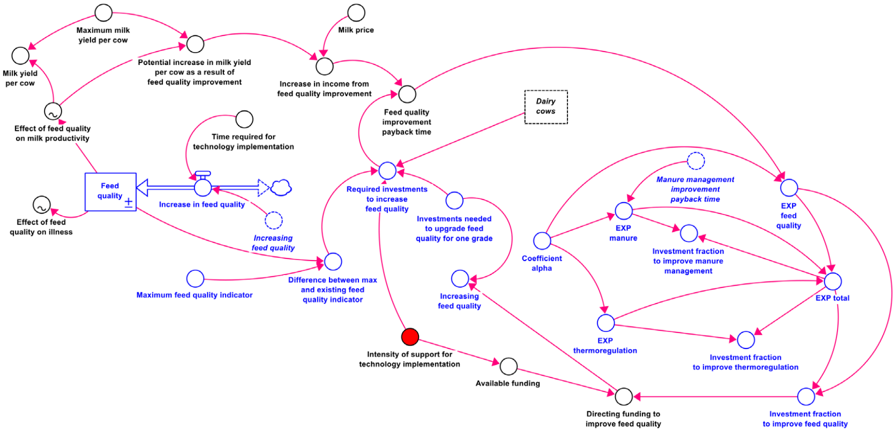


Fig. 1.6. Structure of the investment in feeding quality model.

The increase in the quality of thermoregulation is also affected by the time it takes to implement new technology, as well as the ratio between the funding diverted to improve thermoregulation and the investment to improve by one point. The necessary investment for improvement per cow is determined by the necessary investment for improving thermoregulation by one point, the difference between the maximum and existing levels in the farm, as well as the available support measures.

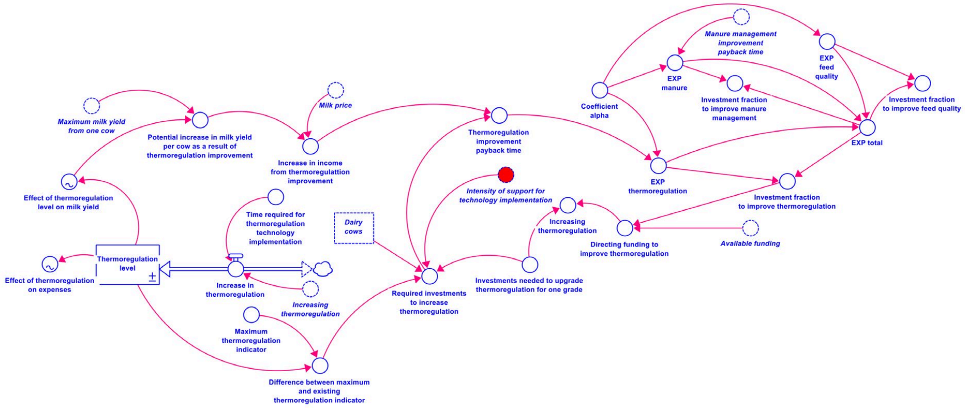


Fig. 1.7. Structure of the investment in the thermoregulation model.

2. RESULTS

2.1. Carbon balance results to evaluate a sustainable production of biogas

To objectively determine the total greenhouse gas emissions from fuel use, it is necessary to convert them into a single unit of measurement – CO_2 equivalents. As the global warming potential (GWP) of 1 t of CH_4 equals 25 t of CO_2 and 1 t to N_2O equals 298 t of CO_2, these values are used to produce total greenhouse gas emissions.

After summarizing the results, in 2017, GHG emissions were generated for the cultivation of maize, in total of 3.53 ktCO_2eq/year to treat it with heavy agricultural machinery which uses diesel fuel. Knowing that 5382 ha of biogas maize were managed in 2017, a result is obtained, which shows that 0.66 tCO_2eq/ha per year of GHG emissions are generated in the management of biogas maize fields with agricultural machinery. As a result, the highest emissions per ha are caused by using fuel to perform all the necessary treatment operations with heavy machinery, which is almost 0.66 tCO_2eq/ha (see Table 2.1). Emissions from tillage with nitrogen fertilizers and crop residue incorporation in the soil after harvest are relatively similar, amounting to 0.468 tCO_2eq/ha and 0.443 tCO_2eq/ha. In total, indicative emissions from biogas production from specially grown maize create 1.567 tCO_2eq/ha.

Table 2.1

Total Indicative Emissions from Biogas Production from Specially Grown Maize per ha

Fuel emissions, tCO_2eq/ha	Crop residue emissions, tCO_2eq/ha	N fertilizer emissions, tCO_2eq/ha	In total, tCO_2eq/ha
0.656	0.443	0.468	1.567

The biogas production process produces a very valuable by-product – digestate. It contains significant amounts of nutrients that are suitable for enriching the soil. The dry weight of digestate from biogas production using only maize is approximately 58.22 %. Digestion of fields with digestate can indirectly reduce greenhouse gas emissions, for example, digestate from 1 ha of maize green matter with a yield of 30 t/ha fully provides the required amount of potassium fertilizer and saves 31 % phosphorus and 44–45 % nitrogen fertilizer.

Accordingly, using a maize yield of 31.8 t/ha, it is possible to provide fertilizer for 1.06 ha of maize. As a total of 25 700 ha of maize was grown in Latvia in 2017, the use of digestate is topical, as well as interviews with farmers conducted within the framework of this study revealed that, unfortunately, there is a digestate shortage for field fertilization product, which is why additional synthetic fertilizers are used.

Using digestate fertilizer in tillage, 1.19 ktCO_2eq emissions were saved in 2017, while indicative emissions show a reduction of 0.22 tCO_2eq/ha (see Table 2.2).

Table 2.2

GHG Emissions Saved Due to Digestate Fertilizer

Harvested area, ha	Possible to fertilize, ha	Necessary nitrogen fertilizer emissions, $ktCO_2eq$	Potential nitrogen savings, %	Saved nitrogen emissions due to maize digestate in 2017, $ktCO_2eq$	Saved nitrogen emissions due to maize digestate in 2017, tCO_2eq/ha
5382.00	5704.92	0.0004683	–44.50	–1.19	–0.22

Although the use of digestate in field fertilization reduces emissions compared to synthetic fertilizers, the digestion of soil with digestate also generates GHG emissions. The results of analyses obtained from a farm producing biogas from maize indicate that the N content of the digestate fertilizer is, on average, 3.8 kg/t. Assuming that the maize harvest in 2017 was 171 147.6 t and that the amount of digestate from the amount of mass fed to the bioreactor usually ranged from 90 % to 95 %, in 2017, 158 311.53 t of maize digestate were obtained. Knowing the N content of digestate per 1 t, it is obtained that the total N per 5382 ha of the whole maize area was 0.60 kt. Based on the level 1 methodology of the 2006 IPCC guidelines, it is estimated that the digestate fertilization caused 2.82 $ktCO_2eq$ emissions in 2017, indicating indicative emissions – 0.0005 tCO_2eq/ha.

The methane content of biogas produced exclusively from maize silage is known to be 52 %, and the biogas yield per ton of maize is 202 cubic meters, which allows to calculate the total amount of biogas produced from maize harvested in Latvia, which is 34 571 815.2 m^3 from 171 147.6 t maize.

At a 1 % biogas leak in its production process in 2017, 2.63 tCO_2eq/year or 0.4963 tCO_2eq/ha GHG emissions were released into the atmosphere.

Calculations from the obtained data, see Table 2.3, show a reduction of 11.92 tCO_2eq/ha per year by using specially grown maize for biogas production in Latvia’s conditions.

Table 2.3

Indicative CO_2eq Emissions in 2017
from Biogas Production Losses According to the Principles Presented in the Scientific Article

Emissions from maize production, tCO_2eq/ ha year	CO_2 absorbed by maize, tCO_2eq/ ha year	Emission losses from biogas production (1%), tCO_2eq/ ha year	Emissions saved due to digestate, tCO_2eq/ ha year	Digestate fertilizer emissions, tCO_2eq/ ha year	Result, tCO_2eq/ ha year
1.61	14.32	0.49	–0.22	0.52	–11.92

2.2. Sustainability SWOT analysis results to evaluate the future of biogas sector in Latvia

Based on the literature review, a table for sSWOT (sustainability Strengths, Weaknesses, Opportunities and Threats) analysis was created accordingly (see Table 2.4), in which the strengths, weaknesses, opportunities, and threats were defined in the context of sustainability to shed light on the recent evaluation of Latvia's biogas sector.

Table 2.4

Aspects of sSWOT Analysis

Strengths	**Weaknesses**
- Great deal of experience and knowledge has been accumulated - Developed biogas sector, major investments have been made in existing equipment - Extensive and highly developed agricultural sector	- The potential of biogas is not fully exploited - Negative public opinion and perception of biogas due to previous experience with the Mandatory Procurement component - Major investments are needed in biomethane treatment and compression equipment - Uneven distribution of stations in the regions of Latvia - Impact and sustainability assessment of each biogas plant is needed
Opportunities	**Threats**
- Reduce emissions from the energy sector, including the transport sector - Reduce agricultural sector emissions and pollution - Opportunity to make full use of by-products - Opportunity for Latvia to meet all climate goals - To promote the involvement and interest of regions and companies in cooperating in the development of a single, effective system	- In the future, the bioeconomy will increasingly develop, taking over part of the stock - Reduction of financial support for biogas production - Strengthened biogas production criteria - Human factor in operational control mechanisms

The summarized aspects show that the sector is already facing various difficulties and future threats due to the forthcoming change, but it has no less strengths and opportunities. Looking at the strengths, it is clear that biogas production is especially suitable for Latvia due to its developed agriculture. The biogas sector in Latvia is also developed, large investments have already been made in it by both companies/producers and the citizens of the country through purchasing renewable energy produced from biogas in cogeneration plants for higher price. This is a testament to the extensive knowledge and experience already gained. But at the same time, the sector has acquired bad reputation and attitude among the citizens due to the conditions of the disorderly mandatory procurement component, causing great resistance and suspicion among energy consumers who are no longer willing to support the sector financially. And as the potential of biogas has not been fully exploited, the transition from cogeneration to biomethane production will again require significant investments. Since there are many but relatively small power stations in Latvia, which are unevenly distributed throughout the country, the question remains whether it is planned to build treatment and compression equipment separately for each small biogas plant. It is not yet clear how to do this more effectively, as no impact and sustainability assessment has been carried out for each biogas plant to understand how smart it would be for stations to promote the change.

Whereas the transition to biomethane will require new knowledge of the operation of the stations, one of the risks is the possible errors caused by human factor, which would delay and hinder proper production and resource management. It must also be kept in mind that the bioeconomy is likely to develop rapidly in the future, which could possibly take over some of the raw materials from which higher-value-added products would be produced. However, given that legislation has been adopted to strengthen the biogas production criteria while reducing financial support for electricity produced in cogeneration plants from biogas, switching to biomethane production, seems an opportunity to save the viability of the biogas sector in Latvia and help to meet the climate goals by reducing emissions in energy, transport and agriculture sector and pollution, making full use of by-products. While unreasoned and short-sighted management could be the next threat to the industry, smart management could, at the same time, encourage the involvement and interest of regions and companies in working together to create a coherent framework for a well-designed strategy for smart investment, financial autonomy, and independence, which leads to an affordable product.

The results obtained using the sSWOT analysis can be used not only at the level of the company but also at the level of the country in order to make a theoretical summary of the conducted literature analysis on the current issue in the context of sustainability, but the results may change depending on events in the country and the world as a whole.

2.3. Multi-criteria analysis results

2.3.1. Ranking of the most suitable bioresources for sustainable biogas production

After the TOPSIS methodology calculations were made, a rating was obtained, which, according to the accepted three criteria (environment, technology, economics), indicates that the given substrate is ranked as the most suitable substrate for biogas production in Latvia. These substrates were ranked from the best (1) to the worst (8), see the list in Table 2.5.

Table 2.5

Feedstock Ranking Determined with the TOPSIS Method

	Place in the rank
Pig manure	1
Poultry manure	2
Straw	3
Cattle manure	4
Sewage sludge	5
Organic waste	6
Maize silage	7
Wood	8

According to the criteria, pig and poultry manure were ranked in the first two places, while straw with pre-treatment was ranked third. The last three places were occupied by organic waste, maize silage, and wood, which took a convincing last place in the ranking (see Fig. 2.1).

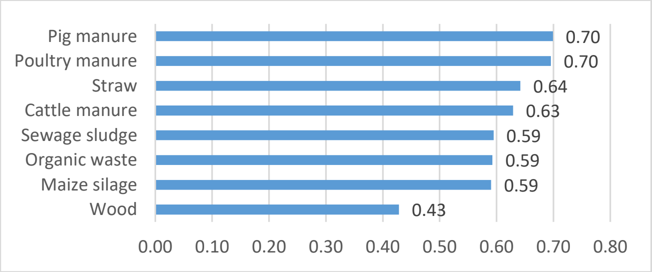


Fig. 2.1. The relative closeness to the ideal solution with the TOPSIS method for biogas production.

2.3.2. Sustainable biogas application in the energy sector

During the research, considering Latvian conditions, two scenarios were found to be sustainable for biogas application in the energy sector (see Table 2.6).

Table 2.6

Designation of Biogas Application Scenarios

Designation	**Biogas application**
Scenario 1	Combustion in CHP unit, when the produced electricity is further used in the transport sector
Scenario 2	Production of biomethane, when it is further used in the transport sector

The results obtained from evaluating scenarios using TOPSIS showed that biogas upgrading and use of biomethane as transport fuel is the optimal solution for Latvia and has the highest relative closeness to the ideal solution. The results of multicriteria analysis are shown in Fig. 2.2.

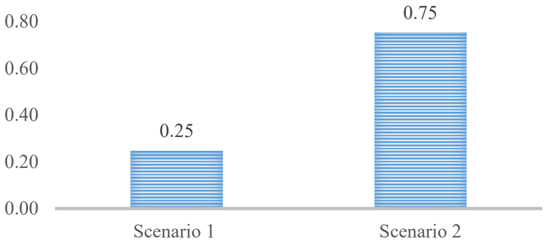


Fig. 2.2. The relative closeness to the ideal solution obtained with the TOPSIS method for biogas application.

The results show that upgrading biogas to biomethane and its further use in the transport sector as a transport fuel has a three times higher suitability rating than the biogas combustion in combined heat and power units to use the produced energy in the transport sector also as a transport fuel for electric vehicles.

2.3.3. Most suitable carbon farming methods

During the literature analysis, 6 possible carbon farming methods were selected, which could be applied in Latvian conditions and would be in accordance with Latvia's National Energy and Climate Plan. The choice was based on the European Commission Report about Sustainable Carbon Cycles and Latvia's Common Agriculture Politics (CAP) Strategic Plan. These methods can also be used in other countries with different levels of agricultural development.

In this article zero and minimal tillage was mentioned as one of the solutions, as it would mainly work as a method to reduce emissions due to significantly reduced diesel consumption and mineral fertilizers. Carbon sequestration with soils was considered and perennial plant cultivation in order not only to capture carbon but also store it. Whereas biogas production is already existing, it is an effective method of preventing agricultural waste emissions and producing a valuable and safe fertilizer. However, biogas development into biomethane is essential to maximize added value and also prevent other sectors' (such as transport) emissions, as discovered in the previous research, of suitable biogas application opportunities. The agroforestry sector is suitable for smallholder farms to increase carbon sequestration and storing in both soils and trees, reduce resource consumption and thereby emissions, and increase income, however, it must be in line with the foundations of biorefineries and focus on the efficient use of resources to achieve environmental, economic, and social goals. These methods are theoretically proving to be sustainable farming methods, which could possibly be introduced with funding for carbon farming to ensure not only environmentally sustainable management in the future but also the economy, reduce costs and maximize local agriculture sector competitiveness.

The final rank for the most suitable carbon farming methods in Latvia is collected and presented in Table 2.7.

Table 2.7

Final Rank for Carbon Farming Method Potential

Final Rank	**Carbon Farming Method**
1	Capture by soils
2	Biomethane
3	Perennial plants
4	Biogas
5	Zero tillage
6	Minimal tillage
7	Agroforestry

The TOPSIS analysis results confirm that by current area, budget, and environmental effectiveness, the biggest potential have such carbon farming methods as capture by soils and biomethane, but the most unsuitable solution in Latvian conditions would be the development of agroforestry (see Fig. 2.3). Minimal tillage and zero tillage as carbon farming solutions also do not show very high results.

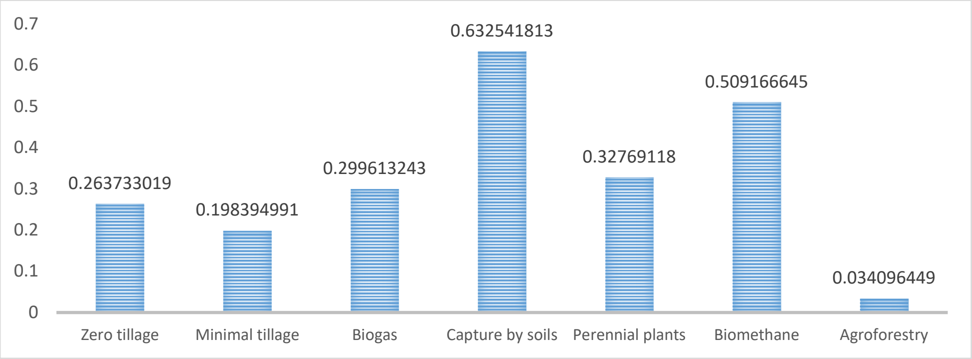


Fig. 2.3. The relative closeness to the ideal solution with the TOPSIS method for carbon farming methods.

2.4. The role of energy management in agriculture

A significant part of GHG emissions in Latvia comes from agricultural lands and cattle's intestinal fermentation, which is why in the Thesis, measures of GHG reduction are explicitly proposed in these areas. As the literature survey shows, a significant amount of emissions comes from land cultivation. The division of produced GHG emissions in both areas is as follows:

- Agricultural land: Implementation of precise fertilization system – plan development and required technique purchase – perform soil analysis. Use of practical techniques and technologies – combined field processing machines, zero or minimal tillage technique implementation. Land reclamation or improvement. Trenches around the cultivated land to avoid water pollution by fertilizers.

- Intestinal fermentation: Nutrient dosage management (plan developed and introduced). Nutrient additive utilization to improve digestion. Purchasing cattle that produce less methane (CH_4) in their metabolic processes.

It is worth noting that the emission division in the agricultural sector emissions does not include the emissions from transport utilization and maintenance. In the Latvian agricultural sector's emissions, fuel produces 11 % of the total GHG emissions. This percentage would decrease if carbon farming measures were implemented.

Five company-level measures were identified by reviewing scientific articles and examining practices in this field of research. The most effective energy efficiency measures for the company level were determined: optimized fertilizer production, energy-saving cultivation practices, improved water management, better livestock feeding, and use of renewable energy sources. By introducing these measures, the emission level, the consumed energy, and resources, as well as expenses can be reduced. During the research, an energy management system (Fig. 2.4) for the agricultural sector at the company level was developed, which can be adapted to evaluate and compare different agricultural companies.

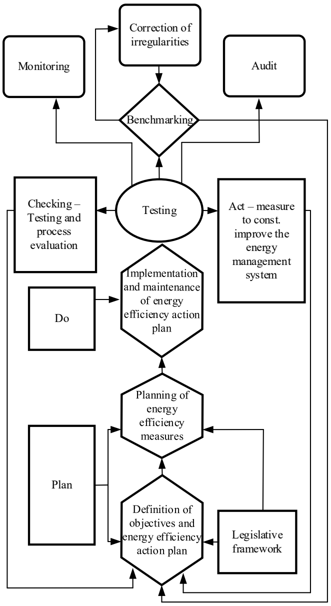


Fig. 2.4. Energy management framework for the agricultural sector at the company level.

The results have shown that using proposed indicators and benchmarking for farm comparisons is beneficial for improving the agricultural sector and reducing greenhouse gas emissions and energy consumption, leading to efficient, sustainable, and competitive farming.

2.5. The importance of resource efficiency and product production with higher added value in agriculture

The baseline scenario's outcome is represented by the flows taken from statistic databases and used as input data for the model with a correct mass balance. The bioresource flows for the base year 2015 are revealed in the Sankey diagram (Fig. 2.5). The amounts of material input criteria are fixed to show a historical perspective of the livestock sector. This shows that the biggest part of the obtained animal products in mass units consists of locally produced and imported milk, locally produced meat, and eggs. Wool and honey obtained in the examined mass units make up a small part of the total volume of animal products. The largest part of the milk and food produced from milk is exported, and a noticeably big part of the products produced is used for local consumption with some losses (mostly from milk production).

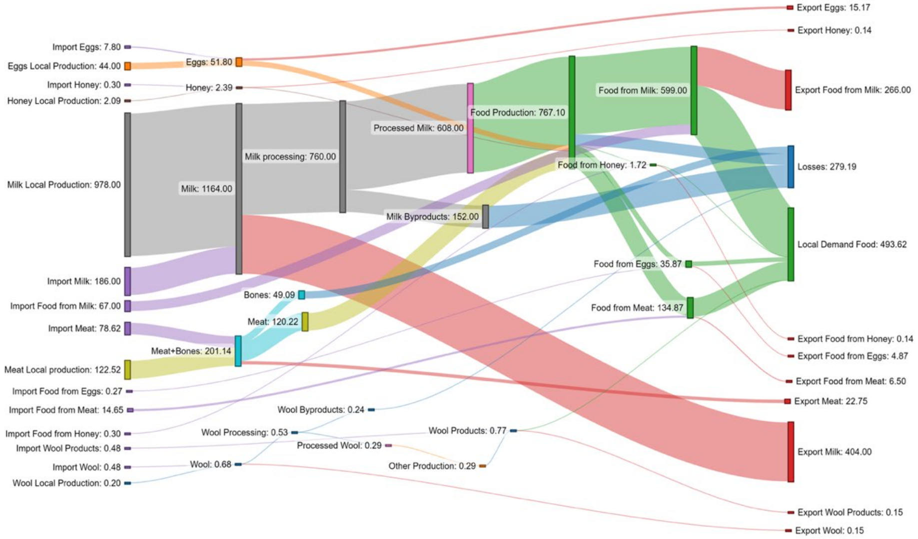


Fig. 2.5. Sankey diagram for the base year results (2015) in thousand tons, kt.

Even after introducing new technologies, the desired result of the complete use of by-products has not been achieved yet in any scenario because of local market limitations. However, it can be observed that trends calculated by the model show an increase in local and imported commodity volumes in 2023 and 2030 compared to the base year 2015 while having a decrease in total material losses. Although only part of the by-products was used in the production of the new products, their economic contribution over the 7-year period is noticeable. When introducing new technologies, the cumulative added value is calculated to exceed the set goal of a 30 % added value increase in bioresources in 2030 by more than two times (62 %) in years 2023–2030 in the case where these technologies are introduced starting in 2023 (see Fig. 2.6).

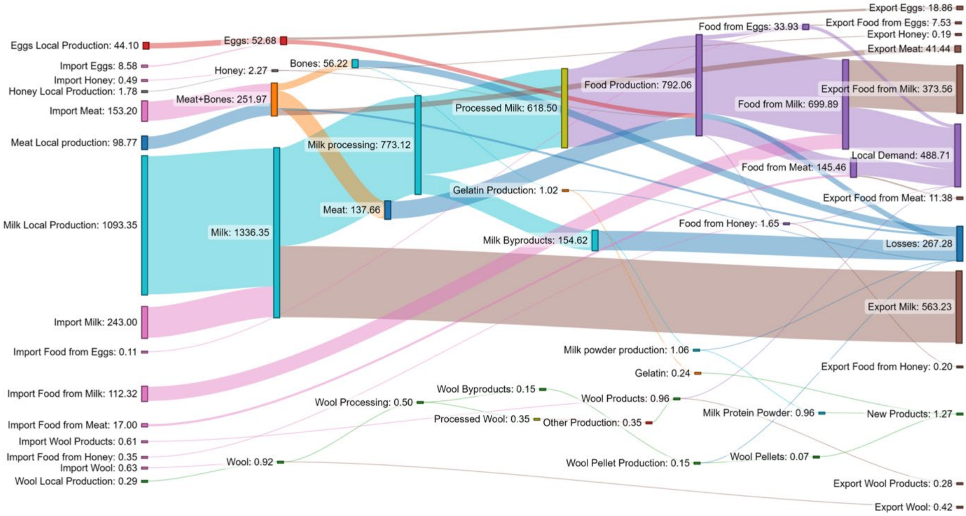


Fig. 2.6. Sankey diagram for the results of the year 2023 in thousand t, kt.

Similarly, a Sankey diagram for 2030 with the results of the simulation, including data added on new products (gelatin, wool pellets, milk whey protein powder, and eggshell powder), is shown in Fig. 2.7. The graph shows that flows for both domestic milk production and imported milk will increase, which are the largest flows, still followed by imported dairy food and meat products. The by-products generated in the milk processing process are almost constant, which is the main source of by-products, but due to the new products, the total resource loss decreases by 33.9 kt. The final food flows show that the volume of exported milk has increased by 1.6 times compared to 2015, while food produced from milk has increased by almost 1.9 times. Other flows have also grown significantly, for example, exported meat by 2.7 times, exported wool and its products by 3.1 times, and exported eggs and their products by 1.7 times, but these flows are smaller against the overall background in mass units.

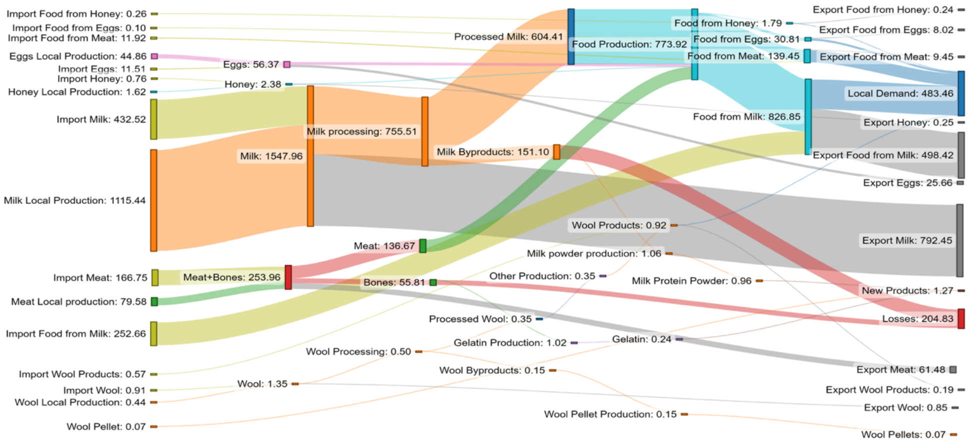
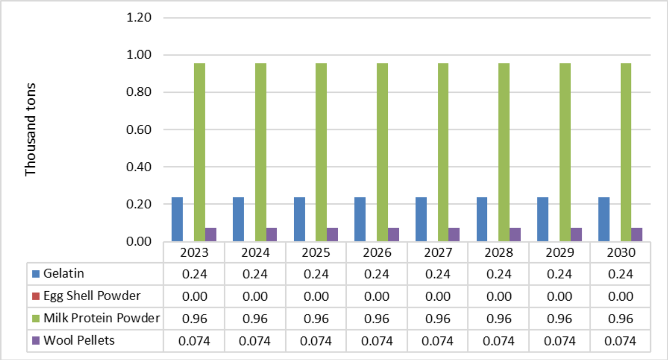


Fig. 2.7. Sankey diagram for the results in the target year (2030) in thousand t, kt.

Among the new products, the model results show produced milk protein powder, gelatin, and wool pellets (see Fig.re 2.8) but no eggshell powder. The production of the new products is influenced by the efficiency and cost of the production processes and the added value per unit because the eggshell powder has a relatively low production efficiency due to the mass ratio and relatively high losses when the powder is produced from a whole egg.



	2023	2024	2025	2026	2027	2028	2029	2030
🟦 Gelatin	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24
🟥 Egg Shell Powder	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
🟩 Milk Protein Powder	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96
🟪 Wool Pellets	0.074	0.074	0.074	0.074	0.074	0.074	0.074	0.074

Fig. 2.8. Number of new products produced, kt.

The model reaches the limits (e.g., the capacity of resource application, economic viability, and demand limit) of available resources for milk protein powder and gelatin; thus, the same amount is produced every year. Protein powder and gelatin reach the available resource limits immediately in 2023, and therefore, their production is constant. As for the wool pellets, all the wool resources available are used to produce wool pellets. The forecasted demand for pellets, on the other hand, is 58.37 thousand tons. The pellets produced are only about 0.1 % of this demand value. If forecasted demand values were removed, then all added value would be covered by milk protein powder.

Value added from new products as a share of total value added in different years ranges from 7.6 % to 8.2 %. On average, the added value is 7.9 % per year. This percentage changes as the number of other products produced changes from year to year, but the number of new products produced remains the same each year (see Fig. 2.9).

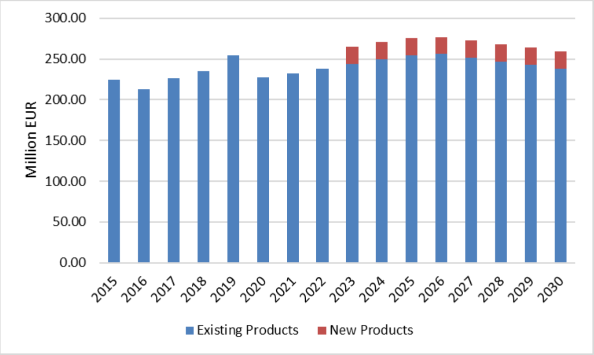


Fig. 2.9. Total existing and new product added value, EUR million.

Figure 2.10 shows the added value for newly produced added-value products. In this case, milk protein powder takes up most of the value added, which is probably since milk products constitute the largest share of food products and the added value per unit of milk protein powder is larger than that of other products.

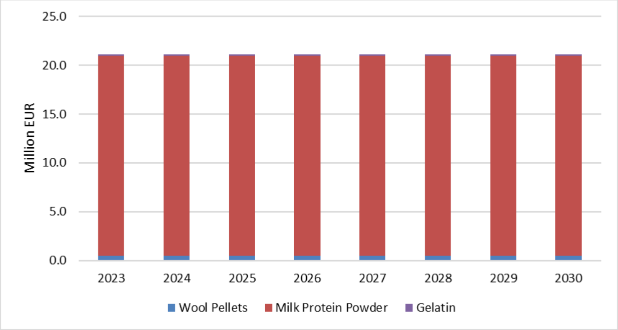


Fig. 2.10. Added value structure for newly produced added-value products.

2.6. Agriculture sector’s transition towards climate neutrality

By the calculations based on the data of the dairy company, it was found that it is possible to achieve several improvements by investing. By building a new barn, the company:

- reduced electricity consumption by 7000 kWh/year, which is a 46 % reduction;
- increased milk yield from one cow by 2129 kg/cow/year, which is a 25 % improvement compared to the year of making the investment;
- increased milk yield from one cow by 3987 kg/cow/year, which is a 42 % improvement, compared to the 10-year average milk yield before the investments.

By investing in feeding technologies, the company increased milk yield by 174 kg/cow/year, which is a 2 % improvement compared to the year of making the investment.

The number of generated emissions increases every year as the number of cows increases, which thus increases the number of emissions generated from intestinal fermentation processes. However, because of the introduction of innovations, it is possible to observe a reduction in emissions, as a higher level of manure management reduces emissions from manure.

When comparing the emissions created in these scenarios, 2017 and 2022 were taken as reference points, and it was determined that with the help of Scenario 2, compared to Scenario 1, emissions were reduced by 0.1 % in 2017 and by 10 % in 2022.

Then, the generated emissions per produced quantity, which is the most essential and objective indicator in agriculture, was examined. Figure 2.11 shows the emissions per produced amount of production, which is measured in ktCO$_2$eq/kt of milk produced. In general, it can be observed that Scenario 1 also produces the highest emissions for production, while Scenario 2 produces fewer emissions than Scenario 1 only from 2015, but in Scenario 3, significant changes can be observed compared to the other two scenarios.

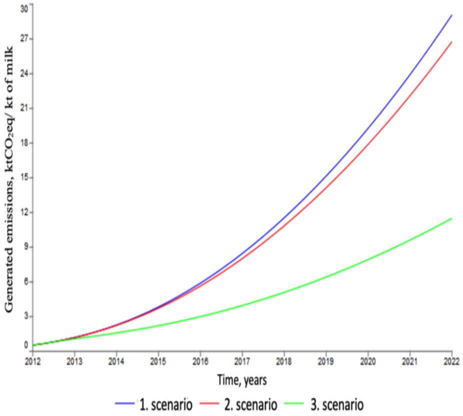


Fig. 2.11. The total amount of emissions generated per amount of output produced in the scenarios.

When comparing the generated emissions between the scenarios, 2022 was taken as a reference point. It was found that by implementing Scenario 2 (when investments only in manure management technology development are made), compared to Scenario 1 (when no improvements are made), it was possible to achieve a reduction in emissions by 8 % (2.32 ktCO$_2$eq/kt of milk) in 2022.

When comparing the generated emissions between Scenario 2 and Scenario 3 (where improvements in manure management, thermoregulation and feed are made), it was found that implementing Scenario 3 would allow to achieve a reduction in emissions by 57 % (15.28 CO$_2$eq/kt of milk) in 2022.

When comparing the generated emissions between Scenario 1 and Scenario 3, it was found that by implementing Scenario 3, it is possible to achieve a reduction in emissions by 60 % (17.59 CO$_2$eq/kt of milk) in 2022.

The increase in the number of cows occurs up to and including 2016, but remains constant thereafter. Comparing the year 2013 with the year 2022, it can be determined that the number of cows has increased by 23 %. The initial milk yield per cow was 6.377 t/cow, which remains unchanged in Scenario 1 and 2, but in Scenario 3, it is possible to observe an increase in milk yield in the maximum average milk yield per cow, which is 15.870 t/cow per year. Comparing the first year of Scenario 3 with the last one, it is possible to observe an increase of 69 % (5261.45 t more), but comparing Scenarios 3 and 1 of 2022, it can be concluded that by investing in the improvement of the farm, it is possible to achieve a 60 % higher amount of production, which is 4550.99 t more (Fig. 2.12).

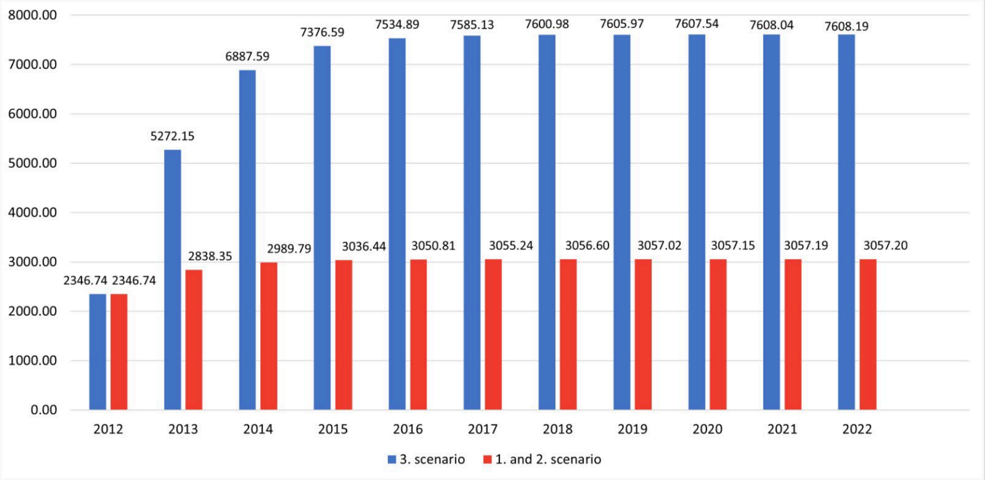


Fig. 2.12. Milk production in Scenarios 1, 2, and 3.

3. SUMMARY OF THE RESULTS AND DISCUSSION

1. Carrying out carbon balance based on the life cycle analysis for assessment of the impact of biogas production from a certain resource, it is possible to determine the environmental impact in terms of GHG emissions.

2. The carbon balance allows to analyze the emission sources and their impact to improve the balance by reducing these emissions; however, it is essential to combine efficiency in agriculture to reduce atmospheric emissions without losing sight of sustainable farming so as not to negatively impact soil, water, and the environment.

The research on carbon balance proves that by its novelty – carrying out carbon balance by the methodology based on life cycle analysis for assessment of the impact of biogas production from maize, it is possible to determine the environmental impact in terms of greenhouse gas emissions on the atmosphere. Despite the consumption of diesel fuel and emissions from the maize production process, maize absorbs much more carbon than is produced during photosynthesis, thus, if 1 % of biogas leakage is assumed in its production process, as well as knowing by previous calculations that 34 571 815.2 m^3 of biogas can be obtained from 5382 ha specially grown maize, its production from specially grown maize can save 1.86 kg CO_2 eq emissions per 1 m^3 of produced biogas.

There are several possibilities in which the carbon balance can be further improved by reducing emissions from the agricultural process by growing the substrate; for example, using zero-emission electric tractors for soil tillage could reduce total biogas maize growing emissions by 43 %. But there are also processes that would not be desirable to reduce emissions, for example, the tractor driving frequency reduction in the field – the fertilization process can theoretically be carried out immediately and at once, but fertilization is divided into several stages in order to gradually spread the substances for a favorable plant vegetation process, as well as not to promote pollution of water due to drainage that leads to erosion. After harvest, 28 % of total emissions come from nitrogen emissions from crop residues (above and below ground). Unfortunately, these are emissions that cannot be reduced because, although these residues could theoretically be used for biogas production, the removal of crop residues from maize fields would have a negative impact on the environment and soil quality. It is essential to combine efficiency in agriculture to reduce atmospheric emissions without losing sight of sustainable farming, so as not to negatively impact soil, water, and the environment.

3. Biogas's transition from cogeneration to biomethane production is a way to maintain the viability and sustainability of the industry; at the same time, it means facing economic, social and technical challenges.

Regarding the transition of biogas from cogeneration to biomethane, because of current decisions, seems to be a way to save the viability and sustainability of the sector. At the same time the sector faces the following challenges:

- reaching a maximally efficient and smart system that involves biogas producers and regions in planning investments;
- being as financially independent as possible in the future;
- changing the negative public opinion and perception;
- bioeconomy development, which may take over part of the stock;
- achieving maximum resource efficiency;
- playing its full role on the way to climate neutrality and reducing agricultural, transport and energy sector greenhouse gas emissions;
- critical assessment of sustainability, resource availability and the possible way of selling the product for each biogas plant.

4. It is important to use of any waste for (at least) energy production, but pig and poultry manure are the most suitable raw materials for biogas production in Latvia, especially if combined with straw or other plant biomass by-products.

To meet some of these challenges and achieve maximum resource efficiency in the context of Latvia, a multi-criteria analysis using TOPSIS methodology was made taking into account three main parameters: economic feasibility, substrate efficiency, and environmental friendliness. It showed that pig manure is the most suitable raw material for biogas production in Latvia, while poultry manure was ranked second, with very little difference in value from pig manure. Despite the claim that lignocellulose-rich plants are not a successful choice for biogas production, straw was the third-best substrate for biogas production in Latvia, while cattle manure was in the 4th place. Wood was in the last place; it was identified as the most unsuccessful choice for biogas feedstock. Specially grown maize for biogas production had the penultimate place in the ranking; until now, it has been a popular substrate for agricultural biogas production. Based on the criteria used in the model, the organic waste and sewage sludge are roughly the same as biogas maize in the rating. This research proves that pre-treatment straws can serve as a great substitute for biogas maize. The use of any waste for energy production is important, but agricultural biogas production from combining manure and straw shows the greatest potential.

5. Biogas application in biomethane production is a more effective and more sustainable solution for the energy sector than biogas combustion in CHP units.

During the biogas application in energy sector research, the sustainable application of biogas for the energy sector was evaluated. The study examined the case of biogas used in cogeneration plants and electricity produced in cogeneration for auto transport versus the conversion of biogas into biomethane for the use of auto transport. Latvia was used as a case study in this research. The research shed light on the sustainability aspects of biogas production and use in future and on how renewable energy applications can move forward in Latvia. TOPSIS method was used to evaluate two scenarios: 1) biogas production and cogeneration in the CHP unit and use of electricity produced in the CHP unit for auto transport, and 2) biogas upgrading to biomethane and use of it for auto transport. The results show that biogas application to produce biomethane is the best and most sustainable solution.

6. The biggest potential for carbon farming methods in Latvia are carbon capture by soils, biomethane production and planting of perennial plants, while agroforestry turned out to be the least suitable method for Latvian conditions.

The study of carbon farming solutions also confirmed the need for and importance of including biomethane in the strategy of climate-neutral agriculture. The TOPSIS analysis results confirm that by current area, budget, and environmental effectiveness, the biggest potential is for such carbon farming methods as capture by soils, biomethane, and perennial plants. As biomethane production is most directly related to biogas production, as well as zero tillage and minimal tillage to carbon capture by soils, it reaffirms that all these methods are interrelated and important for moving towards sustainable agriculture. Agroforestry in Latvian conditions got the lowest compliance in this rank; however, perennial plants received a relatively high-ranking place. These six subjectively selected carbon farming methods and calculations can be used in other countries with different levels of agricultural development. Since the calculations were made based on assumptions from scientific publications, it is recommended to reconstruct these estimates using accurate data if available.

7. Carbon farming cannot ensure complete climate neutrality of the agricultural sector alone, as it mainly focuses on field crop production; therefore, it is important to develop resource and energy efficiency, which is possible to implement in every agricultural enterprise.

However, such solutions cannot ensure complete climate neutrality of the agricultural sector; as the types of agriculture are numerous and very diverse. It is important to view the entire system in its entirety, including all elements and methods to achieve the best result, and it is unimaginable without resource and energy efficient management, where no more is spent than necessary. The energy management system can and should be implemented by agricultural companies. It would reduce energy consumption, optimize costs, and reduce GHG emissions. However, informative measures are required to implement these basic energy management principles in companies. The companies should follow the initial monitoring of energy consumption data to understand where electricity and heat are consumed the most and the potential for reducing this amount. It would be advisable for agricultural companies to install an intelligent energy system. It is a sustainable energy supply system that contains information on energy consumption and options for reducing it based on monitoring the system's performance. The energy management system can be combined with greenhouse gas reduction measures, such as organic farming and other methods and guidelines already introduced in Latvia. However, not all companies follow these guidelines. It is necessary to develop a specific policy and support program for companies to implement energy management, as implementing the basic principles of energy management or the energy system requires investment. By implementing the energy system in an agricultural company, energy consumption in this company can be assessed and measures can be taken to reduce energy consumption. Policy and agricultural guidelines should focus on optimizing farming and manure management. Results from the research show that energy efficiency improvement measures are a more effective way to reduce CO_2 emissions. If measures are applied to reduce GHG emissions from the mixed agricultural companies, the average emissions would be reduced by 43%. By implementing the basic principles of energy management, it would be possible to reduce the average energy consumption by 17 % in the studied companies. However, it depends on the specifics of the company and what measures it can implement.

8. It is crucial to combine resource efficiency with the production of products with higher added value from local agricultural by-products because this would make an outstanding contribution to both the company's and the local economy.

9. The TIMES model makes it possible to evaluate aspects related to an increase in added value empirically with a time reference to find an optimal scenario for the development of the agricultural sector.

If it was found that it would be necessary to introduce energy efficiency measures in any company, then a study was carried out for resource efficiency too. This is very important because when implementing various measures to move towards climate neutrality, a drop in productivity is possible, which reduces the company's income, therefore, it is necessary to explore the possibilities and importance of increasing the added value of resources in the agricultural sector. The study presents a novel model that helps to investigate the application of new technologies in the agriculture sector and evaluate their contribution to the agriculture sector in terms of the production of new competitive products and the development of biorefineries that have a significant impact on agriculture and other sectors' overall resource efficiency. The model shows that the production of local resources with a higher added value would bring a more outstanding contribution to the local economy. In terms of mass, however, the desired result of the maximum use of by-products was not achieved in any scenario. When introducing the new technologies starting in 2023, the local bioeconomy benefits strongly by producing higher-added-value products.

In this study, the evaluation of aspects related to biorefinery implementation is performed with the developed model in relation to the national bioeconomy goal set for a 30 % increase in the added value of bioresources by 2030. The new technologies introduced in the model that create higher added value from bioresources obtained in animal husbandry are the production of protein powder, gelatin, and wool pellets. The new technologies in the model are available starting in 2023 and are used in the production of added-value products. The cumulative added value produced from 2023 to 2030 is about 62 % above the added value produced by currently used technologies. However, the maximum use of bioresources has not been achieved due to assumptions limiting the production of new products in line with the market size for these products. The production of milk protein powder and gelatin reached the set market size limit.

The production of wool pellets reached the maximum of what was possible given the amount of wool processing by-products. The remaining eggshell powder amount could potentially be decreased with higher eggshell powder production efficiency or higher added value for eggshell powder.

The model makes it possible to evaluate aspects related to an increase in added value empirically with a time reference to find an optimal scenario for the development of the agricultural sector. This can be useful for making agricultural stakeholders aware of the development of biorefineries and their positive impact on the local economy. The obtained optimal scenario can be used in national policy planning, as it clarifies which technologies are worth investing in and what agriculture residuals have the most potential to be used to produce higher-added-value products. Further research with statistical data from other sources and the introduction of more new technologies can be applied in the TIMES bioeconomy value model (TIMES-BVM) for defining more possible scenarios for the development of biorefining and development of suggestions for bioeconomy policy planning.

10. Agriculture is the sector where energy and resource efficiency decisions should be examined very carefully because unprofessionally made decisions can not only threaten the existence of companies with productivity losses but also harm the environment.

11. Regarding animal husbandry, the strategic documents emphasize manure management and improving feed quality, but an important missing element is visible – a section on improving the thermoregulation of animals.

12. It should be noted that the larger the volume of production, the lower the number of emissions produced per unit of production. However, in agriculture, it is possible to achieve it mainly through investments in new, modern technologies.

13. The created system dynamics model allows both to understand and to model possible scenarios; to calculate not only the impact of a given company or sector on the environment by calculating the generated emissions per unit of production, but also to calculate the investments required to reduce 1 kt of CO_2eq generated in the company. Such a model makes it possible to make sustainable decisions not only at the level of the company but also at the level of state policy to simultaneously promote environmental goals, economic growth, and the development of the national economy.

Finally, when answers to many topical questions have been obtained, it is important to look at the system as a whole; a dairy company was used for such inspection, which, in the author’s opinion, perfectly reflects the specifics of agriculture in the management of resources and energy – it is a huge responsibility because living creatures live in it and not only their health but also productivity depends on the decisions made. The other subsectors of agriculture should also be looked at in the same manner because, as already revealed in the first study of this Thesis, agriculture is the sector where energy and resource efficiency decisions should be looked at very carefully because unprofessionally made decisions can not only threaten the existence of companies, but also harm the environment.

Regarding animal husbandry, the strategic documents emphasize manure management and improvement of feed quality, but an important missing element is visible – a section on improving the thermoregulation of animals. All these elements (manure management, feed quality, and thermoregulation) are integral parts that must work in one system because their improvement significantly improves productivity, reduces energy consumption, improves resource efficiency, and reduces direct and indirect emissions not only in agriculture but also in the energy and transport sectors. It should be noted that the larger the volume of production, the lower the number of emissions produced per unit of production. However, in agriculture, it is possible to achieve it mainly through investments in new, modern technologies because an ill-considered economy of energy or resources can result in yield losses, which would not be a sustainable solution at the company or at the state level. Agriculture cannot focus only on energy efficiency and greenhouse gas emissions reduction without considering aspects such as the impact of the activities on yield, technology, free available funds, market stability, state support, and others. It is important to look at ways to increase productivity while introducing energy-efficient and resource-efficient methods – a thoughtful management model. Only this way it would be possible to achieve sustainability from both an environmental point and also from an economic point.

However, such technologies require investments, which are directly affected by the company's income and savings and, in turn, are affected by the volume sold and the price of the product in the market, support mechanisms, existing technological level, and efficiency. To ensure the sale of the product on the market at a sufficiently high price for the company to develop innovation, it is important to develop a national policy that guarantees sales of the local producer's products. This is very important because if there is more support and protection for agricultural enterprises in competing countries, not only will the price be competitive but the safety of selling the products on the market will also fall. The ill-considered local policy fails to promote opportunities for local producers' innovation development compared to competing countries' companies. This is especially critical now when adapting to climate change and trying to fulfil the Green Deal goals; failing to develop sustainable policies risks destroying the local market's ability to compete and exist. The created system dynamics model allows us both to understand and to model possible scenarios, to calculate not only the impact of a given company or sector on the environment by calculating the generated emissions per unit of production but also to calculate the investments required to reduce 1 kt of CO_2eq generated in the company. Such a model makes it possible to make sustainable decisions not only at the level of the company but also at the level of state policy to simultaneously promote environmental goals, economic growth, and the development of the national economy.

CONCLUSIONS

1. By carrying out a carbon balance to assess the impact of biogas production from a certain resource, it is possible to determine the impact of this process on the environment in terms of GHG emissions, and such a carbon balance calculation provides an opportunity to analyze the sources of emissions and their impact to improve the balance by reducing emissions.
2. The calculation of the carbon balance for biogas produced from specially grown maize proves that the impact of biogas produced from possibly the most provocative raw material can be evaluated favorably in terms of GHG emissions; moreover, considering that approximately 6th of all available manure resources per year in Latvia were used for the biogas production at the time of the study, it proves the currently underutilized potential of biogas.
3. It is important to use any residual products (at least) for energy production is important, but pig and poultry manure were determined to be the most suitable raw materials for biogas production in Latvia, especially when combined with straw or other plant biomass by-products.
4. Transitioning the use of biogas from burning it in a cogeneration plant to the production of biomethane is a way to maintain the viability and sustainability of the biogas industry to promote the production of renewable energy in the agricultural sector from by-products from which it is not possible to produce other products with a potentially higher added value. Biomethane production could potentially have a positive impact not only on agriculture but also on the transport sector, which is one of the largest GHG emissions sectors.
5. The use of the EU's carbon farming initiative is essential, given that it will be compensated in line with the development of new EU business models. Such a compensation system can potentially serve as an effective support mechanism mainly in field crop production, which would help in the transformation of agriculture towards more sustainable methods. However, at the time, it is very important for each country and company to evaluate the most suitable methods for them, including available soils and conditions. In the study, the suitability of various methods for the conditions of Latvia was determined according to several criteria, in which it became clear that the greatest potential of carbon farming in Latvia is various methods of capturing carbon in the soil, as well as biomethane production, while the most unsuitable is agroforestry.
6. Since carbon farming mainly focuses on field crops, it cannot be the only solution to moving agriculture towards climate neutrality. One of the most important practices is implementing energy efficiency management, which is possible in absolutely every agricultural enterprise.
7. It is essential to combine resource management with the production of the highest value-added products from local agricultural by-products, as this would contribute to strengthening the economy of both the company and the country. This is particularly important not only for the effective use of all available resources but since, during the

transition period from traditional agricultural methods to sustainable ones, there is a possible decrease in yield, it is an opportunity to increase the economic benefit from existing resources.

8. The developed TIMES model makes it possible to empirically evaluate the application of new technologies in the agricultural sector to increase the added value through the production of new products with a higher added value and to find an optimal scenario for the development of the agricultural sector. The case study of animal husbandry proves that with the help of new technologies and using part of animal husbandry by-products that end up as losses, it is possible to increase the added value by an average of 7.9%, which could be increased by covering the export possibilities of the new products.
9. Agriculture is an industry where energy efficiency and resource efficiency decision-making should be developed very carefully, as unprofessional decisions can not only threaten the existence of companies with productivity losses but also environmental damage.
10. Regarding animal husbandry, in the strategic documents, manure management and improvement of feed quality are especially emphasized, but after the case study of the dairy farm, an important missing element can be seen – a proposal for improving thermoregulation of animals, which is the main prerequisite for improving productivity.
11. It is important to consider that in agriculture, it is crucial to look not at the emissions per company but at the emissions per unit of production, which is the most objective indicator of the company's sustainability and progress towards climate neutrality.
12. In agriculture, the increase in productivity in accordance with the implementation of environmental measures can be achieved mainly with new, modern technologies, which require investments. However, for companies to be able to invest in new technologies and develop towards climate neutrality, it is important that favorable conditions are created so that their products are competitive in the local and global markets, as well as the adoption of thoughtful political decisions.
13. The created system dynamics model allows both to understand and to model possible scenarios, to calculate not only the impact of a specific company or industry on the environment by calculating the generated emissions per unit of production but also to calculate the necessary investments to reduce 1 ktCO_2eq generated in the company. Such a model provides an opportunity to make sustainable decisions not only at the level of the company but also at the level of state policy while promoting the achievement of environmental goals, economic growth, and the development of the national economy. The case study proved that with the help of investments in new technologies, it is possible to simultaneously move towards climate neutrality, reducing 60 % of the generated emissions per ton of production, while increasing productivity.
14. The hypothesis was confirmed: effective progress towards climate-neutral agriculture is possible only if it is carried out in a comprehensive way, combining three main prerequisites: resource management, resource efficiency, and carbon farming, as well as

parallel production of products with higher added value and/or non-reduced, preferably increased productivity.

15. To promote the successful progress of local companies towards climate neutrality and at the same time maintain their competitiveness in the market, the strategy determined by the state is very essential to guide the transformation of companies in a professional way, while the methodologies and models developed in the Thesis can be used for decision-making processes.

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