RIGA TECHNICAL UNIVERSITY

**Beate Zlaugotne**

# MIRRORING DECISION-MAKING IN THE RESOURCE VALUE CHAIN

Doctoral Thesis

# RIGA TECHNICAL UNIVERSITY

Faculty of Natural Sciences and Technology
Institute of Energy Systems and Environment

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# MIRRORING DECISION-MAKING IN RESOURCE VALUE CHAIN

**Doctoral Thesis**

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# Annotation

Natural resource depletion, inefficient resource use and consumption as well as related environmental pollution and degradation represent significant challenges driven by conventional economic frameworks. The European Union launched Green Deal framework addresses these issues by advocating for a transition towards a resource-efficient, circular, climate-resilient economic paradigm. Although the policy framework is clearly defined, the execution of effective decision-making for the implementation of the Green Deal driven resource value chains continues to face challenges at the international, national, municipal and even sectoral tiers.

In the Doctoral Thesis "Mirroring decision – making in resource value chain" its author, Beate Zlaugotne, developed a comprehensive yet adaptable in scope multi-factorial decision-making methodological framework to enhance decision-making for sustainable solutions within the resource value chain. The developed decision-making methodology is based on incremental complexity framework, which distinctively combines three essential decision-making levels – strategic fit, sustainability and utility value and covers international, national, municipal and sectorial scopes within energy, waste, industry and agriculture resource sectors. The developed methodology was implemented across nine case studies, each requiring decisions on the most sustainable solutions to managing the resource value chain.

The Doctoral Thesis is based on a set of 14 methodologically unified scientific publications, aligned with the structure of the Thesis. The Thesis consists of introduction and three main chapters and conclusions. The introductory chapter presents the relevance, purpose and hypothesis of the work, in scientific and practical terms, and the general structure of the Thesis. The first chapter presents a literature review that explores the ongoing advancements of European Union countries in resource efficiency and identifies the primary barriers encountered in the decision-making processes concerning resource value chains. The methodological framework of the Doctoral Thesis is presented in the second chapter. It outlines the incremental complexity-based Thesis algorithm and specifies the techniques applied at three levels: strategic fit level – utilising tools such as SWOT analysis and indicator assessment; sustainability assessment level incorporating life cycle assessment, life cycle costing and social life cycle assessment; and utility value – illustrated through a multi-criteria decision-making method. In the third chapter, the developed incremental complexity methodology is tested through nine case studies, including (1) energy use in Latvia's agriculture sector, (2) valorisation of healthcare waste and (3) fishing nets waste, (4) solutions for fish feed production from agricultural products, (5) prioritization of metal scrap melting technologies for Latvia, (6) ranking of eight European countries based on greenhouse gas emission metrics, (7) assessment of renewable energy technologies in a municipality, (8) selection of the most appropriate uses for bran by-products and (9) comparison of globally used healthcare waste treatment technologies. The conclusion chapter provides a summary of the Thesis results.

The Doctoral Thesis is written in English and consists of 269 pages, including annexes – published 14 scientific publications.

# Anotācija

Dabas resursu izsīkšana, resursu neefektīva izmantošana un pārmērīgs patēriņš, kā arī ar to saistītais vides piesārņojums, ir nozīmīgi izaicinājumi, ko veicina tradicionālie tautsaimniecības modeļi. Eiropas Savienība ir izstrādājusi Eiropas Zaļā kursa pakotni, lai veicinātu pāreju uz resursefektīvu, aprites ekonomikā balstītu un klimatnoturīgu tautsaimniecības modeli. Lai gan politikas ietvars ir skaidri definēts starptautiski un dalībvalstu līmenī, efektīvas lēmumu pieņemšanas īstenošana, ieviešot Zaļā kursa vadītās resursu vērtību ķēdes, joprojām saskaras ar izaicinājumiem starptautiskā, nacionālā, pašvaldību un pat nozaru līmenī.

Promocijas darbā "Resursu vērtību ķēde lēmumu pieņemšanas spogulī" autore Beate Zlaugotne ir izstrādājusi visaptverošu, adaptīvu daudzfaktoru lēmumu pieņemšanas metodoloģisko ietvaru, kas uzlabo ilgtspējīgu risinājumu izvēli resursu vērtību ķēdē. Izstrādātā metodoloģija balstās uz pakāpeniskas sarežģītības ietvaru, kas apvieno trīs būtiskus lēmumu pieņemšanas līmeņus – stratēģisko atbilstību, ilgtspējas novērtējumu un lietderības vērtību – un aptver starptautisko, nacionālo, pašvaldību un nozaru līmeņus enerģētikas, atkritumu apsaimniekošanas, rūpniecības un lauksaimniecības resursu nozarēs. Metodoloģija tika piemērota deviņos gadījumu piemēros, kuros bija nepieciešams noteikt ilgtspējīgākos risinājumus resursu vērtību ķēdes pārvaldībā.

Promocijas darbs balstās uz 14 metodoloģiski vienotiem zinātniskiem rakstiem, kas strukturēti atbilstoši darba uzbūvei. Promocijas darbs sastāv no ievada, trim galvenajām nodaļām un secinājumiem. Ievadā atspoguļota pētījuma aktualitāte, mērķis un hipotēze gan zinātniskā, gan praktiskā kontekstā, kā arī sniegts vispārējs ieskats darba uzbūvē. Pirmajā nodaļā apkopots literatūras apskats, kurā aplūkoti Eiropas Savienības valstu sasniegumi resursefektivitātes jomā un identificēti galvenie šķēršļi lēmumu pieņemšanā saistībā ar resursu vērtību ķēdēm. Otrajā nodaļā izklāstīts promocijas darba metodoloģiskais ietvars, aprakstot pakāpeniskas sarežģītības algoritmu un izmantotās metodes trīs līmeņos: (1) stratēģiskās atbilstības līmenī, izmantojot tādus rīkus kā SVID analīze un rādītāju novērtējums, (2) ilgtspējas novērtēšanas līmenī, iekļaujot aprites cikla novērtējumu, aprites cikla izmaksu aprēķinu un sociālo dzīves cikla novērtējumu un (3) lietderības vērtības līmenī, izmantojot daudzkritēriju lēmumu pieņemšanas metodi. Trešajā nodaļā izstrādātā metodoloģija aprobēta deviņos gadījumu piemēros: (1) enerģijas resursu izmantošana Latvijas lauksaimniecības sektorā, (2) veselības aprūpes atkritumu un (3) zvejas tīklu atkritumu valorizācija, (4) lauksaimniecības izcelsmes izejvielu izmantošana zivju barības ražošanai, (5) metāllūžņu pārkausēšanas tehnoloģiju prioritizēšana Latvijai, (6) astoņu Eiropas valstu salīdzinājums pēc siltumnīcefekta gāzu emisiju rādītājiem, (7) atjaunojamo energoresursu tehnoloģiju novērtējums pašvaldībā, (8) kliju blakusproduktu izmantošanas iespēju izvērtēšana un (9) veselības aprūpes atkritumu apstrādes tehnoloģiju salīdzinājums pasaules mērogā. Secinājumu nodaļā sniegts darba rezultātu apkopojums.

Promocijas darbs ir uzrakstīts angļu valodā un tas ietver 269 lapaspuses, ieskaitot pielikumus – 14 promocijas darba saturā atspoguļotie zinātniskie raksti.

# Acknowledgment

First and foremost, I would like to express my deepest gratitude to my supervisors, *Dr. sc. ing.* Jelena Pubule and *Dr. sc. ing.* Julija Gusca, for their thoughtful feedback, continued support and honest insights throughout this journey. Your encouragement at critical moments provided clarity and perspective when I needed it most. Your mentorship has had a profound impact not only on my academic work, but also on my personal development, and I am truly grateful for the opportunity to learn under your guidance.

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To my family, thank you for your unconditional love, patience, and belief in me through every step of this long journey. Your constant presence gave me the foundation I needed to keep going.

A PhD requires discipline, but to complete it you need resilience, compassion and connection. This work reflects not only my own efforts, but also the energy, time and care of many others who walked alongside me.

# Table of Contents

# Abbreviations

| | |
|---|---|
| AHP | analytical hierarchy process |
| BAU | business as usual |
| BSF | black soldier fly |
| DH | district heating |
| CCUS | carbon capture, storage and / or utilisation |
| CHP | combined heat and power |
| COPRAS | complex proportional assessment |
| DH | district heating |
| DHA | docosahexaenoic acid |
| DMC | domestic material consumption |
| EAF | electric arc furnace |
| EF | Environmental Footprint |
| EU27 | 27 Member States of the European Union |
| EU | European Union |
| EVA | ethylene-vinyl acetate |
| FM | fish meal |
| GDP | gross domestic product |
| GHG | greenhouse gas emissions |
| HDPE | high-density polyethylene |
| HEPA | high efficiency particulate air |
| HPP | hydroelectric power plant |
| IH | individual heating |
| iHCW | infectious healthcare waste |
| ISO | International Organization for Standardization |
| LCA | life cycle assessment |
| LCC | life-cycle costing |
| LDPE | low-density polyethylene |
| MCDA | multi-criteria decision analysis |
| NGO | non-governmental organisation |
| PE | polyethylene |
| PEFCR | Product Environmental Footprint Category Rules |
| PET | polyethylene terephthalate |
| PP | polypropylene |
| PTP | polyethylene terephthalate |
| PV | photovoltaics |
| PVC | polyvinyl chloride |
| QSL | Queneau Schuman Luigi process |
| RDF | refuse-derived fuel |
| RES | renewable energy sources |
| S-LCA | social life cycle assessment |
| SME | small and medium enterprise |
| SWOT | strengths, weaknesses, opportunities and threats analysis |
| TOPSIS | technique for order preference by similarity to ideal solution |
| UNEP | United Nations Environment Program |
| VS | valorisation scenarios |
| WPP | wind power plants |

# Introduction

**Topicality of the Thesis**

The dynamic growth of the world's population raises serious concerns about the social well-being of citizens and the increasing challenge of meeting the growing demand for resources and energy consumption. While society encourages resources through daily choices and consumption patterns, overconsumption leads to significant environmental, economic and social problems [1]. The exhaustion of natural resources, the devastation of ecosystems, and the escalation of pollution not only put pressure on the availability of resources for production – resulting in higher costs – but also exacerbate social inequality, disproportionately impacting the most vulnerable segments of society.

In response to these growing concerns, the European Green Deal was launched as a forward-looking growth strategy aimed at increasing resource efficiency, promoting a competitive and sustainable economy, and ensuring social justice – all with the overarching goal of achieving climate neutrality by 2050 [2]. While some countries are performing better than the average of the 27 Member States of the European Union (EU27), others are lagging behind the targets. One of the foremost priorities is the sustainable utilisation of resources, bolstered by the delivery of renewable and eco-friendly energy – both vital to promoting the tenets of a circular economy.

Decision-makers at international, national, municipal and sectoral levels can influence the choice of a solution for a more sustainable resource value chain. Nevertheless, the process of implementing a resource supply chain that is more sustainable in nature is fraught with challenges that must be addressed, including but not limited to technological and economic barriers, as well as regulatory and strategic hurdles, along with the complexities posed by stakeholders who may have differing interests. To successfully navigate and overcome the various challenges that hinder the creation of a sustainable resource supply chain, it is essential to have a unified approach that incorporates coordinated efforts rooted in scientific research and evidence-based practices .

In this Thesis a methodology for decision makers based on a framework of incremental complexity is developed and tested to support the decision makers in the resource value chain, where resources are defined in a broader sense, i.e. material resources and energy. The framework guides decision makers – regardless of their level and scope – through a structured decision-making process tailored to the specific problem within the resource value chain in terms of strategic relevance, sustainability and utility fit to extend the resource value chain. This approach enables knowledgeable and context-sensitive decisions to be made consistently throughout the resource value chain.

**Aim and objectives**

The aim of the Thesis is to develop a comprehensive yet adaptable in scope multi-factorial decision-making methodological framework to enhance sustainable solutions within the resource value chain.

To achieve the aim of the Thesis, the following tasks were set:

1. Explore barriers in the transition of resource value chains to sustainable solutions.
2. Review existing decision-making methods according to their applicability and group them according to their complexity and the type of results obtained.
3. Develop a multifactorial decision-making methodology based on a framework of incremental complexity to support decision-making within resource value chains.

4. Test the developed multifactorial decision-making methodology by decision-making levels (strategic fit, sustainability, utility value), by resource value chain (energy, waste, agriculture, industry) and decision scope (international, national, municipal, sectoral).

## Hypothesis

A multi-factorial methodology based on the incremental complexity framework can be applied to evaluate the decisions across international, national, municipal and sectoral scopes within energy, waste, industry and agriculture resource sectors while pinpointing the most appropriate and sustainable decisions in the resource value chain.

## Scientific novelty

The scientific novelty of this Thesis lies in the development of a new decision-making methodology based on a framework of incremental complexity, which distinctively combines three essential decision-making levels:

- *strategic fit* – strengths, weaknesses, opportunities and threats (SWOT) analysis.
- *sustainability* – life cycle assessment (LCA), life-cycle costing (LCC), social life cycle assessment (S-LCA).
- *utility value* – multi-criteria decision analysis (MCDA).

The privilege of this methodology, firstly, lies in the incremental complexity framework where the decision-making begins with straightforward, low-risk options and progressively incorporates additional variables and information, fostering clearer thought processes – while being approachable and efficient for decision-makers across all skill levels as it is often present in resource management contexts.

Secondly, the methodology is adaptable to the needs of different decision scopes (international, national, municipal, sectoral) and various resource value chains (energy, waste, industry and agriculture), thus facilitating more multi-dimensional, holistic (technological, regulatory, environmental, social, economic), yet specific target-oriented decision-making.

Thirdly, the methodology is adjustable to accommodate and combine various forms of data, whether qualitative or quantitative, and aids in assessing solutions by considering both internal and external influences, along with strategic criteria.

These all benefits bring the developed methodology as an innovative contribution to the resource value chain assessment. Its application across diverse resource value chains, demonstrated in the Thesis, has revealed its high adaptability, as well as its value in deepening the understanding of sustainable decision-making within resource supply chains of varying complexity.
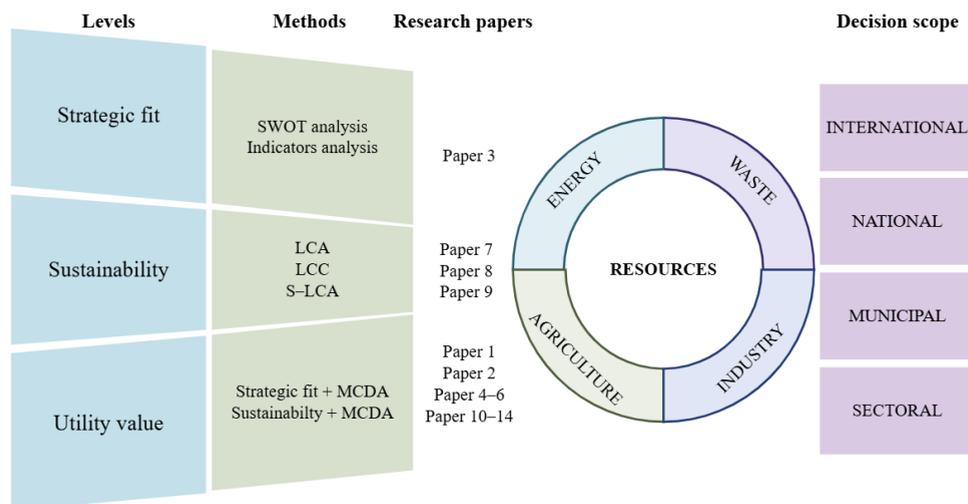
Figure 1. Thesis research framework.

**Practical relevance**

This Thesis has high practical value as a developed resource value chain methodology can serve as a practical tool for decision-makers at international, national, municipal and sectoral levels and across different sectors to systematically assess solutions in the resource value chain. The structured incremental complexity approach helps overcome various obstacles that decision-makers encounter, which often hinder sustainable development and growth within the resource value chain. The multi-scope approach enhances the usefulness of the developed methodology by addressing the diverse needs of decision-makers within the resource value chain – spanning from strategic policy formulation and climate-sensitive, economically feasible, and socially advantageous planning to financial processes and sustainability reporting.

**Approbation of the research results**

1. **Zlaugotne, B**., Zihare, L., Balode, L., Kalnbalkite, A., Khabdullin, A., & Blumberga, D. (2020). Multi-Criteria Decision Analysis Methods Comparison. *Environmental and Climate Technologies*, 24(1), 454–471. https://doi.org/10.2478/rtuect-2020-0028

2. **Zlaugotne, B**., Ievina, L., Azis, R., Baranenko, D., Blumberga, D. (2020). GHG Performance Evaluation in Green Deal Context. *Environmental and Climate Technologies*, 2020, 24(1), pp. 431–441. https://doi.org/10.2478/rtuect-2020-0026

3. **Zlaugotne, B**., Pakere, I., Gravelsins, A. (2021). Spatial energy data acquisition for agricultural sector. Latvia case study. 2021. *Proceedings of the IEEE 62nd International Scientific Conference on Power and Electrical Engineering of the Riga Technical University, RTUCON 2021*. https://doi.org/10.1109/RTUCON53541.2021.9711689

4. **Zlaugotne, B**., Pubule, J., Gusca, J., Kalnins, S.N. (2022). Quantitative and Qualitative Assessment of Healthcare Waste and Resource Potential Assessment. *Environmental and Climate Technologies*, 2022, 26(1), pp. 64–74. https://doi.org/10.2478/rtuect-2022-0006

5. Valtere, M., Kaleja, D., Kudurs, E., Kalnbalkite, A., Terjanika, V., **Zlaugotne, B**., Pubule, J., Blumerga, D. (2022). The Versatility of the Bioeconomy. Sustainability

Aspects of the Use of Bran. *Environmental and Climate Technologies*, 2022, 26(1), pp. 658–669. https://doi.org/10.2478/rtuect-2022-0050

6. **Zlaugotne, B**., Pubule, J., & Blumberga, D. (2022). Advantages and disadvantages of using more sustainable ingredients in fish feed. *Heliyon*, 8(9), e10527. https://doi.org/https://doi.org/10.1016/j.heliyon.2022.e10527

7. **Zlaugotne, B**., Sanchez, F. A. D., Pubule, J., & Blumberga, D. (2023). Protein Alternatives for Use in Fish Feed – Life Cycle Assessment of Black Soldier Fly, Yellow Mealworm and Soybean Protein. *Environmental and Climate Technologies*, 27(1), 581–592. https://doi.org/10.2478/rtuect-2023-0043

8. **Zlaugotne, B**., Diaz Sanchez, F., Pubule, J., & Blumberga, D. (2023). Life cycle assessment of fish feed for oil alternatives-environmental impact of microalgae, rapeseed and fish oil. *Agronomy Research*, 21(3), 1351–1360. https://doi.org/10.15159/AR.23.074

9. **Zlaugotne, B**., Diaz Sanchez, F. A., Pubule, J., & Blumberga, D. (2023). Life Cycle Impact Assessment of Microalgae and Synthetic Astaxanthin Pigments. *Environmental and Climate Technologies*, 27(1), 233–242. https://doi.org/10.2478/rtuect-2023-0018

10. Balode, L., **Zlaugotne, B**., Gravelsins, A., Svedovs, O., Pakare, I., Kirsanovs, V., Blumberga, D. (2023). Carbon Neutrality in Municipalities: Balancing Individual and District Heating Renewable Energy Solutions. *Sustainability*, 2023, 15(10), 8415. https://doi.org/10.3390/su15108415

11. Terjanika, V., Pubule, J., Mihailova, E., **Zlaugotne, B**. (2024). Analysing Metal Melting Methods for Green Transformation of Scrap Metal: Case Study of Latvia using MCDA and SWOT Analysis. *Environmental and Climate Technologies*, 2024, 28(1), pp. 1–11. https://doi.org/10.2478/rtuect-2024-0001

12. **Zlaugotne, B**., & Pubule, J. (2024). From Cradle to Plate: Analysing the Life Cycle Sustainability of Fish Feed Composition. *Environmental and Climate Technologies*, 28(1), 686–694. https://doi.org/10.2478/rtuect-2024-0053

13. **Zlaugotne, B**., Zandberga, A., Gusca, J., Kalnins, S.N. (2025). Environmental Life Cycle Assessment of Healthcare Waste Valorisation Alternatives. *Environmental and Climate Technologies*, 2025, 29(1), pp. 51–67. https://doi.org/10.2478/rtuect-2025-0004

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**Other scientific publications**

1. Laktuka, K., Pakere, I., Kalnbalkite, A., **Zlaugotne, B**., Blumberga, D. (2023). Renewable energy project implementation: Will the Baltic States catch up with the Nordic countries? *Utilities Policy*, 2023, 82, 101577. https://doi.org/10.1016/j.jup.2023.101577

**Monographs**

1. Blumberga, D., Balode, L., Bumbiere, K., Dzalbs, A., Indzere, Z., Kalnbaļķīte, A., Priedniece, V., Pubule, J., Vamža, I., **Zlaugotne, B**., Žihare, L. Bioresursi ilgtspējīgai attīstībai. Rīga: RTU Izdevniecība, 2021. 483 lpp. ISBN 978-9934-22-701-1.

**Approbation of the research results at scientific conferences**

1. **Zlaugotne, B**., Zihare L., Blumberga D. Multi-criteria decision analysis methods comparison. *International Scientific Conference of Environmental and Climate Technologies CONECT 2020*, 13-15 May 2020, Riga, Latvia.
2. **Zlaugotne, B**., Pubule J., Blumberga D. Methodology for composite index for a sustainable assessment for fish feed. *International Scientific Conference of Environmental and Climate Technologies CONECT 2022*, 11-13 May 2022, Riga, Latvia.
3. **Zlaugotne, B**., Pubule J., Diaz Sanchez F. A., Blumberga D. Assessment of the environmental impact of protein source used in fish feed production using Life Cycle Assessment. *17th Conference on Sustainable Development of Energy, Water and Environment Systems SDEWES*, 6-10 November 2022, Paphos, Cyprus.
4. **Zlaugotne, B**., Pubule J., Diaz Sanchez F. A., Blumberga D. Life cycle assessment of fish feed for oil alternatives - environmental impact of microalgae, rapeseed and fish oil. *Biosystems Engineering Conference 2023*, 10-12 May, Tartu, Estonia.
5. **Zlaugotne, B**., Diaz Sanchez F. A., Pubule J., Blumberga D. Environmental impact of natural and synthetic Astaxanthin pigments using Life cycle assessment. *International Scientific Conference of Environmental and Climate Technologies CONECT 2023*, 10-12 May 2023, Riga, Latvia.
6. **Zlaugotne, B**., Diaz Sanchez F. A., Pubule J., Blumberga D. Environmental impact assessment of fish feed proteins from Black Soldier Fly, Yellow Mealworm and soybean using LCA. *International Scientific Conference of Environmental and Climate Technologies CONECT 2023*, 10-12 May 2023, Riga, Latvia.
7. **Zlaugotne, B**., Pubule J. Bibliometric analysis and literature review on sustainability assessment methods in the bioeconomy. *International Scientific Conference of Environmental and Climate Technologies CONECT 2023*, 10-12 May 2023, Riga, Latvia.
8. **Zlaugotne, B**., Pubule J. Review of Social Life Cycle Assessment. *18th Conference on Sustainable Development of Energy, Water and Environment Systems SDEWES*, 24-29 September 2023, Dubrovnik, Croatia.
9. **Zlaugotne, B**., Pubule J. From Cradle to Plate: Analysing the Life Cycle Sustainability of Fish Feed Composition. *International Scientific Conference of Environmental and Climate Technologies CONECT 2024*, 15-17 May 2024, Riga, Latvia.
10. **Zlaugotne, B**., Bostrom M. L., Larsson M., Lareke A., Mockeviciene I., Gusca J. Challenges, Best Practices and Solutions for Sustainable Local Food Supply Chains in Latvia, Lithuania and Sweden. *International Scientific Conference of Environmental and Climate Technologies CONECT 2025*, 14-16 May 2025, Riga, Latvia.
11. Milbreta U., **Zlaugotne, B.**, Jansone-Vevere D., Kalnins S. N., Gusca J. First insight into the efficiency of Latvia's beverage packaging refund system. *International Scientific Conference of Environmental and Climate Technologies CONECT 2025*, 14-16 May 2025, Riga, Latvia.

# 1. Literature review

The European Green Deal growth strategy aims to make resource consumption more efficient and foster a competitive economy in a fair and inclusive way, reaching climate neutrality by 2050 [2]. This includes ensuring clean, affordable and secure energy, transforming towards a circular and low-emission industry, improving the energy and resource efficiency of buildings, promoting sustainable and smart mobility, creating a fair and environmentally friendly food supply chain, restoring ecosystems and biodiversity, and achieving zero pollution for a non-toxic environment [2]. [2]For Europe to achieve its goals, active participation at all levels and in all sectors is needed to jointly promote the belief in the importance of mitigating climate change while improving the efficiency and rational use of energy and resources.

The European Union economy's resource productivity has grown by 44 % between 2000 and 2024, although various crises have had a slight impact on this indicator, but overall resource productivity continues to grow (see Figure 1.1) [3]. Resource productivity measures the ratio between gross domestic product (GDP) and domestic material consumption (DMC) as GDP per unit of resource. In 2023, the EU27 achieved a resource productivity of 2.7 EUR/kg, up from 1.9 EUR/kg in 2014 [4]. Meanwhile, Latvia's performance was lower, with a 2023 value of 1,3 EUR/kg, showing a bit increase from 0,9 EUR/kg in 2014 [4]. However, among the EU27, the best results are for Luxembourg and the Netherlands, which share first place every year. While Luxembourg's resource productivity in 2014 was 4,3 EUR/kg and in 2023 5.6 EUR/ kg, for the Netherlands it was 3.9 EUR/kg in 2014 and 7 EUR/kg in 2023 [4]. The consumption of resources or products is influenced by the behaviour of residents, their economic status, as well as geographical location and the availability of products [5–7]. Generally, better economic conditions lead to higher resource consumption and increased waste generation.
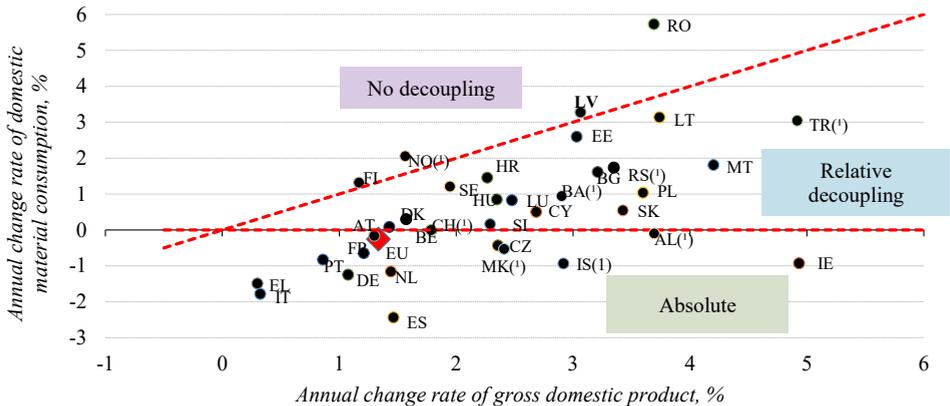


Figure 1.1. Decoupling trends in resource productivity in European Union countries from 2000-2023 [3].

The extraction of new materials continues to have an environmental impact, but a shift towards resource-efficient value chains will ease the transition, reduce the need for new material extraction and promote the reuse of materials, creating sustainable raw materials that contribute to a circular economy [2]. To achieve the goals, it is necessary to reduce the consumption of new resources and to ensure proper application of wasted resources, as well as to assign greater economic value to resources. This can be achieved by inhibiting waste production at its origin, encouraging the utilisation of non-harmful materials, enhancing the reuse of products, establishing an effective marketplace for recycled raw materials, tackling the challenge of waste exports, and overall optimising the resource value chain [8].

Achieving the target of reducing GHG emissions by 60 % compared to 1990 by 2050 requires clean and secure energy, which can be achieved by decarbonising the energy system and relying on renewable energy sources, interconnected in Europe with smart infrastructure, ensuring clean energy at affordable prices [2]. To facilitate the transition to a secure and clean energy, it is necessary to promote the replacement of fossil fuels with renewable energy, to implement energy savings and efficient use, diversifying the import of necessary energy, as well as make an investment in the energy sector for development and to ensure energy security [9]. In 2023, the EU produced 42 % of its own energy and imported 58 % [10]. In 2023, the share of energy from renewable sources in the EU27 was 25 %, but for Latvia it was 43 % [11]. In 2023, 45 % of total electricity generation came from renewable energy sources and 26 % of total energy consumption for heating and cooling came from renewable energy sources in the EU [12]. Meanwhile, in Latvia, 54 % of electricity was generated from renewable energy sources and 61 % of heating and cooling was obtained from renewable energy sources in 2023 [12]. In 2023, energy consumption per capita in Latvia was 98 GJ per capita, while the EU average was 125 GJ per capita [13]. Of course, energy consumption is influenced by a variety of factors, such as the volume of manufacturing and commercial activities, weather conditions, which affect the length of the heating and cooling season and the energy efficiency of buildings, as well as the behaviour of residents and tourists. Although Latvia has relatively good results in the implementation of Green Deal targets, the set goals have not yet been achieved, due to inefficient use of resources [14], GHG emissions from industries [15], and waste recycling [16]. One of the factors slowing Latvia's progress toward its targets is the improper decision-making process [17], which acts as an obstacle: the lack of policy alignment between national and local governance arises from uncoordinated EU-level strategies and tools, coupled with inadequate political will at the national level, which collectively weaken the thoroughness and reliability of the vertical policy framework, subsequently obstructing transition processes. It is important to acknowledge that Latvia is not the sole nation encountering these obstacles [18–20].

Based on the literature review conducted within the Thesis, the primary obstacles hindering decision-makers from implementing sustainable practices in the resource supply chain are multifaceted, involving economic, regulatory, technological, organisational and even cultural challenges. These barriers are compounded by the complexity of supply chains and the diverse stakeholders involved. Despite growing awareness and commitment to sustainability, practical implementation remains challenging due to these obstacles.

- *Technological barriers.* Restricted access to cutting-edge technology, combined with dependence on obsolete systems, greatly hinders the adoption of sustainable practices. Numerous stakeholders (companies, municipalities) also lack the necessary technical know-how and innovative capabilities required to execute green supply chain initiatives along with shortage of skilled personnel and proper training [21–23]. Additionally, the complex nature of supply chains – characterised by numerous stakeholders and interconnected processes – can lead to inefficiencies and resistance to change, further obstructing sustainability efforts [24].
- *Economic barriers.* Financial constraints remain a core challenge, especially for small and medium enterprises (SMEs). Substantial initial expenses associated with sustainable technologies and infrastructure may discourage investment, especially when funding opportunities are scarce and financial risks are considerable [21,25,26].
- *Regulatory and policy barriers.* Unclear and inconsistent government policies generate uncertainty for businesses, which in turn deters long-term investments in sustainability [25,27]. The challenges of manoeuvring through conflicting

regulations across various jurisdictions present an additional hurdle [27,28]. Furthermore, within municipal organisations, the absence of standardized sustainability practices leads to inefficiencies and irregular implementation [29,30].

- *Diverse stakeholder interests.* The diversity of stakeholder values and priorities can create obstacles in reaching a consensus. While engaging a broader range of participants –such as non-governmental organisations (NGOs) and competitors – is essential for effective sustainable supply chain management, their varying expectations can complicate and slow-down decision-making and impede progress [31,32].

- *Supply chain and stakeholder coordination.* Internal opposition to change and organisational inertia pose significant obstacles. Staff and supervisors might hesitate to move away from familiar practices because of perceived dangers, including heightened workloads or diminished flexibility [33,34]. Moreover, the importance of community involvement and education is often overlooked, even though it is essential for the effective implementation of sustainable practices [35–37].

- *Organisational and cultural barriers.* Resistance to change and organisational inertia pose considerable obstacles to achieving sustainability within organisations. Employees and management might hesitate to alter established practices due to fears of increased workloads or diminished flexibility [21,24]. Without a robust commitment from leadership, sustainability initiatives frequently miss the crucial backing and strategic guidance they require [38].

- *Strategic barriers.* Regrettably, but sustainability continues to be relegated to a minor position on the agendas of both political and managerial circles. Consequently, initiatives often face challenges such as inadequate resources, limited institutional support, and a failure to incorporate them into wider strategic frameworks [39].

Navigating these intricate and varied obstacles demands more than just isolated measures; it necessitates a comprehensive, multi-dimensional, yet user-friendly and flexible decision-making framework that can adjust to changing circumstances to facilitate a sustainable transformation in the resource-product supply chain or resource value chain [40]. The resource value chain, as the core object throughout the decision-making process in this Doctoral Thesis, represents the transformative pathway of a resource (raw material or secondary material, including energy) into an added-value product or system. Given that the resource value chain encompasses a multitude of stakeholders and processes, strategic governance and well-planned decision-making frameworks are crucial. For resource value chains to be truly effective, they must be inclusive, interconnected, pertinent, pragmatic and adaptable. An all-encompassing approach offers a holistic perspective of all participants, processes and driving forces, allowing for strategic interventions throughout the entire chain. An interconnected viewpoint reveals the relationships within the value chain and pinpoints leverage points for meaningful transformation. By making value chains relatable, we connect resource utilisation and environmental effects to tangible economic and social contexts, ensuring their relevance. The approach must also be pragmatic, steering decision-makers toward the most significant areas for intervention. Ultimately, it should be adaptable, facilitating application across various sectors, products and regions to promote climate-resilient, sustainable, and circular transitions [41].

# 2. Methodology

The methodological foundation of the Thesis is grounded in the **incremental complexity framework** and encompasses three primary levels – strategic alignment, sustainability, and utility value. The incremental complexity framework is based on the approach of starting with simpler elements and gradually moving towards more complex elements [42]. This framework is universal and can be applied across sectors, including problem-solving and decision-making processes. The use of the incremental complexity framework improves the quality of decision-making, as well as promotes the integration of various types of information and helps to overcome uncertainty because it promotes the individual's ability to distinguish and integrate different dimensions into a decision [43]. This methodology supports an extended resource value chain, focusing on efficiency and resource circularity.

The *strategic fit* (also called strategic alignment) framework allows for a more informed and multidimensional assessment of the problem, so that decision-makers can assess the resource chain. The strategic fit framework identifies the problem and its solutions in line with the level and sector-specific goals and development. It also serves as a critical first filter for decision-makers, ensuring that the assessment considers strategies and guidelines of the appropriate level and scope. A good strategic fit indicates that the current situation is being improved and that growth and development are being strengthened.

The *sustainability* framework assesses specific problems and their solutions in the environmental, economic and social dimensions. The assessment of environmental impacts, economic viability and social impacts provides a holistic approach to decision-making. Good sustainability is one that reduces negative environmental impacts, continues economic growth and is socially responsible.

The *utility value* framework determines the suitability of alternatives to solve the problem and meet the need. Utility value systematically evaluates defined criteria and alternatives to provide decision makers with an outcome that is in line with their objectives. Good utility value considers multiple dimensions and builds a result based on a variety of factors.

Figure 2.1 illustrates the decision-making methodology for resource value chain assessment, following the incremental complexity decision logic.
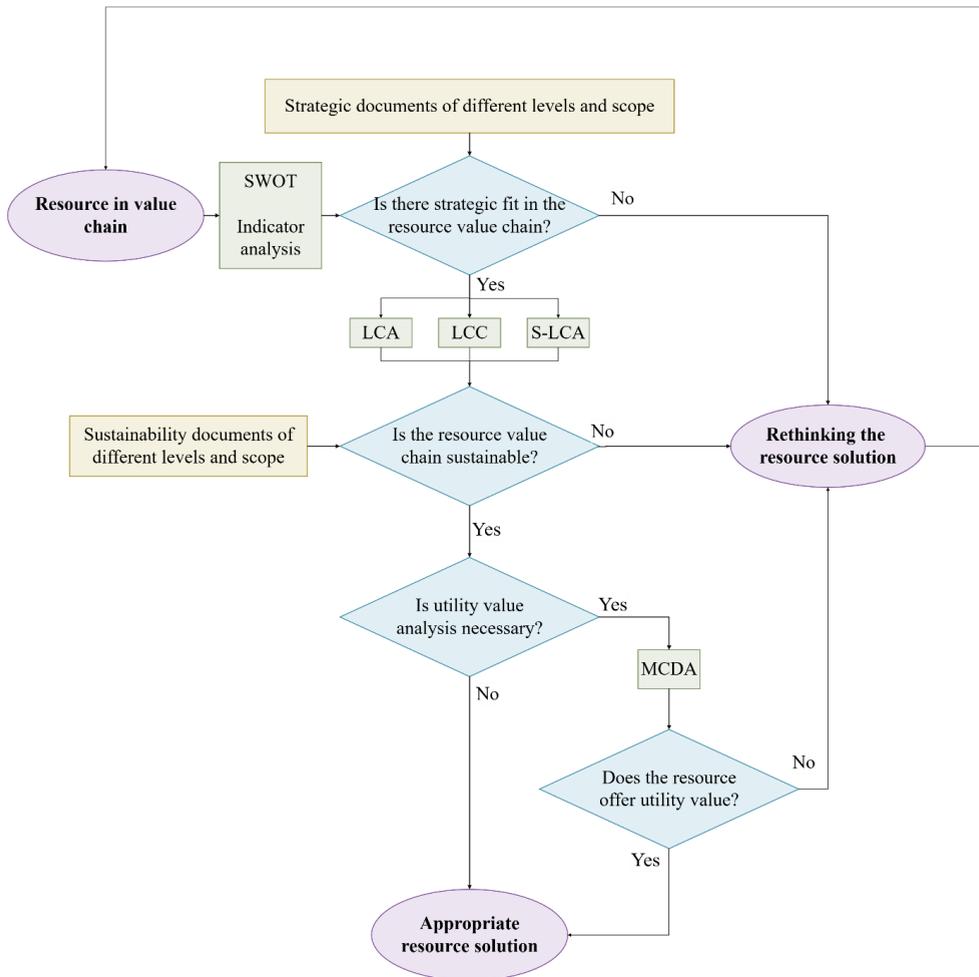
Figure 2.1. Resource value chain decision-making methodology *via* incremental complexity theory approach.

In organisational theory, there is a mirroring hypothesis – a hypothesis that suggests that an organisation's structure tends to reflect the modular architecture of the products it develops [44]. Within the Doctoral Thesis, the author took an opportunity to mimic the mirroring hypothesis approach also to the decision-making process. A replication matrix summarizing how the principles of the mirroring hypothesis are mapped onto the decision-making process is presented in Table 2.1.

Table 2.1

Mirroring principles reflecting the hypothesis in the decision-making process

| Mirroring hypothesis in **organisational structures** | Mirroring hypothesis in **decision-making** |
|---|---|
| **Change dynamics**. The rate of technological change and product complexity at the component level demands flexible organisational architectures to enhance coordination, reduce complexity, and improve performance [45]. | Decision-making models should be based on a modular or incremental complexity process, characterised by complex, while adaptable, criteria. Criteria or indicators-based models ensure the suitability of the decision-making models to the changing priorities of decision-makers. |
| **Strategic priorities and value creation**. Strategic priorities, such as value creation and capture, also influence the relationship between product and organisational architectures [46,47]. | Just as product complexity requires flexible architectures, varying decision scopes (international, national, municipal, sectoral) and decision levels (strategic fit, sustainability, utility value) call for adaptable decision-making frameworks that adjust to the complexity and priorities of each decision level. |
| **Industry and institutional context**. The industry and institutional context also play a role in shaping the relationship between product and organisational architectures [48]. | To ensure the delivery of the decision to the defined aim or values, the alignment with the strategic documents/frameworks via criteria and weights needs to be defined. |
| **Decision-making homomorphism**. The mirroring of a product's technical dependencies and organisational ties supports problem-solving by conserving cognitive resources, as real-time interdependencies require coordination within technical constraints – forming a cognitive homomorphism between technical and organisational networks [44] . | The decision-making process requires ongoing interactions between defined priorities (such as values and policy objectives), selected criteria, the opinions of various decision-makers (involved stakeholders), and the strength of these opinions as expressed through weighting. Thus, the cumulative decision-making model should be coherent with all these components. |

## 2.1. Strategic fit level

In the process of making decisions, it is crucial for proposed solutions to exhibit strategic alignment, meaning they should effectively support the intended goals and avoid any contradictions. Assessing options from diverse viewpoints improves the quality of decisions, and strategic alignment ought to serve as the foremost standard for verifying consistency with objectives.

The strategic fit approach is rooted in the idea that organisations must align their strategies with their external environment to achieve optimal performance. This alignment is critical in the context of environmental protection, where organisations must consider ecological, social, and economic factors. The key principles of the strategic fit approach include:

- *Alignment of internal and external factors*. The strategic fit approach emphasizes the importance of aligning internal organisational capabilities with external environmental conditions. This alignment ensures that organisational strategies are responsive to environmental challenges and opportunities [49].
- *Integration of environmental considerations*. Environmental protection requires the integration of environmental considerations into organisational strategies. This involves incorporating environmental drivers into performance management systems and aligning environmental goals with business objectives [50,51].
- *Stakeholder engagement*. The strategic fit approach recognises the importance of stakeholder engagement in achieving environmental goals. Organisations must consider the pressures and expectations of various stakeholders, including customers, regulators and NGOs), when developing environmental strategies [52,53].

- *Dynamic adaptation*. Environmental conditions are dynamic and subject to change. The strategic fit approach emphasizes the need for organisations to adapt their strategies in response to changing environmental conditions and stakeholder expectations [54].
- *Performance measurement*. The strategic fit approach requires the use of performance metrics to evaluate the effectiveness of environmental strategies. Key performance indicators (KPIs) are critical for assessing the alignment between organisational strategies and environmental goals [55,56].

Strategic fit operates at multiple levels – international, national, municipal and sectoral. On the international level, it encompasses treaties, protocols, agreements, declarations, memoranda of understanding, joint statements, multilateral action plans and overarching global strategic frameworks. The national tier includes strategies, legislative structures, policy directives, action plans, development agendas and roadmaps that correspond with global commitments [57]. The local level consists of community regulations and development agendas that align with national strategies [58]. Sector-specific documents – such as targeted strategies, thematic action plans, implementation frameworks, and product category rules – guarantee consistency within fields or industries.

Strategic fit must be coherent and operate not only at the structural level, but also in the context of the linkages between sectors to ensure development. To adequately assess strategic fit, it is necessary to select appropriate methods where qualitative or quantitative data approaches or combined approaches can be applied [59].

**Qualitative data analysis**

One of the most recognised and extensively used tools for strategic decision-making is the SWOT analysis, which assesses strengths, weaknesses, opportunities and threats [60]. SWOT analysis is based on the analysis of qualitative or semi-qualitative data affected by internal and external factors [61]. Based on the results of the analysis, the organisation can determine the development path, reduce the impact of potential threats, adapt to various factors and assign strategies for further work, development and / or behaviour in the context of the decision being made [62]. Furthermore, SWOT can serve as an approach to qualitatively evaluate a situation by examining both advantages and disadvantages for informed decision-making.

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**Quantitative data analysis**

Indicator analysis serves as a crucial quantitative data analysis tool for decision makers, particularly focused on assessing diverse dimensions including technological, environmental, economic, social, and others. An indicator is a variable that shows changes over time, but problems can arise with the collection of the necessary data and its interpretation [63]. This type of method allows for a better understanding of specific outcomes and helps laypeople to understand the situation more easily [64].

## 2.2. Sustainability assessment level

Sustainability assessment consists of environmental, economic and social dimensions, which can be assessed as individual dimensions or as an overall sustainability assessment [65]. However, to conduct an effective assessment of the environmental, economic and social sustainability of a resource value chain, it is important to define clear boundaries, assumptions, collect appropriate data and use appropriate assessment methods to obtain the desired interpretation of the data.

### 2.2.1. Life cycle assessment

To assess and compare products and services based on environmental impact, life cycle assessment (LCA) is used. LCA is performed according to ISO 14040 "Environmental management – Life cycle assessment – Principles and framework" and ISO 14044 "Environmental management – Life cycle assessment – Requirements and guidelines" standards [66,67]. These standards explain the conceptual framework and principles of LCA, as well as a detailed explanation of how to conduct an LCA – objective and scope (determines the boundaries of the study), inventory (relevant input/output data), impact assessment (assessment based on an assessment method) and interpretation. LCA can be performed based on three main approaches: the cut-off approach, the partitioning approach and the avoided burden approach as system expansion approach [68]. Depending on the chosen approach, the environmental impacts of multiple products or processes in a system are distributed, which is particularly important for the consistency of LCA results. LCA impact assessment is concerned with reflecting desired outcomes in a specific impact category assessment and obtained impact assessment results can be expressed in different environmental characteristics units. Also, LCA results can be expressed as a single value as points (Pt) – the unit of the eco-indicator where one thousand of annual environmental load of an average European citizen is considered as 1 Pt [69].

In this Thesis, Environmental Footprint (EF) version 3.0 (European method) and ReCiPe 2016 (Global method) impact assessment methods are used. The EF 3.0 method has been developed by the European Commission and is part of efforts to harmonise environmental impact assessment [70]. The EF 3.0 method is used in the Product Environmental Footprint Category Rules (PEFCR) and the Organisation Environmental Footprint Sector Rules; impact categories are in Table 2.2 [71]. The updated version of the impact assessment method includes human toxicity, ecotoxicity and land use impact categories, as well as improved and expanded other impact categories [71].

Table 2.2

EF 3.0 impact categories and their description [70,71]

| Impact category, abbreviation | Indicator description | Unit |
|---|---|---|
| Climate change | Impact of greenhouse gas emissions on the increase in average global temperature | kg $CO_2$ eq |
| Ozone depletion | Impact of emissions on stratospheric ozone depletion by increasing UV-B radiation exposure | kg $CFC_{11}$ eq |
| Human toxicity, cancer | Impact of chemical emissions on human health through contact with air, water and soil | CTUh |
| Human toxicity, non-cancer | Impact of chemical exposure through air, water and soil on human health | CTUh |
| Particulate matter | The impact of emissions of particulate matter and its precursors on human health, measured as morbidity per kg of PM2.5 emitted | kg PM2.5 |

| Ionising radiation | Impact of exposure to ionizing radiation on human health, considering emissions only under normal operating conditions | kBq U$_{-235}$ eq |
|---|---|---|
| Photochemical ozone formation | The impact of ground-level ozone formation on human health and ecosystems | kg NMVOC eq |
| Acidification | The impact of acidifying emissions on ecosystems and water quality, contributing to forest loss and fish mortality | mol H+ eq |
| Eutrophication, terrestrial | Impact of nitrogen and phosphorus emissions on terrestrial ecosystems, causing nutrient overload and vegetation imbalance | mol N eq |
| Eutrophication, freshwater | Impact of nitrogen and phosphorus emissions on freshwater ecosystems, causing excessive algal blooms and oxygen depletion | kg P eq |
| Eutrophication, marine | Impact of nitrogen and phosphorus emissions on marine ecosystems, leading to nutrient enrichment and algal growth, which is mainly driven by nitrogen | kg N eq |
| Ecotoxicity, freshwater | Impact of chemical toxicity on ecosystems, affecting species and ecosystem functions | CTUe |
| Land use | Impact of land use and conversion on soil quality and biodiversity, affecting species loss, soil organic matter content and erosion | Pt |
| Water use | Impact of water abstraction on local water availability and scarcity | m$^3$ depriv. |
| Resource use, minerals and metals | Impact of mineral resource depletion, reflecting the increasing difficulty of providing future generations with access to high-quality resources | kg Sb eq |
| Resource use, fossils | Impact of extracting non-renewable fossil resources on future availability, reflecting the depletion of finite resources | MJ |

The ReCiPe 2016 method is an updated and expanded version of "ReCiPe 2008", which includes both midpoint (problem-oriented) with 18 impact categories and endpoint (damage-oriented) with 3 impact categories [71]. In this method, it is possible to obtain impacts expressed in terms of individualistic (I), based on short-term interest, hierarchical (H), based on the most common policy principles regarding timing and other issues, and egalitarian (E), as the most cautious perspective [71]. In Table 2.3 are ReCiPe 2016 midpoints (H – *Hierarchist*) method impact categories. The *Hierarchist* perspective reflects a cultural viewpoint, aiming to achieve consensus while adopting a 100-year timeframe.

Table 2.3

ReCiPe 2016 midpoints impact categories and their description [72,73]

| Impact category, abbreviation | Indicator description | Unit |
|---|---|---|
| Global warming, GW | Impact of greenhouse gas emissions on climate change | kg CO$_2$ to air eq. |
| Stratospheric ozone depletion, SOD | Impact of ozone layer depletion on human health, particularly focusing on risks like skin cancer and cataracts across various time horizons | kg CFC-11 eq. |
| Ionizing radiation, IR | Impact of radiation exposure on human health, considering different types of cancers and using time-horizon-specific characterisation factors. | kBq Cobalt-60 to air eq. |
| Ozone formation (hum), OFHH | Impact of ground-level ozone on human health, particularly respiratory issues, using global and region-specific characterisation factors | kg NOx eq. |
| Fine particulate matter formation, PM | Impact of PM2.5 on health, including lung cancer and cardiovascular risks, using global and region-specific factors | kg PM2.5 to air eq. |

| | | |
|---|---|---|
| Ozone formation (eco), OFE | Impact of ground-level ozone on terrestrial ecosystems, focusing on damage to plant life and overall ecosystem health | kg NOx eq. |
| Terrestrial acidification, TA | Impact of acidifying emissions, such as $SO_2$, on soil quality and plant life, leading to potential ecosystem degradation | kg $SO_2$ to air eq. |
| Freshwater eutrophication, FE | Impact of nutrient enrichment, particularly phosphorus, on freshwater ecosystems, leading to issues like algal blooms and oxygen depletion | kg P to freshwater eq. |
| Marine eutrophication, ME | Impact of nutrient enrichment, particularly nitrogen, on marine ecosystems, leading to issues like algal blooms and oxygen depletion | kg N to marine eq. |
| Terrestrial ecotoxicity, TEC | Impact of toxic substances on terrestrial ecosystems, using characterisation factors to assess potential harm to soil organisms and plant life | kg 1,4-DCB to industrial soil eq. |
| Freshwater ecotoxicity, FEc | Impact of toxic substances on freshwater ecosystems, using characterisation factors that reflect the potential harm to aquatic life | kg 1,4-DCB to freshwater eq. |
| Marine ecotoxicity, MEC | Impact of toxic substances on marine ecosystems, using characterisation factors to assess potential harm to marine life | kg 1,4-DCB to marine water eq. |
| Human carcinogenic toxicity, HCT | Impact of chemical exposure on cancer risk in humans, using specific characterisation factors for different chemicals | kg 1,4-DCB eq. |
| Human non-carcinogenic toxicity, HNCT | Impact of chemical exposure on non-cancer health effects, using specific characterisation factors for various substances | kg 1,4-DCB eq. |
| Land use, LU | Impact of land occupation and conversion on biodiversity, focusing on species loss and ecosystem disruption | $m^2 \times$ yr annual cropland eq. |
| Mineral resource scarcity, MRS | Impact of mineral extraction on resource scarcity, expressed in terms of increased future extraction costs | kg Cu eq. |
| Fossil resource scarcity, FRS | Impact of fossil fuel extraction on resource scarcity, focusing on the depletion of reserves and increased future extraction costs | kg oil-eq. |
| Water consumption, WC | Impact of water consumption on human health and ecosystems using region-specific characterisation factors | $m^3$ water-eq. consumed |

### 2.2.2. Life cycle costing

There are several methods to assess the economic dimension of processes and products, such as technical-economic assessment *via* CAPEX and OPEX (also called conventional life cycle costing), cost-benefit analysis, environmental life cycle costing and societal life cycle costing [74].

Life cycle costing (LCC) is a multifaceted method that is divided into sub-methods with the following features [74,75]:

- Conventional LCC is used in this Thesis, which includes direct costs as acquisition and ownership costs with a reference unit to the product or project.
- Environmental LCC is used in this Thesis, which includes direct and external costs as environmental and life cycle costs with a reference unit functional unit.
- Societal LCC, which is not used in this Thesis, includes direct and external costs, including environmental and social aspects with reference unit's functional unit.

Additionally, there exists a method for calculating environmental damage costs, which assesses the harm inflicted by environmental pollutants expressed in euros per unit of pollutant [76], which is applied in this Thesis. Since the environmental damage cost is not directly observable, it must be calculated based on LCA damage assessments and economic impact studies [76]. Environmental damage costs are updated periodically with the latest release being from 2021 [76]. To obtain environmental prices that reflect the relevant year (for example, 2025 was relevant for this Thesis – see Papers 13–14), environmental cost inflation

was adjusted using World Bank data and forecasts for that year [77,78]. The adjusted environmental damage costs by impact category are presented in Table 2.4.

Environmental damage costs [76]

| Impact category | Euro$_{2025}$ per unit |
|---|---|
| Climate change | 0.16 |
| Ozone depletion | 34.76 |
| Ionising radiation | 0.0052 |
| Oxidant formation, human health | 2.76 |
| Oxidant formation, terrestrial ecosystems | 0.51 |
| Particulate matter formation | 121.95 |
| Acidification | 6.47 |
| Freshwater eutrophication | 4.59 |
| Marine eutrophication | 17.53 |
| Terrestrial ecotoxicity | 0.00079 |
| Freshwater ecotoxicity | 0.0257 |
| Marine ecotoxicity | 0.00393 |
| Human toxicity, cancer-related | 4.9 |
| Human toxicity, non-cancer-related | 0.0873 |
| Land use | 0.1216 |
| Mineral extraction | 0.0172 |
| Fossil extraction | 0.0344 |
| Water consumption | 0.5002 |
| NO$_2$ addition | 7.83 |

### 2.2.3. Social life cycle assessment

To analyse the social dimension – social impact or social benefit – in the decision-making processes, social life cycle assessment (S-LCA) is applied in the Thesis [79]. It is essential to promote social benefits in the evaluation of any product or service that increases the well-being of individuals and society [80]. Social assessment can be carried out using the United Nations Environment Program (UNEP) guidelines or one of the database assessment methods (e.g. Social Hotspots Database or PSILCA calculation software), with these methods being regularly updated and expanded [81,82]. Recently, the UNEP guidelines were successfully expanded and integrated in a social impact assessment standard ISO 14075:2024 "Environmental management – Principles and framework for social life cycle assessment", which sets out the basic principles, specifies requirements and provides guidelines for conducting a social life cycle assessment of a product [83].

In this Thesis, UNEP guidelines for social assessment are used. UNEP guidelines provide consistent guidance to promote context-appropriate applications to support social assessment [84]. The guidelines also include an inventory indicator with examples of data sources – databases, reports, interviews with insiders and other data sources [81].

UNEP's social assessment is divided into six main impact categories and 40 subcategories [81].

- The *worker category* considers the freedom of association and equal opportunities of workers, their salary and working hours, child labor, forced labor, workers health and safety, and social benefits.
- The *local community* category considers access to material and immaterial resources, cultural heritage, relocation and migration, safe and healthy living conditions, indigenous rights, community involvement, local employment.

- The category considers actors in the *value chain (excluding consumers)* in terms of fair competition, social responsibility, supplier relationships, intellectual property rights and wealth distribution.
- The *consumer category* looks at aspects such as health and safety, feedback mechanisms, consumer privacy, transparency and end-of-life responsibility.
- The *society category* includes aspects such as contribution to sustainability issues and economic growth, prevention and mitigation of armed conflict, technological development, corruption, ethical conditions for animals and poverty alleviation.
- There is also a *children's category*, which considers the provision of education in the local community, children's health as consumers, and children's concerns about marketing practices.

Social impact can be assessed for all stakeholder categories and all subcategories mentioned, or it is possible to select the relevant stakeholder categories and subcategories based on needed social assessment. Social impact can be both positive and negative pressure on social parameters or the well-being of stakeholders [85].

Social category assessment can be expressed as a social reference scale or a social risk assessment [86]. In this Thesis, the scoring from +2 to –2 is applied for the S-LCA studies [86], where

- +2 reflects the ideal performance / best in class.
- +1 as beyond compliance.
- 0 as compliance with local and international laws and/or basic societal expectations.
- -1 as slightly below compliance level.
- -2 as starkly below compliance level.

## 2.3. Utility value level

The utility value method serves as a multi-criteria decision-making framework that allocates numerical values to various outcomes, aiding in choices, especially in uncertain situations. This approach is grounded in utility theory, which offers a systematic means to assess alternatives based on their anticipated results and the preferences of those making the decisions.

The utility value method is grounded on several principles:

- *Multi-attribute utility theory basis*. Based on this theory, at the utility value level decision-makers are empowered to assess alternatives grounded in various, frequently opposing criteria. It organises choices by identifying the essential characteristics (such as environmental, economic and social factors) and allocating significance to each according to its relevance. The total utility of a choice is subsequently computed as a weighted aggregate of its performance across these characteristics [87,88].
- *Handling uncertainty.* The utility value method directly tackles the uncertainty that is a fundamental aspect of environmental decision-making. This is accomplished by employing probabilistic modeling and conducting sensitivity analysis [89,90].
- *Value of information analysis*. Value of information analysis quantifies the benefit of resolving uncertainty by collecting additional information [87,89].
- *Stakeholder participation*. The utility value approach emphasises the importance of incorporating stakeholders' preferences and values. This is particularly important in environmental decisions, where diverse stakeholders often have conflicting objectives. In the context of stakeholder engagement, aspects such as participatory process techniques are essential to guarantee transparency and robustness [90–92].

Utility values act as a numerical representation of how good or bad an option is, but it is important to use structured and sound arguments in the problem-solving and decision-making process, so multi-criteria decision analysis (MCDA) improves the quality of decision-making [93]. MCDA is a multi-step process consisting of a set of methods to structure and formalise decision-making processes in a transparent and consistent manner [94].

MCDA includes various methodologies and serves as a mechanism for evaluating related and conflicting criteria to assess options and identify the optimal solution [95]. Each MCDA method has its own calculation approach for ranking alternatives, and therefore, it cannot be assumed that the same input data will produce identical results across different methods. To understand the applicability of MCDA methods to the specific case studies addressed in this Thesis, a comprehensive review was conducted (see also Paper 1). A summary of the MCDA methods and their key characteristics is provided in Table 2.5.

Table 2.5

Comparing the properties of the most popular MCDA methods

| | TOPSIS | VIKOR | COPRAS | MULTIMOORA | PROMETHEE-GAIA | AHP |
|---|---|---|---|---|---|---|
| **Type of normalization** | Vector normalisation (square root of sum (L2 normalization)) | Linear normalization (L1 normalization) | Vector normalization (sum) | Vector normalization (square root of sum) | Normalization is performed automatically | Vector normalisation (sum) |
| **Suitability** | Choice problems, ranking problems | Choice problems, ranking problems | Choice problems, ranking problems | Choice problems, ranking problems | Choice problems, ranking problems, description problems (GAIA) | Choice problems, ranking problems, sorting problems (AHPsort) |
| **Inputs** | Ideal and anti-ideal option and weights | Best and worst option and weights | Best and worst option and weights | Best and worst option and weights | Indifference and preference thresholds and weights | Pairwise comparison on ratio scale (1−9) |
| **Preference function** | Distance metric (Euclidean distance, Manhattan distance, Tchebycheff distance) | Distance metric (Manhattan distance) | Min – Max | Min – Max | Usual, Linear, U-shape, V-shape, Level, Gaussian | |
| **Approach** | Qualitative and/or quantitative | Quantitative | Quantitative | Quantitative | Qualitative and/or quantitative | Qualitative |
| **Ranking scale** | 0 to 1 | Positive values | Positive values | Positive values | -1 to 1 | 0 to 1 |
| **Best alternative** | Max value | Min value | Max value | Max value | Max value | Max value |
| **Consistency levels** | no restrictions | no restrictions | no restrictions | no restrictions | 7±2 | 9 |

**Criticality in the selection and application of MCDA methods**

To assess the appropriateness of various MCDA methods in the field of environmental engineering, a comparative analysis was conducted. A singular decision-making challenge was addressed utilising five different approaches –TOPSIS, VIKOR, COPRAS, MULTIMOORA, and PROMETHEE-GAIA – and the outcomes were meticulously analysed to comprehend how variations in methodology influence results.

The case study concentrated on identifying the most suitable renewable energy technology for Latvia among solar photovoltaic (PV), wind power plants (WPP), hydroelectric power plants (HPP), and biomass/biogas combined heat and power (CHP) systems. These options were evaluated against seven criteria to determine the optimal choice.

The MCDA input data – criteria with values and alternatives – have been extracted from the research study "Progress in renewable energy technologies: innovation potential in Latvia" [96] and are presented in Table 2.6. In each method, data are the most important element to rank alternatives because these values are used in the calculation process.

Table 2.6

MCDA input data for comparing method results [96–102]

| | Criteria | Solar PV | WPP | HPP | Bio-energy CHP | Weight | Ideal solution |
|---|---|---|---|---|---|---|---|
| C1 | Installed electrical capacity, MW | 1 | 77 | 1565 | 155 | 27 % | MAX |
| C2 | Investment cost, €/kW | 1238 | 3565 | 1388 | 1113,5 | 12 % | MIN |
| C3 | Operation and maintenance cost, €/kW | 12,37 | 26,7 | 2,67 | 0,00446 | 13 % | MIN |
| C4 | RES equipment prices by manufacturer, €/kW | 430 | 1380 | 1290 | 3787,5 | 11 % | MIN |
| C5 | Levelled cost of electricity, €/kW | 0,08 | 0,06 | 0,09 | 0,075 | 8 % | MIN |
| C6 | Life-cycle $CO_2$ emissions, g $CO_2$eq/kWh | 200 | 150 | 150 | 200 | 7 % | MIN |
| C7 | Job creation, thousands | 3095 | 1155 | 865 | 528 | 22 % | MAX |

The comparison of the results of the methods is shown in Figure 2.2 and as can be seen, the distribution of alternatives by location is similar, but not identical (results are shown in order of ranking, that is 1 as the best alternative is ranked as 1). TOPSIS and PROMETHEE-GAIA methods had similar alternative rankings, but VIKOR, COPRAS and MULTIMOORA methods had similar and different alternative rankings. This means that the approach of the MCDA method alone can affect the result, and the appropriate method should be selected based on applicability.
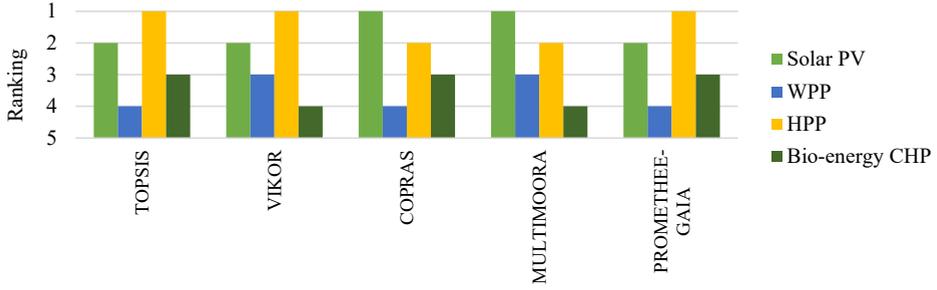
Figure 2.2. Comparison of alternative ranking using different MCDA methods. (1 is the best alternative, 5 is the lowest alternative).

### 2.3.1. Multi-criteria decision analysis

Within the Thesis, two MCDA methods were applied: the Analytic Hierarchy Process (AHP) and Technique for Order Preference (TOPSIS).

**Analytic Hierarchy Process** (AHP) is a structured method for decision making based on pairwise comparisons between the given criteria [103]. One of the most important AHP indicators is the number of criteria, as it affects the consistency of the results and more than seven criteria increase the inconsistency of the results [104]. The AHP model facilitates organising different variables at different levels of hierarchy and it helps experts evaluate criteria [105].

AHP method calculation steps and equations [104]:

- Create a pairwise comparison matrix and rate on an importance scale from 1 to 9, where equal importance is 1, strong importance is 5 and extreme importance is 9.
- Calculate the normalized matrix using equation 1:

$$X_{ij} = \frac{c_{ij}}{\sum c_{ij}} \qquad (1)$$

where
$C_{ij}$ – criteria value;
$\sum C_{ij}$ – column sum.

- Calculate the priority vector using equation 2:

$$W_{ij} = \frac{\sum X_{ij}}{n} \qquad (2)$$

where
$\sum X_{ij}$ – sum of the normalized matrix column;
n – number of criteria.

- Calculate the consistency index (CI) and consistency coefficient (CR) using Equations 3-6:

$$\lambda_i = \frac{A \times W}{W_i} \qquad (3)$$

$$\lambda_{max} = \frac{\sum \lambda}{n} \qquad (4)$$

$$CI = \frac{\lambda_{max} - n}{n - 1} \qquad (5)$$

$$CR = \frac{CI}{RI} \tag{6}$$

where
A – matrix;
W – priority vector;
RI – randomness index depending on the size of the matrix ( Table 2.7).

Randomness index [104]

| n | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|
| RI | 0 | 0 | 0,58 | 0,90 | 1,12 | 1,24 | 1,32 | 1,41 | 1,45 |

The values obtained from AHP can be used as weights in other decision-making methods where alternatives are compared. In addition, the results obtained with AHP can provide insight into the importance of each criterion and help determine which indicator most effectively solves the decision problem

**Technique for Order Preference** (TOPSIS) – by Similarity to Ideal Solutions is method that evaluates the distance of alternatives to ideal and anti-ideal point and alternative with shortest distance to ideal point is the best alternative. TOPSIS is one of the most popular MCDA methods and was presented by Hwang and Yoon in 1981 [106]. The TOPSIS framework starts with collecting input data, then calculations of the normalized matrix and the weighted standard matrix. The next step is the distance from ideal and non-ideal solutions and calculations of closeness between each alternative to the ideal solution, and the best alternative is the one with highest closeness [106]. The TOPSIS method equations [107]:

- Calculate normalized matrix using Eq. (7):

$$R = \frac{X}{\sqrt{\sum X^2}} \tag{7}$$

where
X – criteria value;
$\sum X$ – sum of criteria value.
- Calculate normalized weight matrix from Eq. (8):

$$V = R \times W \tag{8}$$

where
R – normalized matrix value;
W – criteria weight.
- Define best and worst value of criteria: best values $V^+$=max and worst values $V^-$=min; best values $V^+$=min and worst values $V^-$=max.
- Use of formulas as shown in Eq. (9) and (10) to difference value from best or worst value
-

$$d_a^+ = \sqrt{\sum (v^+ - v_{a)}^2} \tag{9}$$

where
$V^+$ - ideal or best value;
$V_a$ – normalized weighted matrix value.

$$d_a^- = \sqrt{\sum (v^- - v_{a)}^2} \tag{10}$$

where:
$V^-$ - non-ideal or worst value;

$V_a$ - normalized weighted matrix value.

- Find the relative closeness and rank the alternatives using Eq. (11)

$$C_a = \frac{d_a^-}{d_a^+ - d_a^-} \tag{11}$$

where:

$d_a^-$ – non-ideal or worst value;
$d_a^+$ – ideal or best value.

TOPSIS scores are obtained based on the relative distance from these ideal and anti-ideal points – the smaller the difference between the best and worst values of a criterion, the closer the alternative ratings will be to each other. A TOPSIS sensitivity analysis of the criteria can also be performed to determine which of them had the greatest impact on the final ranking.

# 3. Results

## 3.1. Strategic fit approach

The developed multi-factorial decision-making methodology is grounded in a framework of incremental complexity. Within this methodology, the assessment of strategic fit serves as the initial step and is applied to a case study comparing energy resource use across agricultural sub-sectors in different Latvian regions.

### 3.1.1. Strategic fit approach to the national energy sector

In the context of the national energy sector, the strategic fit approach is a crucial first step in assessing energy resources. It provides a basic understanding of the existing situation and helps decision-makers to identify aspects that need improvement to develop an efficient and sensible resource chain.

Agriculture in Latvia is one of the three largest sectors that emit GHG emissions [108]. To understand strategic fit, the agricultural sector was divided into subcategories based on farm size and type, and energy consumption estimates were obtained from official Latvian statistical data. Data were obtained from the public registers of the State Environmental Service and Pollution Permits provided detailed information to more accurately assess energy consumption in different agricultural sub-sectors. Indicators such as the consumption of transport energy by different processes were obtained from the permits and based on publicly available energy balance data, and agricultural types such as crop production, dairy farming, pig and poultry farming and mixed crop and livestock production were analysed in the case of Latvia, Figure 3.1.



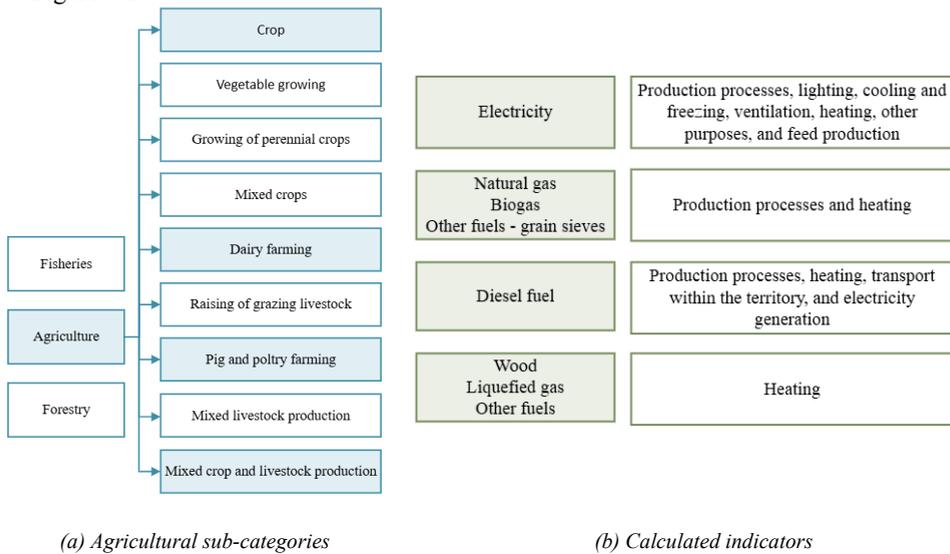(a) Agricultural sub-categories                    (b) Calculated indicators

Figure 3.1. Agricultural sub-sectors and indicators considered [109].

Data were extracted from 46 relevant pollution permits and expressed as agricultural production units, which represent the number of livestock or arable land on specific farms. It

was assumed that the energy consumption at the national level for various processes is the same as that indicated in the pollution permits of the analysed farmers. 2017 is the base year for assessment, and the results are expressed by regions – Pieriga, Vidzeme, Kurzeme, Zemgale, and Latgale, as spatial differences are considered.

The type and amount of energy consumed varies according to the specific characteristics of each agricultural sub-sector and the technologies used. Figure 3.2 shows an example of a specific energy consumption indicator that reflects electricity consumption on pig farms. Based on data from several farms, the average electricity consumption for each process was calculated and expressed per pig. Similar calculations were made for all sub-sectors, determining the energy consumption per unit of production.
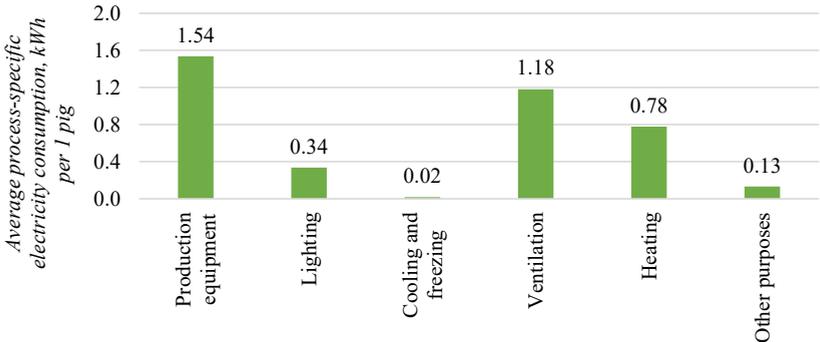


Figure 3.2. Average process-specific electricity consumption in the Latvian pig farming sub-sector.

Energy consumption in crop production is measured per hectare and electricity consumption is given in MWh/ha. The main fuels used during crop harvesting are natural gas, diesel, fuel oil, wood and biogas, which mainly support production processes and heating. Figure 3.3 presents data on the area under crop production in Latvia, which was 703 498 hectares in 2017. Energy consumption in crop production is seasonal and is determined by activities such as land preparation, sowing, tillage, harvesting and post-harvest activities that take place from spring to autumn.
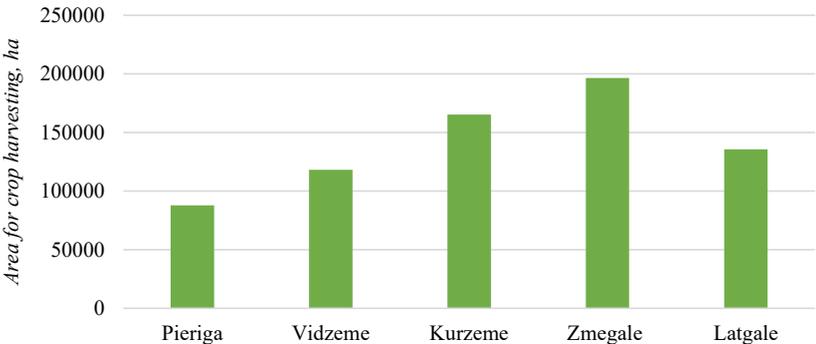


Figure 3.3. Regional distribution of crops harvested area in Latvia.

Dairy farming in Latvia is concentrated in the Latgale and Vidzeme regions, while pig farming is mainly in Zemgale and Pieriga, see Figure 3.4. Energy consumption is measured in MWh per animal.

Based on the literature review, electricity is consumed for milk cooling, milk harvesting (vacuum pumps), water heating, water pumping, lighting, and other processes [110]. According to the literature review, a dairy farm consumes 48.9 watts of electricity per 1 kg of milk. However, the most energy-intensive process results differ, as some researchers believe it is a milk cooling process, but others indicate that milk harvesting, or water heating consumes the most electricity [110].
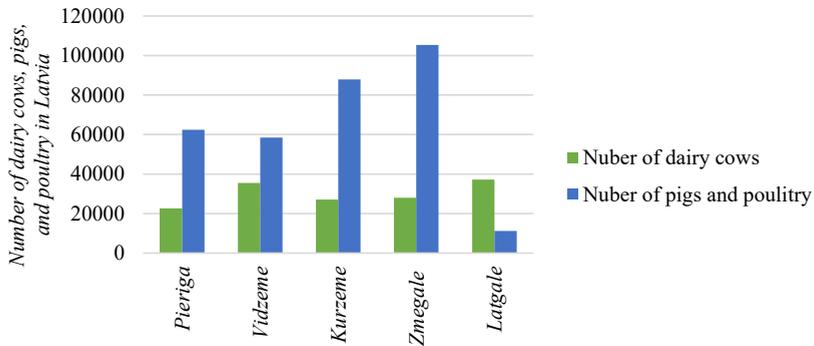


Figure 3.4. Regional distribution of dairy cows, pigs and poltry in Latvia.

Mixed crop and livestock production is a separate sub-sector. However, there are no more in-depth statistics regarding this subsector available in Latvia. Most of the mixed agriculture sub-sector in Latvia is pig farming with additional crop production, and the total number of farms varies from year to year. For example, in 2010, there were 10 814 farms, but in 2013 there was an increase to 12 257 farms. In 2016, mixed farms decreased to only 10 319 mixed agriculture farms [109].

The data on energy consumption shows the breakdown in 2017. Figure 3.5 illustrates the regional energy consumption in the crop production sub-sector. Zemgale (143 GWh) and Kurzeme (120 GWh) recorded the highest energy consumption, with diesel (167 GWh) and biogas (95 GWh) being the main energy sources.
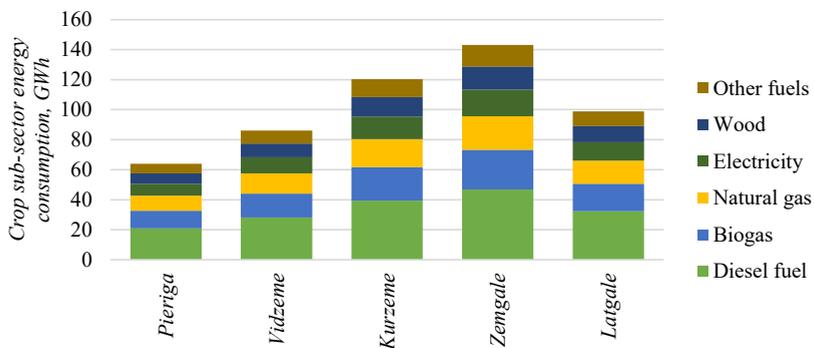


Figure 3.5. Regional distribution of energy consumption in the crop production subsector.

In the pig and poultry subsector, Figure 3.6 shows that Zemgale (124 GWh) and Kurzeme (106 GWh) also lead in energy consumption. The main energy sources in this sub-sector are grain sieves (183 GWh) and biogas (140 GWh).
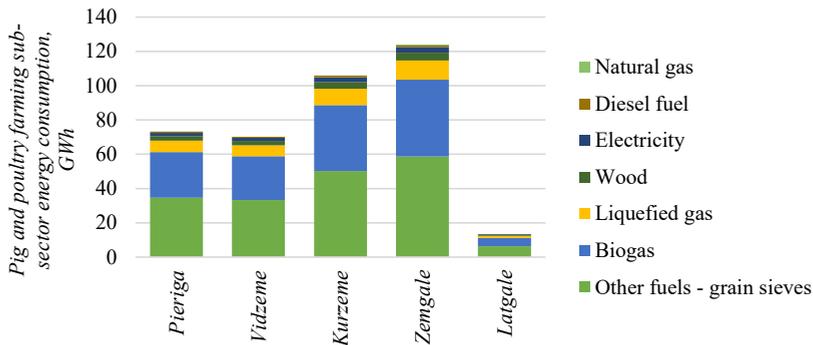
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Figure 3.6. Regional distribution of energy consumption in the pig and poultry farming subsector.

Figure 3.7 shows the total energy consumption in Latvia's agricultural sector by region. The main energy sources are diesel, biogas, electricity and fuels such as those used in grain sieves. Kurzeme and Zemgale have the highest agricultural energy consumption, due to the importance of crop and pig farming in these areas. The calculated energy consumption by sub-sector was compared with the 2017 Latvian energy balance data, confirming the consistency of the overall consumption.
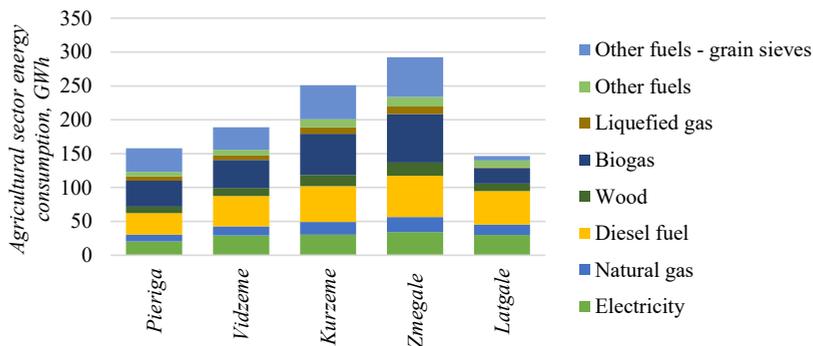


Figure 3.7. Regional distribution of energy consumption in Latvia's agricultural sector.

The strategic fit analysis of Latvian agricultural energy consumption shows the importance of aligning energy resource planning with sector characteristics and regional realities. The results show significant differences between Latvian regions and also between agricultural sub-sectors. Therefore, a regionally tailored strategy is needed to achieve the set goals, as unique approaches to energy solutions are shared by different farm types. Strategic fit provided a clearer and more detailed picture of current energy consumption in the sector but also demonstrates that there needs to be more regional decision-makers for progress to happen.

## 3.2. Sustainability approach

If the resource value chain solution aligns with the *strategic fit* level requirements, decision-makers can proceed to the subsequent, more complex level of assessment – the life cycle analysis-based sustainability assessment of the proposed solution. This evaluation considers environmental, economic and social factors, carried out at the suiatable level and scope to

effectively support decision-making. The sustainability assessment approach is applied to two case studies:

(1) Comparative assessment of healthcare waste valorisation scenarios.
(2) Selection of the ideal solution for fishing waste management options.

### 3.2.1. Sustainability approach to the national waste sector

To support decision-makers in waste management planning, a strategic fit analysis was conducted to explore potential circular economy solutions for infectious healthcare waste (iHCW) and assess the current and a circular economy-oriented waste management system from an environmental and economic sustainability perspective.

A review of Latvia's waste management sector found that iHCW has recycling potential but is currently landfilled in Latvia. A qualitative data analysis of the potential uses of waste as a resource was carried out for strategic fit. However, an environmental and economic sustainability assessment is needed to compare recycling options with the current situation of waste landfilling, as the amount of waste increases, as shown in Figure 3.8.
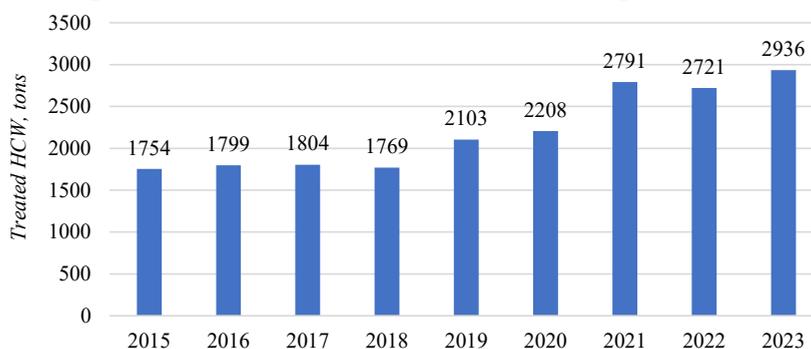


Figure 3.8. Annual amount of treated iHCW in Latvia [111].

This LCA examines the current situation and potential valorisation scenarios for treated iHCW. A total of seven scenarios are analysed in this study: the "business as usual" (BAU) scenario and seven treated iHCW valorisation scenarios (VS). The BAU scenario reflects a linear economy approach, where treated iHCW is disposed of in sanitary landfills. Alongside incineration, landfilling remains one of the most widely used methods for managing treated healthcare waste globally [112]. VS1–VS6 (see Table 3.1) represent circular economy approaches where six distinct products are derived from treated iHCW: reinforced asphalt, reinforced cement, RDF, syngas, acoustic panels and plastic components for hydroponics. These products were selected based on factors such as their added-value potential, the maturity of recovery technologies and their industrial symbiosis potential under Latvian conditions. The materials utilised in the product development (plastics, textiles or all iHCW) and their proportions in the final products vary across scenarios (see Table 3.1). A substitution approach is applied in all valorisation scenarios, where virgin raw materials are replaced with iHCW-recovered materials. These approaches are based on two waste management strategies: recycling and energy recovery. According to the waste management hierarchy [113], recycling is prioritized after waste prevention and reuse, whereas energy recovery is considered a less favorable option, positioned just above landfill disposal. Consequently, energy recovery should be applied only to non-recyclable or hard-to-recycle waste. Treated iHCW is frequently classified as non-recyclable due to processes like soaking and post-shredding. However, modifications to these processes – such as avoiding shredding –

and enhanced segregation practices (e.g., sorting waste into specific fractions or materials at the source) can improve alignment with the waste hierarchy, thereby promoting recycling and material recovery. Building on this framework, an additional scenario (VS7) will be developed as an optimized solution. This scenario aims to maximize the use of recycling strategies with the lowest LCA results while incorporating the energy recovery strategy with the lowest LCA impact for the remaining fractions of treated iHCW (e.g., metals, wood, mixed waste and rubber) – ReCiPe 2016 midpoint method.

Table 3.1

Valorisation scenarios and iHCW share in the product

| Scenario | Waste hierarchy approach | iHCW share used | iHCW material type used |
|----------|--------------------------|-----------------|-------------------------|
| VS1: reinforced asphalt | Recycling | 34 % | Plastics |
| VS2: reinforced cement | Recycling | 31 % | Textile |
| VS3: RDF | Energy recovery | 100 % | All iHCW |
| VS4: syngas | Energy recovery | 100 % | All iHCW |
| VS5: acoustic panel | Recycling | 31 % | Textile |
| VS6: plastic components used for hydroponics | Recycling | 34 % | Plastics |
| VS7: combination of products | Max. recycling, min. energy recovery | 100 % | All iHCW |

Following the strategic fit assessment, an environmental and economic sustainability assessment is carried out.

**Goal and scope**

The goal of this environmental LCA is to define the environmental impacts associated with the management of iHCW under both linear economy conditions (treatment and landfilling) and circular economy conditions (treatment of iHCW and its subsequent use as a raw material for the development of new products).

**Functional unit**

The study considered two functional units: 1 ton of treated iHCW and the annual amount of treated HCW generated in Latvia. 1 ton of treated iHCW is a well-established unit for measuring waste generation, allowing for comparisons across regions. On the other hand, focusing on the annual quantity of treated HCW generated in Latvia is particularly valuable for policymakers and potential investors at the local scale, as it helps assess the availability and management of such resources on a broader, more practical level.

While both functional units were considered in the study, the focus on 1 ton of treated iHCW was particularly relevant given the variability in waste generation over recent years. This variation is reflected in the data summarized in Figure 3.8.

The data on treated iHCW (180103, 180202, 180207) in Latvia from 2015 to 2022 shows an average of 2,209 tons of treated waste per year. Volumes on iHCW have been relatively similar between 2015 and 2019 but have become more variable since the start of the COVID-19 pandemic. All scheduled healthcare services were suspended at the beginning of the pandemic, and therefore there is less treated waste in 2020 than in 2021 and 2022, when planned services were restored. Since iHCW volumes have been so variable in recent years, the functional unit (FU) in this environmental LCA is 1 ton of treated iHCW.

**System description**

The technological system boundaries of the present environmental LCA are "gate-to-gate": from generation of the iHCW in hospitals to the end-of-life stage of the iHCW – landfilling (defined as business as usual (BAU) scenario) or one of the six valorisation scenarios (see Figure 3.9). The time boundaries of the present LCA are October 2022 – September 2023, a period when the inventory data collection was performed. The geographical boundaries of the LCA cover Latvia.
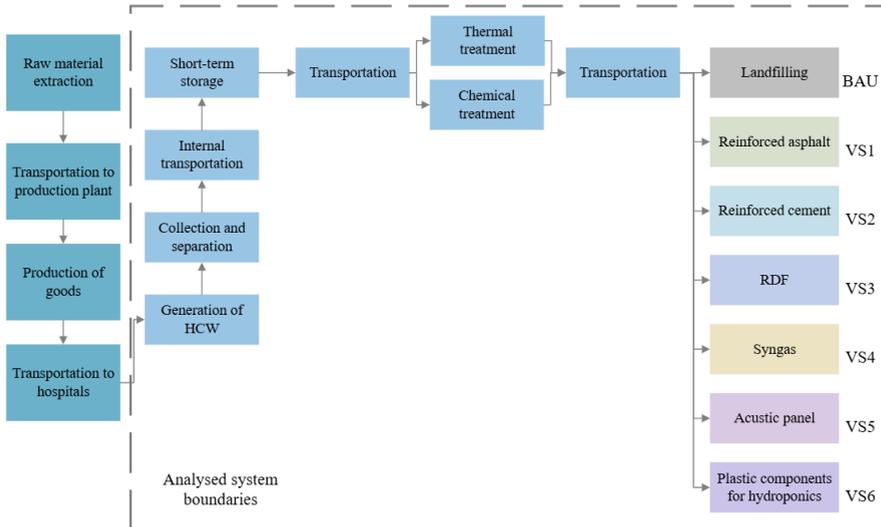


Figure 3.9. Technological system boundaries of the analysed scenarios.

The definition of the scenarios to be analysed was based on several key considerations. First, the composition of iHCW, which is heterogeneous and varies depending on factors such as seasons, disease outbreaks, location, type of healthcare facility, and the economic and social conditions of a country [114]. Notably, iHCW is predominantly composed of plastic waste (e.g., polypropylene, nylon, polyester), followed by various textiles (e.g., cotton and cellulosic materials) [115]. Second, the mass characterisation of iHCW after treatment at iHCW treatment plants was considered. Both technologies involve shredding the treated waste into particles ranging from 13 to 55 mm in size. Third, the presence of symbiotic enterprises in the region – such as energy plants, cement and concrete factories, or asphalt plants – near the iHCW treatment facilities was also considered. A detailed description of the valorisation scenarios is provided in the inventory section.

**Life cycle impact assessment**

Life cycle assessment modeling software SimaPro v9.5 [116] was used for the study. ReCiPe 2016 (Midpoint, *Hierarchist* perspective) was used as an impact assessment method [73] which includes 18 midpoint indicators covering three damage fields – damage to human health, damage to ecosystems and damage to resource availability.

**Environmental life cycle inventory**

Overall approach on data collection and limitations

Inventory data required for the survey was collected from Latvian companies involved in the iHCW supply chain, including hospitals, iHCW transportation providers and iHCW treatment companies, as well as a landfill operator. Since none of the analysed valorisation

scenarios (VS1-VS6) have been implemented in practice, inventory data for the end-of-life stage was sourced from scientific papers and adjusted to match the analysed supply chain conditions.

In addition, some generalised assumptions are defined:

- The separation of iHCW into fractions (refer to Table 3.2) is performed at the point of generation, in hospitals, immediately after the product is used. All these fractions are considered infectious and needed to be treated to assure microbial inactivation.
- iHCW is collected from healthcare institutions across Latvia, encompassing both human and veterinary healthcare facilities. While the maximum distance from an iHCW generation point to a treatment plant is 302 km, most healthcare institutions utilising these services are concentrated within a 60 km radius of the treatment plant. Based on this, the levelized distance from an iHCW generation point to the treatment plant is assumed to be 100 km.
- The valorisation scenarios (VS1-VS6) include the transportation of treated iHCW to a production plant. Given the variety of products to be generated from treated iHCW and the varying locations of the associated production sites, a market analysis was conducted to identify the closest feasible options. This analysis prioritized economic considerations, which are a core factor for iHCW treatment companies during the selection process. Consequently, 50 km was established as the assumed distance from the iHCW treatment plant to a production plant.
- Supply chain actors' (hospitals, transportation and treatment companies, landfill management companies) provided data is used as much as possible within the life cycle inventory. However, if no proper qualitative data was able to be submitted by the companies, relevant data was used from "Ecoinvent" database, specifically related to Latvian parameters. If such data is not available, then data related to RER (Europe) parameters is used. This ensures a hierarchy in data preference, choosing the most relevant and specific information whenever possible.
- Energy (for mechanical separation in fractions) and consumables (additional bins, bags. etc.) used to segregate iHCW streams according to material type are excluded from the inventory. These simplifications are possible because the most proper segregation method for the iHCW is segregation at generation points, i.e. in healthcare facilities, instead of segregation at waste treatment plants or recycling companies.

<u>iHCW generation at healthcare institutions and transportation</u>

The composition of iHCW generated in healthcare facilities varies and depends on such factors as hospital service profile, segregation practices applied in a specific facility, as well as the behaviour of medical personnel in the provision of qualitative segregation.

In the current research, a levelized composition of iHCW is utilised for inventory purposes. The compositional data (refer to Table 3.2) was obtained through experimental testing of mixed iHCW collected from various healthcare institutions across Latvia and delivered to two centralised iHCW treatment facilities in the country. This data was previously reported by Zlaugotne et al. [115].

Table 3.2

Levelized composition of iHCW generated in Latvian healthcare facilities [115]

| Fraction | Share in total mass, % |
|---|---|
| Plastic | 34 |
| Cotton | 31 |
| Latex, rubber, nitrile | 19 |

| Fraction | Share in total mass, % |
|---|---|
| Mix of different fraction | 12 |
| Aluminium | 3 |
| Wood | 1 |

Generated iHCW from healthcare facility rooms is collected in waste bins and subsequently transferred, with both infectious waste and sharps discarded into 1.1 m³ containers. This mixed iHCW is then transported to treatment plants using specialized trucks owned by iHCW treatment companies. These trucks have a load capacity of 15 tonnes and comply with EURO 6 emission standards, which regulate vehicle emissions by category and engine type.

iHCW treatment

Considering the nature of iHCW, it required to be treated assuring the microbial inactivation reduction of various bacteria, viruses, parasites and other microorganisms present at least at a 6Log10, as well as inactivation of *B. atrophaeus* and *G. stearothermophilus* spores at a 4Log10 reduction or more [117]. In Latvia, treatment of iHCW is provided by two centralised iHCW treatment companies – thermal and chemical treatment companies.

Thermal waste treatment plant uses a thermal treatment technology to treat iHCW from many healthcare facilities in the country (market share based on collected iHCW mass balance is 48 %) [111]. The thermal treatment unit is an integrated steam treatment system that uses an inclined horizontal stainless steel pressure vessel with a rotating inner drum containing vanes in the internal surface of the drum. iHCW is piled into 660-liter wheeled red bins. The waste is then loaded into the treatment unit's drum by means of an automatic loader. After the iHCW is introduced into the drum and the vessel door is sealed, a steam jet ejector system is used to pull a vacuum after which steam is introduced to treat the waste. The system is computer controlled. During the treatment process (at proper temperature (up to 132 °C) and pressure levels, the inner drum rotates causing bags and containers to be ruptured and their contents mixed inside the vessel. After a sufficient steam exposure time (from 30 to 60 minutes based on the amount of waste treated), a post-treatment vacuum cycle removes the steam and reduces the moisture content. The vessel door is then opened, and the treated waste is then ejected onto a conveyor which brings the waste into the hopper of a heavy-duty shredder. The finely shredded treated waste (microbial inactivation efficiency of the treatment unit is tested regularly) is then ejected into another series of conveyors into a compactor and roll-off container.

The chemical iHCW treatment plant utilises a technology that uses $ClO_2$ to treat iHCW (their market share based on the treated iHCW amount is 52 %) [111]. iHCW containers (660 liters) are first lifted and their contents deposited into a hopper. Once waste is dropped into the hopper, shredding of material occurs. During the shredding process, air from the hopper is extracted through a HEPA filtration process. A four-shafted shredder reduces the waste to small particles. This particalized waste falls into a chamber below the shredder which contains a liquid solution of $ClO_2$ (cold water and $ClO_2$). A probe monitors the $ClO_2$ concentration. The entire treatment process is monitored by a control panel that provides the operator with the $ClO_2$ concentrations as well as a video of the interior of the hopper. If more $ClO_2$ is required, staff inject the chemical until acceptable levels are reached. After the treatment process (15-25 minutes long) the treated waste is conveyed from this chamber *via* a screw conveyor to be discharged into a collection bin. The treated waste (microbial inactivation efficiency of the treatment unit is tested regularly) has a moisture content of approximately 50-60 %. As a result, it is stored in specialized containers for several hours to reduce the moisture level to 40-42 % through the passive deliquification process.

Lastly, in both companies, the treated iHCW is transported to the "end-of-life" or recovery site *via* specialised iHCW treatment companies' owned trucks (load capacity –15 tonnes, EURO 6 (emission limits by vehicle category and engine type)).

Considering the shared market of the iHCW treatment activities between two iHCW treatment companies and the selected FU, the mass allocation (52 %:48 %) is performed to demonstrate the proper HCW treatment conditions in Latvia.

iHCW end-of-life

The conventional method for managing treated HCW in Latvia is landfilling, which is also applicable to the BAU scenario. The BAU scenario inventory for both Latvian companies managing iHCW is presented in Paper 13.

While the processes of iHCW generation, transportation, treatment, and the transportation of treated iHCW to the end-of-life point are consistent across all analysed scenarios, the end-of-life outcomes for the treated waste vary between the scenarios, as detailed in the description of each scenario below.

*VS1: Feedstock for reinforced asphalt*

Treated iHCW is transported to an asphalt production plant. In the production of asphalt, the raw materials are natural aggregates (gravel), aggregates and asphalt binding agent (bitumen), and after crushing and grinding the raw materials, the asphalt mixture is produced [118]. Different research has examined the use of various plastics in the production of asphalt, the most popular plastics being high-density polyethylene (HDPE), low-density polyethylene (LDPE), polypropylene (PP), polyethylene terephthalate (PET), ethylene-vinyl acetate (EVA), polyvinyl chloride (PVC), polyethylene (PE) and polyethylene terephthalate (PTP) [119]. Research shows that adding plastic waste improves the strength and stiffness of asphalt, but it is important to understand the morphology of plastic waste because it affects the asphalt production method (dry or wet method) and the performance of the resulting asphalt mixture) [119]. In the research different percentage values are mentioned for the addition of plastic waste to asphalt mixture – 5.7 % of the total asphalt weight [120], 6 % of the bitumen weight [121,122] and 6.5 % of the bitumen weight [123]. In this scenario, it will be used that 6 % of bitumen is replaced by plastic waste from the treated iHCW, while other iHCW fractions are landfilled. In Paper 13 are scenario inventory data.

*VS2: Feedstock for reinforced cement*

Treated iHCW is transported to a concrete production plant, where raw materials such as cement, water, aggregates (sand, gravel, crushed stone and additives) are used [20], [21]. Waste materials, including glass, polypropylene, carbon, polyester and textile fibers, can be incorporated into concrete as reinforcement agents [22]. In VS2, it is assumed that treated iHCW textile waste will partially replace the sand used in concrete, with the previous research [23] noting that replacing 20 % of sand with textile waste yields optimal results. The remaining iHCW fractions are landfilled. The inventory for the value-added product, reinforced concrete, is provided in Paper 13.

*VS3: Feedstock for RDF*

Treated iHCW is transported to an energy generation plant from refuse derived fuel (RDF) generated from treated iHCW. RDF is a specific type of alternative fuel with a high calorific value (on average 16-18 MJ/kg) and uniform particle size [124]. RDF is obtained from non-hazardous waste and is most often composed of 10-75 % high- and low-density plastic waste, 12-85 % paper and cardboard waste, 5-66 % textile waste, 5-30 % organic waste and up to 10 % non-combustible fraction waste [125]. To recover the valuable material, partially homogenize and eliminate water, $CO_2$ and the non-combustible fraction from waste, the waste are mechanically (crushing, sorting, drying, shredding) or biologically (mechanical treatment with additional biostabilization and biodrying) processed [125]. Within VS3 all treated iHCW is used to produce RDF and replaces natural gas used for heat production. Inventory for VS3 is given in Paper 13.

Treated iHCW is transported to an energy generation plant from refuse derived fuel (RDF) generated from treated iHCW. RDF is a specific type of alternative fuel with a high calorific

value (on average 16-18 MJ/kg) and uniform particle size [124]. RDF is obtained from non-hazardous waste and is most often composed of 10-75 % high- and low-density plastic waste, 12-85 % paper and cardboard waste, 5-66 % textile waste, 5-30 % organic waste and up to 10 % non-combustible fraction waste [125]. To recover the valuable material, partially homogenize and eliminate water, $CO_2$ and the non-combustible fraction from waste, the waste are mechanically (crushing, sorting, drying, shredding) or biologically (mechanical treatment with additional biostabilization and biodrying) processed [125]. Within VS3 all treated iHCW is used to produce RDF and replaces natural gas used for heat production. Inventory for VS3 is given in Paper 13.

*VS4: Feedstock for syngas production*

Treated iHCW is transported to a syngas production plant. Syngas can be produced from various carbon sources – fossil fuel (coal gasification, natural gas, oil), but it is also possible to use waste gasification to obtain syngas [126]. Gasification is a process when insignificant materials (including waste) are converted into gaseous products with usable heat capacity and after purification processes, syngas can be used as an alternative fuel to produce thermal energy and electricity [127]. All treated iHCW will be used to produce syngas, which will then be used to generate electricity, and it will replace electricity from the grid. VS4 inventory is in Paper 13 value added product produced syngas from the treated iHCW

*VS5: Feedstock for acoustic panel*

Treated iHCW is transported to an acoustic panel production plant. Sound absorption panels (or acoustic panels) are made from porous synthetic materials such as stone wool, glass wool, polyurethane, polyester and others [128]. The use of waste in the production of sound-absorbing panels is a possible alternative, as they can have good acoustic properties and are like traditionally used materials [128]. It is concluded that the recycled textile waste has good acoustic properties to be used in the production of panels [129]. Research on thermal and acoustic panels from recycled materials, where the main raw materials are wastepaper and textile waste [130]. To produce 1 m$^2$ of insulation panel, a total of 5.2 kg of raw materials are required – 3.4 kg of wastepaper and 0.4 kg of textile waste, as well as 1.4 kg of glue [130]. All textile waste from the treated iHCW is used to produce acoustic panels, others iHCW fractions are landfilled. Value added product produced acoustic panel from the treated iHCW and inventory data is in Paper 13.

*VS6: Feedstock for plastic components in hydroponics*

Treated iHCW is transported to hydroponic systems production plant. Hydroponics and aquaponics are closed environments where plant crops and/or aquatic animals are grown under optimized conditions using soilless systems [131]. A vertical farm system combines hydroponics, aeroponics or aquaponics systems [132]. The technological infrastructure of these systems uses many different plastic products, such as different types of containers and connecting tubes [132]. Plastic waste from iHCW can thus be recycled into various plastic products [133]. Plastic products that would be suitable for a vertical farm are various garden items such as growing containers, water system pipes and others. In this scenario, plastic waste from the treated iHCW is replaced by plastic pellets, while remaining iHCW fractions are landfilled. VS6 inventory data is in provided in Paper 13.

**Life cycle impact assessment results**

Table 3.3 shows the results of the life cycle impact assessment using ReCiPe 2016 midpoint (H) method, where the scenario results are indicated in numbers (a positive result indicates that the system influences the given environmental indicator, while a negative result signifies an avoided impact, thereby providing an environmental benefit). The results are also marked with colours on a scale from very low environmental impact (bright green) to very high

environmental impact (orange). As seen from Table 3.3, the environmental impacts in VS3 and VS4 are entirely negative due to the high share of iHCW being recycled rather than landfilled.

ReCiPe 2016 Midpoint (H) results for BAU and VS1-VS6

| | BAU | VS1 | VS2 | VS3 | VS4 | VS5 | VS6 |
|---|---|---|---|---|---|---|---|
| GW, kg $CO_2$ eq | 1.51E+03 | 1.25E+03 | 6.03E+02 | 1.95E+02 | 2.37E+02 | 5.98E+02 | 1.18E+03 |
| SOD, kg CFC11 eq | 8.08E-05 | 8.21E-05 | 8.89E-05 | 2.14E-05 | 1.87E-04 | 8.73E-05 | 6.02E-05 |
| IR, kBq Co-60 eq | 2.77E+00 | 2.66E+00 | 2.93E+00 | 7.60E-01 | 4.33E+01 | 2.58E+00 | 1.45E+00 |
| OFHH, kg NOx eq | 2.98E-01 | 1.96E-01 | 2.19E-01 | 1.65E-01 | 5.39E-01 | 2.07E-01 | 3.11E-02 |
| PM, kg PM2.5 eq | 8.76E-02 | 7.02E-02 | 7.71E-02 | 2.80E-02 | 2.89E-01 | 6.96E-02 | −4.53E-02 |
| OFT, kg NOx eq | 3.13E-01 | 2.11E-01 | 2.37E-01 | 1.88E-01 | 5.71E-01 | 2.24E-01 | 4.18E-02 |
| TA, kg $SO_2$ eq | 1.91E-01 | 1.49E-01 | 1.64E-01 | 7.37E-02 | 5.68E-01 | 1.51E-01 | −2.22E-02 |
| FE, kg P eq | 9.86E+00 | 4.62E+00 | 6.56E+00 | −3.33E-03 | −4.94E-02 | 6.55E+00 | 4.57E+00 |
| ME, kg N eq | 2.06E+00 | 6.10E-01 | 1.81E+00 | 2.35E-03 | 5.31E-03 | 1.80E+00 | 6.06E-01 |
| TEC, kg 1,4-DCB | 9.98E+02 | 1.20E+03 | 1.30E+03 | 4.02E+02 | 3.82E+03 | 1.27E+03 | 9.56E+02 |
| $FE_C$, kg 1,4-DCB | 5.18E+02 | 3.58E+02 | 4.59E+02 | 4.49E-01 | 6.52E+00 | 4.59E+02 | 3.51E+02 |
| MEC, kg 1,4-DCB | 6.87E+02 | 4.73E+02 | 6.12E+02 | 1.16E+00 | 1.20E+01 | 6.12E+02 | 4.63E+02 |
| HCT, kg 1,4-DCB | 2.04E+01 | 1.89E+01 | 2.17E+01 | 8.87E+00 | 3.23E+01 | 2.10E+01 | 1.10E+01 |
| HNCT, kg 1,4-DCB | 1.23E+04 | 8.07E+03 | 1.12E+04 | 2.50E+00 | 1.22E+02 | 1.12E+04 | 7.97E+03 |
| LU, $m^2$a crop eq | 5.72E+00 | 4.81E+00 | 4.70E+00 | 2.56E-01 | 2.52E+01 | 4.48E+00 | 3.68E+00 |
| MRS, kg Cu eq | 1.50E-01 | 1.57E-01 | 1.79E-01 | 1.05E-01 | 4.58E-01 | 1.62E-01 | 5.76E-02 |
| FRS, kg oil eq | 2.09E+01 | 2.09E+01 | 2.43E+01 | 7.43E+01 | 7.48E+01 | 2.29E+01 | 6.74E+00 |
| WC, $m^3$ | -5.67E+00 | -3.11E+00 | -6.07E+00 | 1.58E-01 | 2.06E+00 | -6.09E+00 | -3.35E+00 |

Colour scale: Very low — Low — High — Very high

Overall, the lower environmental impact results were achieved in the VSs, where the entire iHCW stream was recycled for energy recovery (VS3 and VS4), but this does not properly align with the circularity principles, where the focus needs to be given on re-use, recycling and recovery. To keep the focus on circularity, VS7 was created: it represents an integrated recycling and energy recovery process – plastic and textile fractions of iHCW are recycled, the remaining fraction (rubber, metals, wood and mix of fines), which cannot be yet recycled to any of the analysed recycling scenario, is transferred to energy recovery. Based on the LCA results (see Table 3.3), this includes plastics recovery *via* VS5, textiles recovery *via* VS7 and the remaining treated iHCW directed to syngas production through VS4. The impact of transportation is similar in all considered scenarios (from 0,4Pt to 1,5Pt) due to the distance assumptions made, and the impact of the iHCW treatment process as well as – being in the range from 0,29 Pt to 0,44 Pt.

For better representation of BAU and VS results, Figure 3.10 provides the results in single score manner and the values are expressed in EcoPoints (Pt). The single-point results are formed from three main groups: iHCW treatment, transportation and end-of-life. As can be seen, the greatest impact is caused by landfilling iHCW, while the impact of transport and iHCW treatment has similar Pt values in all scenarios.
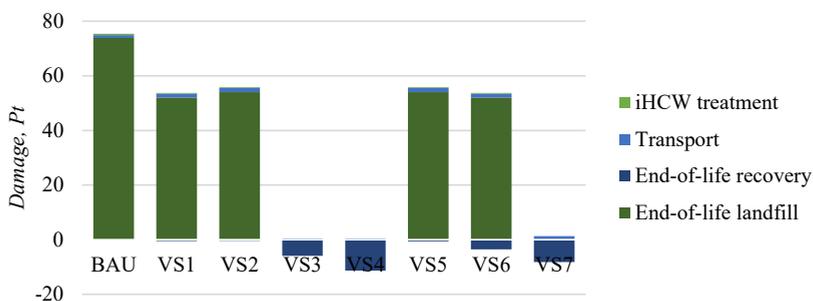


Figure 3.10. Single score results for BAU and VS1 – VS7 (ReCiPe 2016 midpoint (H)) method.

Using a literature review to determine the strategic fit of the alternative and the current situation regarding the management of iHCW, several scenarios were defined. Using an environmental sustainability assessment, a more in-depth comparison of the alternatives was obtained, which shows decision-makers the alternative with the lowest impact.

### 3.2.2. Sustainability approach to the national waste sector

The aquatic sector presents sector-specific challenges that require sustainable management options for the generated waste. A literature review was therefore used to understand the strategic relevance of the management options, and then alternatives were compared based on environmental and economic sustainability results, enabling decision-makers to choose the most suitable alternative for waste management.

Starting to identify possible waste management options for determining strategic fit, an additional challenge emerged – to identify the amount of the waste stream to better assess management options based on volume. Some research on fishing net waste relies mainly on interviews, surveys, literature reviews and estimate the amount of discarded nets, a more extensive review is the Paper14.

To conduct a strategic fit and sustainability assessment, it is necessary to define boundaries. This study concentrates on Latvia (Europe) and the corresponding fishing area of the Baltic Sea. The Baltic Sea shoreline of Latvia stretches for 497 km, which constitutes roughly 0.7 % of the overall coastline within the European Union. Furthermore, the inland waterways – including lakes and rivers – encompass an area of 2340 km², which accounts for approximately 3.6 % of Latvia's entire land area.

The research encompasses the years 2018 to 2023, a timeframe distinguished by two significant occurrences that profoundly impacted fishing operations. The first, the COVID-19 pandemic, and the second, Russia's war in Ukraine, disrupted both fishing activities and the manufacturing of fishing equipment. In an effort to alleviate the repercussions of the pandemic, a sum of 2.8 million Euro in public funding was allocated across all sectors of the fishing industry [134]. Furthermore, an additional 5 million Euro in assistance was designated to counterbalance the ramifications of the conflict, encompassing the escalation of energy and raw material expenses, as well as the diminishment of export markets in Ukraine, Belarus and

Russia [134]. Both occurrences also played a role in the decline of fishing net production and a reduced prevalence of discarded nets in the Baltic Sea, attributable to diminished fishing intensity and catch rates.

**Quantification of discarded fishing nets**

The methodology is based on three data collection approaches. The first is statistical data collection on import and export of fishing nets, the second is interviews with fishing net manufacturers and retailers, fishermen and association of fishermen, port authorities, waste management companies, national authorities (State Environmental Service, the Ministry of Agriculture of the Republic of Latvia Fisheries Department) and the third – extrapolation of missing data.

The interviews with fishermen revealed that fishing nets retrieved from waters, but not ghosted, are as long as possible repaired and reused directly for fishing or in other applications, such as, farming, thus avoiding discarding. However, when nets become unusable, they are often discarded in mixed municipal waste rather than being sorted for recycling. Waste managers also confirmed that fishing nets appear irregularly in waste sorting facilities. Therefore, to enable the valorisation of unusable fishing nets, a proper collection system must be developed and implemented.

Fishing nets suitable for valorisation can also be sourced by retrieving ghost nets and historically lost nets from the sea. However, their quantity and material composition remain unpredictable, leading to periodic fluctuations in the availability of resources for valorisation. To establish a more stable resource supply, fishing net production companies operating in Latvia could play a key role. These companies generate production scraps that are well-suited for recycling alongside discarded fishing nets, as they are made of the same material. Additionally, the quantity of these scraps is documented in company reports and remains stable, making them a reliable resource for waste recycling.

In Figure 3.11 presents the methodology for quantifying manufacturing scraps (pre-consumption) and discarded fishing nets (post-consumption) across all material types. Combining both pre-consumption and post-consumption waste ensures a sufficient and stable supply of resources for recycling.

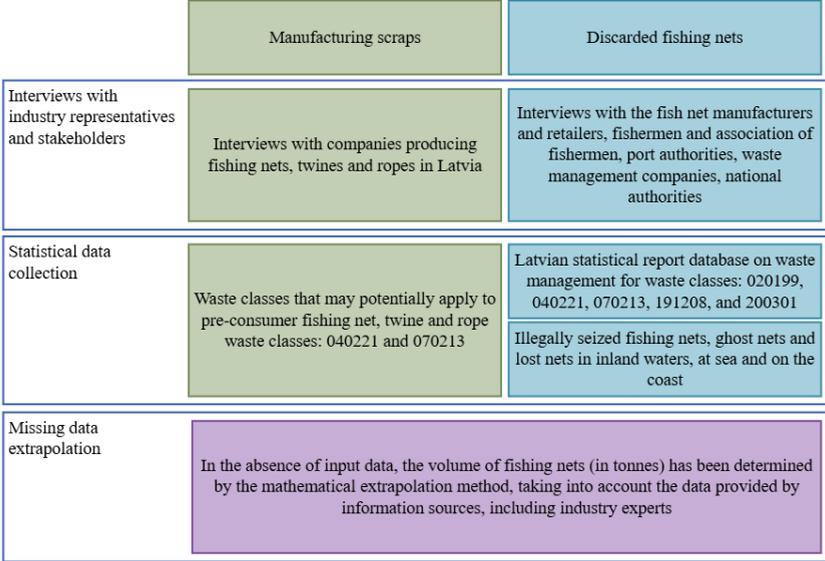| | Manufacturing scraps | Discarded fishing nets |
|---|---|---|
| Interviews with industry representatives and stakeholders | Interviews with companies producing fishing nets, twines and ropes in Latvia | Interviews with the fish net manufacturers and retailers, fishermen and association of fishermen, port authorities, waste management companies, national authorities |
| Statistical data collection | Waste classes that may potentially apply to pre-consumer fishing net, twine and rope waste classes: 040221 and 070213 | Latvian statistical report database on waste management for waste classes: 020199, 040221, 070213, 191208, and 200301 |
| | | Illegally seized fishing nets, ghost nets and lost nets in inland waters, at sea and on the coast |
| Missing data extrapolation | In the absence of input data, the volume of fishing nets (in tonnes) has been determined by the mathematical extrapolation method, taking into account the data provided by information sources, including industry experts | |

Figure 3.11. Methodology for quantification of manufacturing spars and discarded fishing nets. Latvian case study.

There are certain methodological limitations, primarily related to the availability and quality of current data and assumptions made. Where data on generated and managed ALDFG waste amount was missing or incomplete, assumptions were made based on information provided by industry representatives, which may be specific to the Latvian context and not directly transferable to other regions. For example, estimates regarding the replacement frequency of fishing gear, total quantities in use in Latvia and characteristics of the most used equipment. These limitations should be considered when interpreting the findings and assessing their generalizability.

The results show the data obtained on the volume of pre-consumer and discarded fishing nets collected in Latvia, as well as the comparison of fishing net management measures based on circular economy indicators.

Fishing net waste amount in Latvia

The amount of nets comes from ghost nets, discarded nets and illegally removed nets. In Latvia, a total of 1659 illegal fishing gears were seized in 2023, with the most common being fishing lines (613 pieces), followed by fishing nets (355 pieces) and then crayfish traps and chalks (334 pieces) [135]. Figure 3.12 illustrates the amount of Latvia's import and export fishing nets, twine, ropes and sails. As shown, these volumes fluctuate significantly from year to year, with 2022 recording the lowest export volume and the highest import volume, and on average, the import volume is twice as large as the export volume. The net domestic trade, therefore, ranges from 9 to 435 tons.
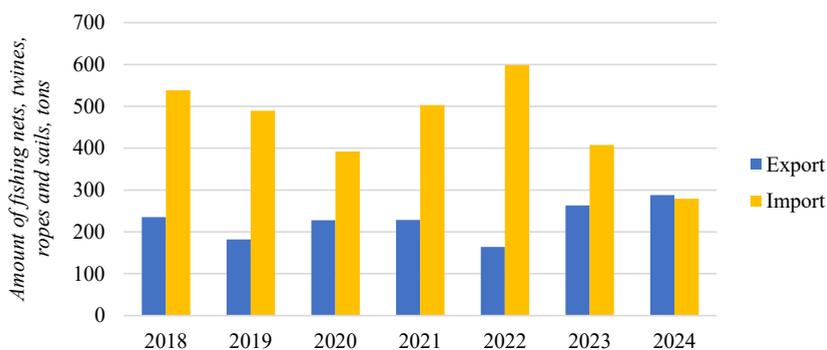


Figure 3.12. Annual amount of imported and exported fishing nets, twine and ropes, sails [136].

Previous research [137], which estimated gear losses in coastal fisheries in the Baltic Sea based on national statistics and literature review, has highlighted a significant accumulation of abandoned fishing gear, particularly gillnets, entangling nets and traps, over the past 10 years. Another study quantified marine litter on the Baltic Sea floor, identifying fishing gear as a main source. This study, which involved collecting litter as part of the catch, found an average litter volume of 9.2 L/km², with polyethylene being the most common polymer [138].

Latvian ports accept ship waste in accordance with the legislation, which includes a category for fishing gear in the corresponding form. However, this type of waste is rarely transferred at Latvian ports. It is licensed that in 2025, 42 vessels will carry out industrial fishing in the Gulf of Riga [139]. For industrial fishing in inland waters, coastal waters and at sea as well as for self-consumption fishing, the fishing nets and lines with limited lengths are used. According to the regulations set up in Latvia [140], the allowed annual length of inland water (lakes) fishing nets is 142 000 m, in coastal waters – over 350 000 m [140,141]. This type of data provides the maximum annual net length allowed in the national waters.

Historical data on the amount of fishing nets in national waters can only be found by cleaning up the waters. Finnish oil refining company Neste in collaboration with partners from Latvia (Latvian Maritime Academy and Science and Innovation Center of the Riga Technical University), Lithuania (Nardymo Academy) and Estonia (Teeme Ära) is working to clean up the Baltic Sea from ghost nets, develop innovative technological solutions for cleaning the sea pollution and recycling it [142]. In the summer of 2023, a tugboat sunk during World War II was cleared near a small port town in Latvia, and within two days, 1 $m^3$ of nylon nets, consisting of 1970s lute trawls and 40-year-old herring trawls, were brought to shore [143]. In 2024, fishing gear with a total length of 280 m was found near a small Latvian port city lying 5-10 m deep at the sea bottom [144]. Industry professionals have reported numerous new shipwrecks in the Gulf of Riga, many of which are surrounded by ghost nets. Efforts to survey and map these wrecks will continue until 2026. Meanwhile, divers predict that approximately 2 tons of ghost nets will be removed, marking a significant increase compared to the previous year [145]

Discarded fishing nets amount

Discarded fishing net, twine and rope waste is generated after fishing and accurate data of this type has not been yet collected for Latvia. Therefore, interviews with stakeholders were held to estimate the data. In addition, the data from the state authorities, who regularly carry out inspections in inland waters, seas and coasts and remove illegal fishing gear, was collected (see Figure 3.13).

Although the number of inspections in Latvia's inland and marine waters varies from year to year, there is a slight overall trend of decline. Inspection practices are evolving through the adoption of innovative technologies such as drone surveillance, echo sounders, GPS navigation devices, thermal imaging cameras, and night vision equipment. In addition to technological advancements, administrative changes have expanded the authority to remove illegal fishing gear. This responsibility is no longer limited to inspectors from the State Environmental Service, but also includes public environmental inspectors, municipal police, municipal environmental control officers, the State Police, the State Border Guard and the Coast Guard Service of the National Armed Forces Navy. Moreover, international cooperation plays a crucial role in marine fisheries control. Inspectors from the Latvian State Environmental Service actively participate in international inspection missions. However, this cooperation was disrupted by the COVID-19 pandemic, and in 2020, Latvian inspectors took part in fewer international missions as a result.
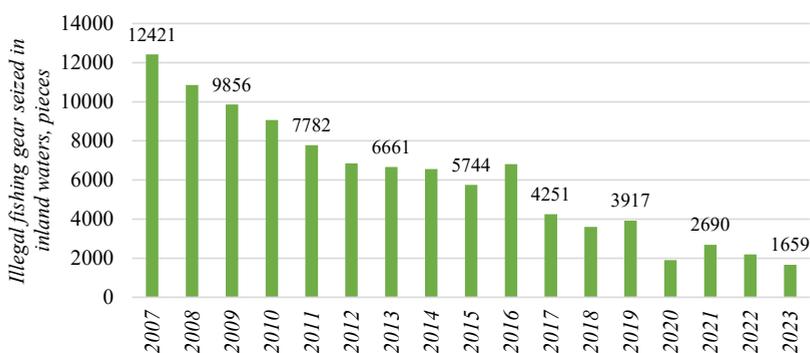


Figure 3.13. Illegal fishing gear seized in Latvian inland waters from 2007 to 2023 [135].

The discarded fishing net, twine and rope waste amounts were calculated considering the volume of seized illegal fishing nets and the amount of discarded fishing nets. Used assumptions for calculations are:
- the average weight of one net is 0.5 kg (the weight of the most used fishing net).

- 40 % of fishing nets are replaced once a year and 60 % of fishing nets – once every 4 years.

The calculations use data such as the total length of nets – 490 000 m. The most used fishing net type (0.17 mm nylon net, 30 m, wall height – 1.8 m, mesh size – 40 mm, weight – 0.5 kg) was used to calculate the volume of waste. The total estimated volume is 5 tonnes per year.

Fishing net manufacturing scraps amount

Latvia has companies that produce various types of fishing gear. Nylon, polyester, polyamide and polypropylene tows, cords, ropes are produced, as well as fishing threads from polyamide fibre and polyester fibre. These companies generate production scraps and residues, which are managed in accordance with regulatory enactments and this type of waste is managed by companies in Latvia and neighbouring countries.

Figure 3.14, the data about the waste generated in Latvia under the waste classes 040221 "Wastes from unprocessed textile fibres" and 070213 "Wastes from the MFSU of plastics, synthetic rubber and man-made fibres" according to the European waste catalogue [146] are summarised. The average amount for 2018-2023 is 47 tons of manufacturing scrap waste.
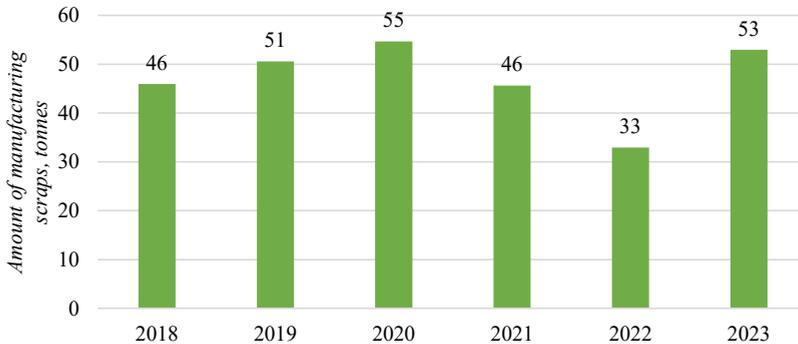


Figure 3.14. Amount of manufacturing scraps – fishing net, twine and rope waste, tonnes [147].

Amount of discarded fishing nets and manufacturing scraps

Figure 3.15 illustrates the estimates regarding the total amount of fishing net waste, which includes both discarded fishing gear and manufacturing by-products. As depicted, the annual volume remains consistent, except for the years 2021 and 2022, when a significant decrease in fishing net waste was noted. This decline is probably associated with the effects of the COVID-19 pandemic, which disrupted the activities of fishing vessels and manufacturing firms – especially in areas heavily impacted by serious outbreaks.
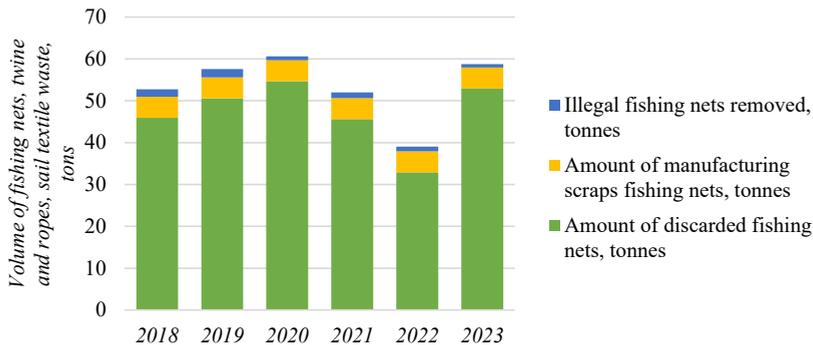
Figure 3.15. Amount of fishing net waste in Latvia in 2018-2023.

Looking at the amount of manufacturing scraps and discarded fishing nets waste provides insight into the waste dynamics of the sector and the opportunity to assess waste management options. The amount of manufacturing scraps is important because they are off-cuts from the fishing net manufacturing processes and are therefore clean waste that can be subsequently recycled into a high-value product, and do not require a major waste treatment step. Discarded fishing nets data are not systematically recorded and are based on estimates, but the management of this waste is also important, although the amounts in Latvia are smaller than the amount of manufacturing scraps . However, Latvia generates an average of 53 tonnes of fishing net waste that needs to be managed effectively.

The strategic fit assessment is followed by an environmental and economic sustainability assessment.

### Goal and scope

The goal of the study is to evaluate and compare the environmental impact of management scenarios with discarded fishing nets. The functional unit selected for the LCA study is 1 ton of discarded fishing net after pre-treatment (i.e. after the separation of unnecessary fractions, such as organics, from the nets). The avoided burden approach is used to evaluate the environmental impact of different waste management scenarios scenarios for different types of fishing nets.

### System boundary

The LCA system boundaries (see Figure 3.16) defined in the study are "cradle-to-cradle" (for S1–S3) and "cradle-to-grave" (for S4), and as the avoided burden approach is applied, it is modelled that the discarded fishing net as a resource completely or partially replaces the traditional raw materials used in production of nylon or asphalt additive. The installation and transportation stages as well as the use phase (including maintenance, reuse, repair and replacement of fishing nets) are excluded from the assessment due to their similarity across different types of synthetic fishing nets (thus negligible) and the lack of reliable inventory data for these stages.
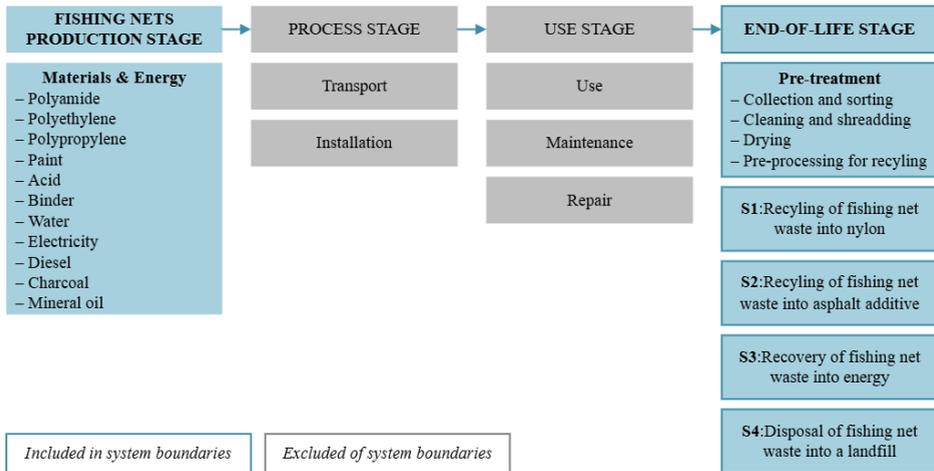
Figure 3.16. System boundaries for environmental assessment of management of discarded fishing nets.

**Inventory**

Relevant inventory data, including data on fishing net production, nylon and asphalt production, is obtained from literature review and Ecoinvent database and is presented in Paper 14.

**Assumptions**

It was assumed that the entire amount of fishing nets collected, weighing 1 tonne, is suitable for either recycling or landfilling. This assumption simplifies the assessment and the possibility of comparing the valorisation scenarios considered.

**Impact assessment**

The results from the ReCiPe 2016 midpoints method are reflected in Table 3.4. The negative values are considered as benefits to the environment and the positive values – as negative impacts to the environment. The negative results obtained are considered a benefit to the environment, and the positive results obtained are considered an impact on the environment. The results are marked with colours on a scale from low environmental impact (bright green) to very high environmental impact (orange).

The results show that S1 is the most sustainable of the fishing net valorisation scenarios, but the results of S2 also indicate that it is a sustainable alternative. The results of S3 are moderately sustainable, but the greater environmental impact results from the S4 valorisation scenario.

Table 3.4

LCA characterisation results

| Impact category | Unit | S1 | S2 | S3 | S4 |
|---|---|---|---|---|---|
| Climate change | kg $CO_2$ eq | −7847.76 | −636.36 | 156.10 | 12080.46 |
| Ozone depletion | kg CFC-11 eq | 0.000003 | −0.000048 | 0.000003 | 0.000024 |
| Terrestrial acidification | kg $SO_2$ eq | −26.69 | −2.06 | 0.39 | 28.24 |
| Freshwater eutrophication | kg P eq | −0.39 | −0.02 | 0.02 | 1.18 |

Table 3.4. continued

| | | | | | |
|---|---|---|---|---|---|
| Marine eutrophication | kg N eq | −8.95 | −0.06 | 0.02 | 30.99 |
| Human toxicity | kg 1,4-DB eq | −65.14 | −38.04 | 6.37 | 5105.51 |
| Photochemical oxidant formation | kg NMVOC | −19.99 | −7.95 | 0.51 | 29.09 |
| Particulate matter formation | kg PM10 eq | −8.01 | −0.66 | 0.19 | 9.36 |
| Terrestrial ecotoxicity | kg 1,4-DB eq | −0.06 | −0.09 | 0.02 | 2.54 |
| Freshwater ecotoxicity | kg 1,4-DB eq | −6.97 | −1.70 | 2.09 | 1481.87 |
| Marine ecotoxicity | kg 1,4-DB eq | −3.92 | −1.84 | 1.85 | 1193.81 |
| Ionising radiation | kBq U235 eq | 43.03 | 32.07 | 42.59 | 128.51 |
| Agricultural land occupation | m²a | 60.03 | 56.39 | −443.56 | 1591.82 |
| Urban land occupation | m²a | −0.93 | −7.67 | −2.56 | 61.73 |
| Natural land transformation | m² | 0.02 | −0.48 | 0.01 | −2.61 |
| Water depletion | m³ | −228.18 | 18.07 | −0.89 | 96.98 |
| Metal depletion | kg Fe eq | 1.10 | −29.30 | 5.45 | 64.55 |
| Fossil depletion | kg oil eq | −273.71 | −9.18 | 4.13 | 322.40 |

Colour scale: | Low | Medium | High |

The environmental damage costs per impact category are reflected in Table 3.5. The most expensive environmental damage categories are particulate matter and ozone depletion. In this case, the impact of ozone depletion and particulate matter formation is related to electricity consumption and fishing net production. Similarly, to the LCA results, some of the environmental damage costs results are negative, thus presenting economic benefits (revenues) for the environment and society.

Table 3.5

Environmental damage costs for fishing net waste management scenarios based on 2025 monetary values

| Impact category | S1 | S2 | S3 | S4 |
|---|---|---|---|---|
| Climate change | −1255.64 | −101.82 | 24.98 | 1932.87 |
| Ozone depletion | 0.00010 | −0.00166 | 0.00011 | 0.00082 |
| Ionising radiation | 0.22 | 0.17 | 0.22 | 0.67 |
| Oxidant formation, human health and terrestrial ecosystems | −65.37 | −26.01 | 1.65 | 95.14 |
| Particulate matter formation | −977.32 | −81.00 | 23.45 | 1142.00 |
| Acidification | −172.66 | −13.34 | 2.55 | 182.72 |
| Freshwater eutrophication | −1.78 | −0.09 | 0.08 | 5.44 |
| Marine eutrophication | −156.88 | −1.14 | 0.31 | 543.29 |
| Terrestrial ecotoxicity | −0.00005 | −0.00007 | 0.00001 | 0.00201 |
| Freshwater ecotoxicity | −0.18 | −0.04 | 0.05 | 38.08 |
| Marine ecotoxicity | −0.02 | −0.01 | 0.01 | 4.69 |
| Human toxicity, cancer-related and non-cancer-related | −324.85 | −189.72 | 31.78 | 25462.73 |
| Land use | 7.19 | 5.92 | −54.25 | 201.07 |
| **Total** | **-2947** | **-407** | **31** | **29609** |

The strategic relevance assessment of the problem of fishing net waste management reflected the critical point regarding the missing common methodology for determining the volume potential of waste. Consequently, a methodology was developed to determine the volume potential, followed by an environmental and economic assessment of management alternatives.

LCA and environmental damage costs showed significant environmental benefits from recycling fishing nets. The results show the importance of avoiding landfill and instead prioritising recycled fishing nets as replacements for new nylon (S1) and asphalt reinforcement (S2) to provide the greatest environmental benefit. Although synthesis gas production (S3) has a greater impact than S1 and S2, it is still a desirable secondary waste management option.

## 3.3. Utility value approach

If, after completing the sustainability assessment, decision-makers require the integration of multi-dimensional factors (such as environmental, economic, social, and strategic), along with both qualitative and quantitative data to compare or rank potential resource value chain solutions, the utility value method should be applied. This method offers a holistic approach to decision-making, providing more strategic and sustainable justifications for the results.

Within the Thesis utility value approach is applied to several problem-solving areas:
1) multifactorial assessment of alternative raw materials used in fish feeds;
2) environmental and technical assessment of a metal melting furnace to obtain a comparison of possible alternatives;
3) a cross-country comparison based on GHG emission indicators;
4) the possibility for municipalities to use RES technologies for heating of public and multi-apartment buildings;
5) identifying the best use of agricultural by-products;
6) the environmental, technical and economic performance of infectious healthcare waste management technologies.

### 3.3.1. Utility value approach to the agriculture sector

Strategic fit assessed potential fish feed raw material alternatives, then environmental sustainability assessed potential raw material alternatives, as well as potential fish feed alternatives. Economic aspects were also assessed as conventional LCC and damage costs for fish feed alternatives and social assessment for fish feed protein raw material alternatives. After a strategic fit, a technical assessment of fish feed alternatives was also carried out. The results obtained from the environmental, economic, social and technical assessment were entered into the TOPSIS method to be able to make a decision on the best fish feed taking into account four dimensions as utility value.

To assess strategic fit, a literature analysis was carried out on the value of different vitamins ingested in fish and the subsequent benefits for people consuming fish. Benefits for fish and humans [148–151]:
- *Vitamin A* is an important micronutrient for fish and plays an important role as an immunostimulant, but for humans it is necessary for vision, growth and immune function.
- *Vitamin D* impact to fish as affects skeletal formation and ossification, but in humans it prevents bone diseases and promotes immune system function.
- *Vitamin B12* derived from fish and affects new cell development in humans.

- *Iron* affects biological reactions for fish, but for human it helps with production of haemoglobin.
- *Zinc* helps fish with metalloenzymes, and in humans promotes immunity and growth.
- *Calcium* helps with bone health in both fish and humans.
- *Selenium* is an important microelement for fish and in humans it acts as an antioxidant, stimulates the immune system and is also an important microelement.
- *Omega-3* slows the development of cardiovascular disease in humans.
- Iodine affects thyroid hormones in fish but helps maintain normal metabolism in humans.
- *Protein* provides energy for fish but is an essential amino acid for humans and is necessary for cells.
- *Potassium* is necessary for fish to maintain acid-base balance and osmoregulation, but necessary for humans to maintain nervous system, muscle function, and heart rate.

Since fish is a good source of protein and omega-three fatty acids, which also benefit human health, fish food must be good quality for fish and humans afterward. Protein is more important for fish in the early stages of growth and as they are growing, protein requirements decrease [152].

Feed ingredients not only have an impact on fish, but also on the environment, as it is necessary to evaluate feed raw material source, as well as environmental impact. The fish feed alternative must be high quality and high nutritional value (omega-3 fatty acids, high protein content, adequate amino acids, digestibility, and taste), as well as insoluble carbohydrates, fiber and heavy metals need to be low because it affects the fish growth process and affects low feed conversion ratio, feed costs must be economically justified and feed production [153].

The use of insects in fish feed production is one of the most sustainable and economically viable alternatives [154]. Also, insect meals are rich in polyunsaturated fatty acid (PUFA), which is one of the healthy fats [155]. Black Soldier Fly is a more suitable fish meal alternative than plant-based alternatives, especially when considering specifically the gut health of fish [155]. For Black Soldier Fly as protein source advantages and disadvantages are [154,156–159]:
- *Advantages*: it is possible to use food waste as feed, contains high-quality protein and is a rich source of lipids, balanced amino acids, a good source of iron, zinc, potassium, phosphorus, manganese and magnesium, as well as a sustainable alternative and good palatability for use in feed.
- *Disadvantages*: compared to other protein alternatives, the price is high, the unbalanced feed protein used can affect growth, land occupation for cultivation processes, and the nutritional value and effect of the feed on fish varies depending on the insect species.

The mealworm industry is evolving from a manual sector that is not very efficient to one that is becoming more efficient and profitable [160]. Yellow mealworm as protein source advantages and disadvantages are [161–163]:
- *Advantages*: good taste for use in feed, sustainable alternative, good nutrition and a valuable source of protein and amino acids, grows and reproduces quickly, and effectively converts low-quality organic matter into high-quality protein and fat, and does not require large areas to produce such a protein source.
- *Disadvantages*: high price compared to other protein alternatives, too high a proportion of food can have consequences on growth, and nutritional value depends on the species and the food consumed.

Soybean flour contains crude protein that makes the feed easily digestible, more sustainable than fishmeal, balanced amino acid content, and low price, but there is a possibility that

biologically active compounds can affect fish health, growth, and reproductive development [164]. Advantages and disadvantages for soybean alternative are [152,153,156,158]:

- *Advantages*: high protein content, improves fish growth, widely available alternative and affordable.
- *Disadvantages*: presence of indigestible fibers, low methionine and phosphorus content, lack of essential amino acids, which affects fish quality, risk of mycotoxins, as well as not being a sustainable alternative and also poor palatability.

Fishmeal and fish oil are derived from wild fish, but catches are limited in a few inseparable ways, so more sustainable solutions and alternatives are being sought [153]. Fishmeal as protein source advantages and disadvantages are [153,156]:

- *Advantages*: promotes growth, has good taste and is easily digestible, balanced nutritional values, low feed conversion ratio, resulting in less feed waste.
- *Disadvantages*: price changes, not as readily available and not a sustainable alternative.

However, to better compare potential and existing fish feed protein sources in terms of minerals, Table 3.6 summarizes the mineral values.

Table 3.6

Comparison of protein sources according to their mineral values [165–179]

|  | Black soldier fly | Mealworm | Soybean | Fishmeal |
|---|---|---|---|---|
| Iron (mg/kg) | 100–630 | 9.61–245 | 92,9-919 | 81-715 |
| Zinc (mg/kg) | 42–300 | 33.8–117.4 | 41,4-77,0 | 56-381 |
| Magnesium (mg/kg) | 2100–5610 | 620–2027 | 2550-4940 | 700-4000 |
| Calcium (mg/kg) | 5360–61,620 | 156–435 | 1600-4660 | 11800-80100 |
| Phosphorus (mg/kg) | 6,800–13,220 | 2640–7061 | 5640-7660 | 1530-43400 |
| Sodium (mg/kg) | 890–2500 | 225–3644 | 60-1090 | 3200-19800 |
| Potassium (mg/kg) | 10,200–18,790 | 3350–9480 | 20200-25200 | 330-15700 |
| Copper (mg/kg) | 7.5–34.25 | 8.3–20 | 9,0-18,7 | 3-108 |
| Manganese (mg/kg) | 190–730 | 3.2 | 29,7-70,8 | 3-37 |

Another important component of fish feed is oil. Fish oil in traditional aquaculture has been widely used in fish feed, but now the supply of fish oil is dependent on fossil energy and increasing demand for fish [180]. As well as the production of fish oil, contributes to the loss of biodiversity and has an impact on the environment [180]. As fish oil advantage is cns polyunsaturated fatty acids, including docosahexaenoic acid (DHA) six times the unsaturated fatty acid, but as disadvantage is not as effective as plant oil [180,181].

Algae oils and fish oils are the primary natural sources of omega-3, but the advantage of algae oils over fish oils is their consistency, sensory properties, and ease of production [182]. The pigment obtained from microalgae improves the colour of meat for salmonids and shrimps, increases the antioxidant content in meat, and improves the reproductive health of aquaculture [183]. Advantages are compared to terrestrial plants, it has higher productivity, and algae can be cultivated in the sea or in wastewater, so there is no need to use land and freshwater, improves the health of aquatic species, improves the appearance of aquatic species, which is important for buyers and is rich in omega-3 fatty acids [153,158]. The disadvantage is the high production cost and microalgae have a rigid cell wall which makes digestibility difficult [153,158].

As plant oil most used are soybeans, linseed, rapeseed, sunflower, palm oil, and olive oil in fish feed [181]. As a good alternative, soybeans and rapeseed oil are considered salmon because they are rich in PUFAs (polyunsaturated fatty acids), especially linoleic acid and oleic

acid, and do not contain n-3 PUFAs [181]. Replacing 50-60 % of fish oil with plant oil results in fish growth processes as with 100 % of fish oil [181]. The advantages are high productivity and a widely available alternative, good economic value and rich in omega 6 fatty acids, but the disadvantages are that it is poor in omega-3 fatty acids [153,181].

In Table 3.7 are comparison of fatty acid values (g/100g) of algae oil, flaxseed oil (vegetable oil) and fish oil alternatives.

Table 3.7

Fatty acid composition [184]

|  | Algae oil | Plant oil – Flaxseed oil | Fish oil |
|---|---|---|---|
| Omega 3 (g/100g) | 47.74 | 37.07 | 38.65 |
| Omega 6 (g/100g) | 7.88 | 20.26 | 3.22 |
| Omega-3/Omega-6 ratio | 6.06 | 1.83 | 12.02 |
| MUFA (g/100g) | 3.62 | 26.37 | 24.79 |
| PUFA (g/100g) | 55.62 | 57.33 | 41.78 |

MUFA – monounsaturated fatty acid, PUFA – polyunsaturated fatty acid

The nutritional value and quality of the feed are essential for fish feed and the physical properties of the feed, as physical properties are more important for aquatic animals than for terrestrial animals [151]. When choosing new feed ingredients, it is necessary to look at how this affects the technical properties of fish feed.

To assess the sustainability of fish feed raw material, existing and potential protein, oil and pigment alternatives are evaluated using LCA. Also, LCA is used to obtain environmental assessments of fish feed alternatives.

**Goal and scope**

The goal is to assess the environmental impact for protein (black soldier fly, yellow mealworm and soybean), oil (microalgae oil, rapeseed oil and fish oil) and pigment (natural pigments from the microalgae *Haematococcus Pluvialis* and synthetic pigments).

The scope is the raw materials and energy needed for production, but transport and the by-products and waste generated are not considered. PEFCR defines the functional unit as 1 ton of animal feed, this study uses 1 kg to match collected data flow.

**System boundaries**

To be able to compare different alternatives, it is defined that this LCA accounts for the product life cycle as "cradle to gate", where the assessment is from resource extraction to factory gate.

System boundaries for protein alternatives, as the inputs, processes and outputs are similar. However, specific system boundaries for black soldier fly protein [185], Yellow mealworm protein [186] and soybean protein are defined for each individual alternatives described in Paper 7.

System boundaries for oil alternatives described are in Paper 8 provides more detailed information about microalgae oil [187], rapeseed oil and fish oil system boundaries.

Detailed system boundaries for pigment alternatives described are in Paper 9 for natural pigments [188] and synthetic pigment [189].

**Inventory**

The LCA inventory section has a complete list of raw materials to produce one functional unit for all products. Input data is taken from the literature review and Ecoinvent database and the collected input data are expressed for 1kg of the final product.

- LCA inventory data for protein alternatives data from literature [185,186] and data from "Ecoinvent v3.8" database are presented in Paper 7.
- Microalgae oil, rapeseed oil, and fish oil inventory data from literature [187] and data from "Ecoinvent v3.8" database on oil alternatives are presented in in Paper 8.
- Inventory data for pigment alternatives data from literature [188,189] and are presented Paper 9.

**Impact assessment**

The PEFCR for food-producing animal feed defines the relevant impact assessment categories, and the EF 3.0 methodology was used to obtain the impact assessment results for the assessment of feed alternatives. The results of the full impact assessment for protein alternatives are presented in Paper 7, for oil alternatives in Paper 8 and for pigment alternatives in Paper 9.

However, when comparing the results according to the most used impact assessment categories in assessing the environmental impacts of food and feed, the results for protein alternatives are:

- by climate change category, the highest impact is by yellow mealworm protein (1,7 kg $CO_2$ eq), followed by soybean protein (0,83 kg $CO_2$ eq) and black soldier fly protein (0,1 kg $CO_2$ eq).
- by acidification category, the highest impact yellow mealworm protein (0,2 mol H+ eq), followed by soybean protein (0,0043 mol H+ eq) and black soldier fly protein (0,00044 mol H+ eq ).
- by land use category, the highest impact yellow mealworm protein (161 Pt), followed by soybean protein (129 Pt) and black soldier fly protein (1,2 Pt).
- by water use category, the highest impact the highest impact yellow mealworm protein (3,8 $m^3$ depriv.), followed by black soldier fly protein (0,23 $m^3$ depriv.) and soybean protein (0,06 $m^3$ depriv.).
- by resource use, fossils category the highest impact the highest impact yellow mealworm protein (16,5 MJ), followed by soybean protein (3,6 MJ) and black soldier fly protein (1,7 MJ).

Overall, black soldier fly protein has the lowest environmental impact in most categories, while yellow mealworm protein has the highest impact, particularly in land use, water use, and eutrophication. Soybean protein falls in between but generally has a higher impact than Black Soldier Fly protein.

The results of oil alternatives according to the most used impact assessment categories in the environmental impact assessment of food and feed are:

- by climate change category, the highest impact is by microalgae oil (9,4 kg $CO_2$ eq), followed by rapeseed oil (1,7 kg $CO_2$ eq) and fish oil (1,4 kg $CO_2$ eq);
- by acidification category, the highest impact microalgae oil (0,1 mol H+ eq), followed by rapeseed oil (0,04 mol H+ eq) and fish oil (0,02 mol H+ eq );
- by land use category, the highest impact microalgae oil (686 Pt), followed by rapeseed oil (187 Pt) and fish oil (4 Pt);
- by water use category ,the highest impact the highest impact microalgae oil (9,1 $m^3$ depriv.), followed by rapeseed oil (1,2 $m^3$ depriv.) and fish oil (0,06 $m^3$ depriv.);
- by resource use, fossils category the highest impact the highest impact microalgae oil (111 MJ), followed by fish oil (19,3 MJ) and rapeseed oil (12,8 MJ).

Overall, microalgal oil is more intensive and has a higher environmental impact in terms of climate change, eutrophication and ecotoxicity compared to rapeseed oil and fish oil.

When looking at the results of both pigment alternatives according to the most used impact assessment categories in the environmental impact assessment of food and feed, they are:

- by climate change category, the highest impact is by microalgae pigment (335 kg $CO_2$ eq) and followed by synthetic pigment (7,2 kg $CO_2$ eq).
- by acidification category, the highest impact microalgae pigment (0,24 mol H+ eq) and followed by synthetic pigment (0,003 mol H+ eq).
- by land use category, the highest impact microalgae pigment (886 Pt) and followed by synthetic pigment (30,7 Pt).
- by water use category, the highest impact the highest impact microalgae pigment (23,9 $m^3$ depriv.) and followed by synthetic pigment (2,7 $m^3$ depriv.).
- by resource use, fossils category the highest impact the highest impact microalgae pigment (423 MJ) and followed by synthetic pigment (284 MJ).

Overall, synthetic pigments are generally more environmentally friendly than microalgal pigments in most impact categories, including climate change, human toxicity, eutrophication, and resource use.

The protein, oil and pigment alternatives had significant differences in terms of environmental impacts. However, an important aspect in fish feed is how these potential fish feed raw materials are used in the overall fish feed production, what their proportions are and how the fish take up these new fish feed types. After several fish feed trials, five types of fish feed were defined, which were analysed according to environmental, economic and social dimensions, as well as technical aspects.

**Goal and scope**

The goal is to assess the environmental impact of five fish feeds, where the proportion of the other fish feed ingredients varies according to the protein source and is reflected in five alternatives:

- A1_ traditional protein – 100 % fish meal;
- A2_ traditional protein – fish meal and 5 % of traditional protein replaced by black soldier fly protein;
- A3_ traditional protein – fish meal and 10 % of traditional protein replaced by black soldier fly protein;
- A4_ traditional protein – fish meal and 15 % of traditional protein replaced by yellow mealworm protein;
- A5_ traditional protein – fish meal and 30 % of traditional protein replaced by yellow mealworm protein.

The scope is a necessary ingredient for fish feed, although required energy consumption, transport and packaging, as well as the by-products and waste generated are not considered. The function unit for LCA is 1 tonne of animal feed based on PEFCR feed for food-producing animals [190].

**System boundaries**

Fish feed LCA is "cradle to gate" and system boundaries are given in Figure 3.17. The impact of raw materials is considered.
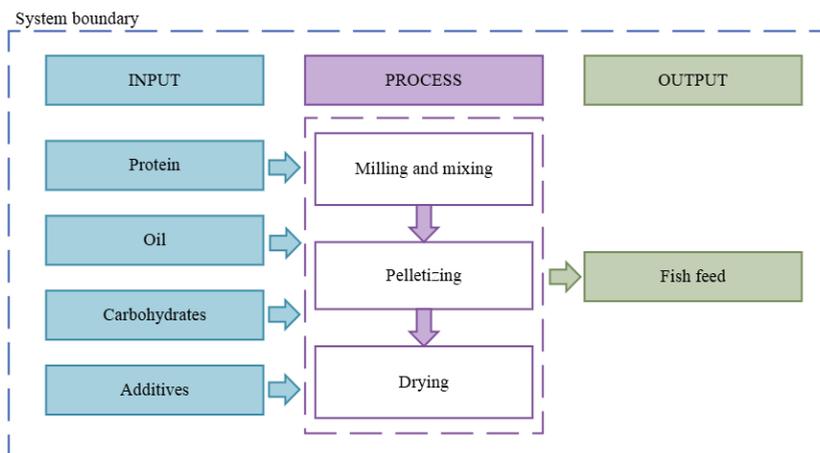
Figure 3.17. System boundaries for fish feed.

**Inventory**

In the Table 3.8 shows the inventory data for five fish feed alternatives, with changes mainly in the form of the protein, which are partly attributed to some insect protein source.

Table 3.8

Fish feed alternative inventory data

| Ingredients | 100 % FM | 5 % BSF | 10 % BSF | 15 % MW | 30 %MW |
|---|---|---|---|---|---|
| Black soldier fly larvae meal | - | 5 | 10 | - | - |
| Meal worm meal | - | - | - | 15 | 30 |
| Fish meal | 20 | 20 | 20 | 20 | 20 |
| Soy protein concentrate | 20 | 20.04 | 19.71 | 15.3 | 2 |
| Wheat gluten | 14.5 | 12.9 | 11.5 | 9.5 | 9.6 |
| Vegetable raw material | 18.8 | 18.8 | 18.8 | 18.8 | 18.8 |
| Fish oil | 13.3 | 13.3 | 13.3 | 13.4 | 14.2 |
| Rapeseed oil | 6.2 | 4.4 | 2.6 | 3.6 | - |
| Other (incl. pigment) | 7.2 | 5.6 | 4.1 | 4.4 | 5.4 |
| Yttrium | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 |

**Assumptions**

The data used are derived from a literature review and the Ecoinvent v3.8 database with assumptions about the relevant background data. It is assumed that the protein, oil and pigment are produced in Norway and the input data are adjusted to reflect Norwegian or European conditions and the raw materials are sourced from Norway or Europe wherever possible.

The assessment does not consider transportation, production infrastructure and the lifespan of technical equipment, as well as product packaging and storage, as no relevant data was publicly available.

Sensitivity analyses were also performed to consider assumptions about alternative insect feeds and how the impact would change if a product was produced in a different location than the one originally modeled.

**Impact assessment**

After defining the five fish feeds, LCA results were obtained for the entire feed. Table 3.9 summarises the environmental impact results per 1 ton of fish feed. Overall, the environmental impact of feeds where the protein is partly insect protein results in environmental savings, particularly in terms of climate change and eutrophication.

LCA results of fish feed alternatives

| Impact category, unit | 100 % FM | 5 % BSF | 10 % BSF | 15 % MW | 30 % MW |
|---|---|---|---|---|---|
| Climate change, kg CO2 eq | 2708.11 | 2331.15 | 1968.55 | 2199.53 | 2346.57 |
| Ozone depletion, kg CFC11 eq | 0.00027 | 0.00026 | 0.00024 | 0.00025 | 0.00026 |
| Human toxicity, cancer, CTUh | 0.000006 | 0.000005 | 0.000005 | 0.000006 | 0.000007 |
| Human toxicity, non-cancer, CTUh | 0.000041 | 0.000035 | 0.000030 | 0.000043 | 0.000045 |
| Particulate matter, disease inc. | 0.00021 | 0.00018 | 0.00015 | 0.00018 | 0.00021 |
| Ionising radiation, kBq U-235 eq | 64.56 | 54.70 | 45.44 | 58.63 | 75.33 |
| Photochemical ozone formation, kg NMVOC eq | 8.87 | 8.08 | 7.31 | 8.48 | 9.46 |
| Acidification, mol H+ eq | 14.93 | 13.18 | 11.49 | 15.22 | 17.44 |
| Eutrophication, terrestrial, mol N eq | 44.62 | 38.90 | 33.32 | 48.68 | 56.51 |
| Eutrophication, freshwater, kg P eq | 0.53 | 0.45 | 0.38 | 0.44 | 0.51 |
| Eutrophication, marine, kg N eq | 9.30 | 8.23 | 7.14 | 12.31 | 14.89 |
| Ecotoxicity, freshwater, CTUe | 97729.89 | 88337.57 | 78714.88 | 87455.20 | 79705.46 |
| Land use, Pt | 80726.97 | 75247.93 | 69653.32 | 88135.89 | 93985.75 |
| Water use, m3 depriv. | 1399.08 | 1251.31 | 1115.30 | 1551.14 | 2112.78 |
| Resource use, minerals and metals, kg Sb eq | 0.007 | 0.006 | 0.005 | 0.007 | 0.009 |
| Resource use, fossils, MJ | 24063.16 | 19112.91 | 14466.47 | 15803.78 | 19214.63 |

Colour scale: | Low | Low | High |

**Sensitivity analysis**

Sensitivity analysis is performed to determine how replacing a specific component affects the environmental impact. Sensitivity analysis of black soldier fly and yellow mealworm protein by changing feed composition (Figure 3.18 and Figure 3.19) was performed to assess its impact. Feed was chosen for comparison because it significantly influences the environmental impact of the product and literature-based feed composit
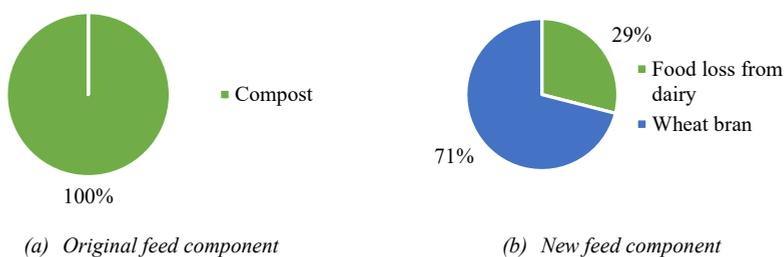


*(a) Original feed component*      *(b) New feed component*

Figure 3.18. Black soldier fly feed component.

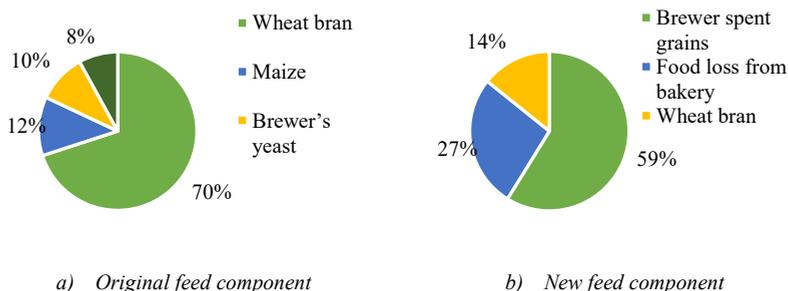a) *Original feed component*  b) *New feed component*

Figure 3.19. Yellow mealworm feed component.

The results of the sensitivity analysis for protein alternatives by impact category are presented in Paper 7. However, sensitivity analysis results for alternative protein sources show that changes in insect diet significantly affect the results – the new diet structure increases the impact of black soldier fly protein by 96 %, while the total impact of yellow mealworm protein increases by 40 %.

Also, sensitivity analysis was performed for the oil alternative using microalgae as an oil alternative and changing the extraction location and thus the electricity source. Was compared microalgae oil production using the US electricity and compared to production using Norwegian electricity, detailed results per impact categories are presented in Paper 8. The sensitivity analysis results show significant differences due to the energy source, as Norway is mostly renewable, while the US gets a significant portion of its energy from fossil fuels.

Sensitivity analysis of pigment alternatives was performed for microalgae pigment where changes were made only to electricity because it is the second largest impact contributor. In original, electricity was produced by hydropower, but in sensitivity analysis, it will be compeered by a country mix from Norway, detailed results per impact categories are presented in Paper 9. The results of the sensitivity analysis showed the difference in impacts depending on the source of energy production.

To evaluate fish feed from an economic perspective, the conventional LCC method was used. The differences in the raw material ratios of each feed were considered and the costs were estimated based on publicly available raw material prices in 2022. The publicly available data were for different amounts, so all aggregated raw material price data were converted to 1 kg of feedstock, which is shown in the Table 3.10. Although the cost of all feed materials was calculated for 1 ton of fish feed.

Table 3.10

Raw material prices per 1 kg with data adjusted for 2025 [191–196]

| Raw material | Price per 1 kg |
|---|---|
| Black soldier fly larvae meal | 8.27 |
| Mealworm meal | 10.48 |
| Fish meal | 2.61 |
| Soy protein concentrate | 6.51 |
| Wheat gluten | 1.62 |
| Vegetable raw material | 8.33 |
| Fish oil | 3.09 |
| Rapeseed oil | 4.41 |
| Other (incl. pigment) | 82.36 |
| Yttrium | 3.00 |

The cost of protein sources is a significant factor in the overall cost of fish feed, as they make up most of the feed composition. Fishmeal is still 3 to 4 times cheaper than the alternative protein sources evaluated. As a result, more environmentally friendly raw material options do not always offer economic advantages. In Figure 3.20 are economical results for 1 ton of fish feed and results and the total direct feed costs for the options considered vary around 20 % of the range.
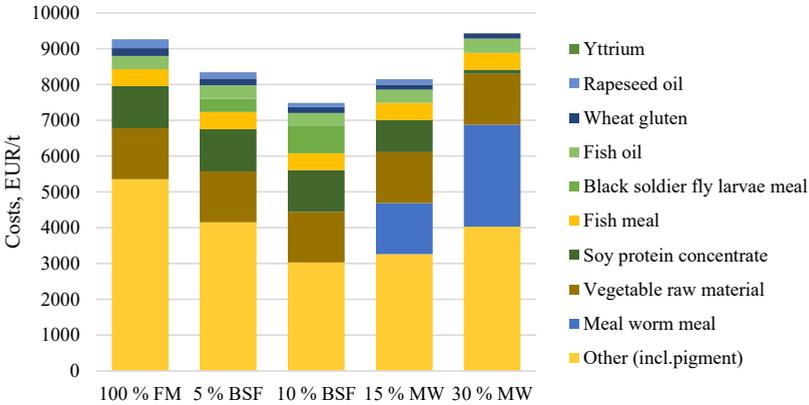


Figure 3.20. Conventional LCC results in euro based per 1 ton of fish feed.

Using environmental sustainability fish feed models, damage cost estimates for fish feed alternatives were obtained by changing the impact assessment category. Figure 3.21 shows the total results for fish feed alternatives considering conventional LCC results and environmental damage cost results.
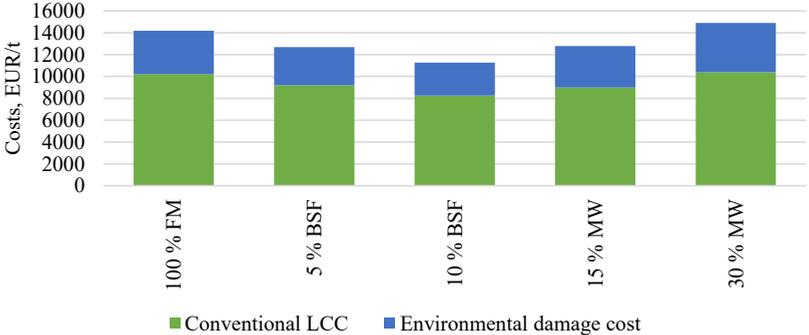


Figure 3.21. Results of conventional LCC and environmental damage cost results of fish feed alternative.

Traditional LCC and damage cost economic valuations are in the same order of fish feed alternatives and therefore the total will also correspond to the individual economic valuation.

**Social sustainability**

To assess the social impact of protein, which is one of the main ingredients in fish feed, the UNEP Guidelines methodology was used. Also, only relevant subcategories were evaluated, considering publicly available data, to allow for a fair comparison of the alternatives considered.

The social dimension assessment considered the country of production of each protein alternative: Black Soldier Fly protein is sourced from Denmark, Yellow Mealworm protein is sourced from Norway, fishmeal protein is sourced from Peru and soybean protein is sourced from Brazil. For social assessment is used publicly available data and for worker and society category is used country specific data, but for local community and value chain actors (not including consumers) category is used publicly available data from protein company from a specific country, Table 3.11.

Table 3.11

S-LCA data and assessment [197–204]

| Category | Subcategory | Black soldier fly protein | Yellow mealworm protein | Fishmeal protein | Soybean protein |
|---|---|---|---|---|---|
| Worker | Fair salary | No national minimum wage; wages set by collective bargaining. | Minimum wages are set *via* collective bargaining, not nationally mandated. | The law sets a national minimum wage above the poverty line. | The law guarantees a minimum wage above the poverty line. |
| | Average weekly hours per worker | 34.5 | 33.5 | 37.3 | 37.9 |
| | Share of workers with 49+ weekly hours | 6 % | 4 % | 31 % | 12 % |
| | Forced labour | The law bans all forced and child labour, with effective enforcement. | Forced labour is criminalised and strictly enforced by the government. | The law bans "slave labour," incl. forced labour, debt bondage, long hours and degrading conditions. | "Slave labour", incl.forced work, debt bondage, long hours and abuse – is banned by law. |
| | Equal opportunities/ discrimination | 1.3 % of workers faced discrimination, rising to 20% among minority youth (ages 15–24) in the service sector. | Women earned 12 % less; 46 % held part-time jobs. Immigrant unemployment was higher, 7.1 % among Africans. | Women earned 72 % of men's wages; pregnant workers faced bias despite equal pay laws. | 78 % of men, 56 % of women employed; NGOs report bias in pay and promotion persists. |
| | Health and safety (workers with labour health insurance (%)) | 88 | 90 | 7,4 | 48,7 |
| | Employment ratio (%) | 60 % | 63 % | 69 % | 57 % |
| Local community | Access to material resources | The company uses local food waste and organic by-products to produce insects. | It offers sustainable products that cut methane, water use and land consumption. | The company sources its product from anchovy fishing | It employs certified advanced technology for safety, productivity and sustainability. |
| | Access to immaterial resources | Good accessibility | Good accessibility | Difficult accessibility | Difficult accessibility |
| Value chain actors (excl. consumers) | Promoting social responsibility/supplier relationships | Maximising resources by using local food waste and organic by-products *via* industrial synergies. | It prioritises environmental impact by producing sustainable products and reusing delivery boxes. | The company builds long-term partnerships to enhance the quality of life and supports employee growth. | It supports local communities and motivates employees with career growth and added benefits. |
| Society | Public commitments to sustainability issues | 77.9 | 59.3 | 39.8 | 43.6 |
| | Contribution to economic development (2022) | 3,8 % | 3,3 % | 2,7 % | 2,9 % |
| | Poverty alleviation | 1,18 % | 1,96 % | 4,22 % | 6,07 % |

| Evaluations scale: | +2 | +1 | 0 | –1 | –2 |
|---|---|---|---|---|---|

The results indicate that the insect-based protein alternatives have better social outcomes than the other two protein sources. In particular, the better outcomes are related to sustainability, fair wages, working conditions and resource availability. The social evaluation of fishmeal protein is more negative, especially due to the depletion of local resources, as well as the working environment. Similarly, the social evaluation of soy protein is negative, with negative social impacts on the working environment.

**Utility value**

The aim of utility value is to find the best fish feed alternative, considering the environmental impact of the feed, feed costs, social impact, and technical parameters of the feed. Input values for TOPSIS are collected in Table 3.12. It was defined that all four dimensions have the same weight (25 %) and that the best for each dimension is the lowest score (MIN).

Table 3.12

Input data for utility value comparison for fish feed alternatives

| | 100 % FM | 5 % BSF | 10 % BSF | 15 % MW | 30 % MW | Weight | Best result |
|---|---|---|---|---|---|---|---|
| LCA, ranking | 3 | 2 | 1 | 4 | 5 | 25 % | MIN |
| LCC, ranking | 4 | 3 | 1 | 2 | 5 | 25 % | MIN |
| S-LCA, ranking | 5 | 4 | 3 | 2 | 1 | 25 % | MIN |
| Technical, ranking | 4 | 1 | 3 | 1 | 3 | 25 % | MIN |

Figure 3.22 shows TOPSIS results for five fish feeds of different composition. Alternative A1 has the lowest rating in this case and this is the conventional fish feed composition. Alternative fish feed ingredients are used in the composition of A2, A3, A4, A5 fish feed composition. However, the best alternatives are A3 and A4, although slightly different proportions of ingredients and different alternative protein raw materials are used, but the same result was obtained.
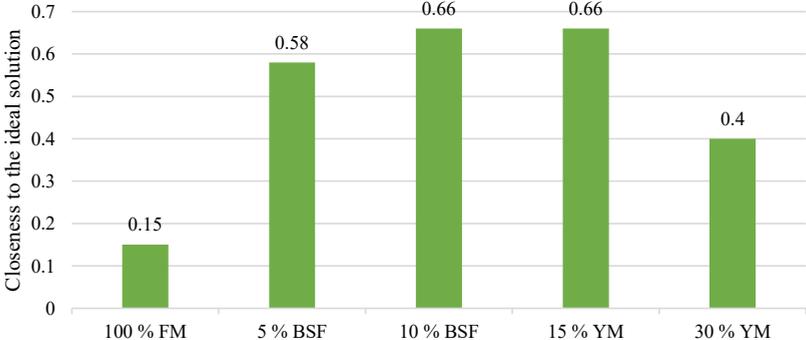


Figure 3.22. Comparison of utility value of fish feed composition alternatives, TOPSIS result.

**Sensitivity analysis**

In Figure 3.23 are the sensitivity analysis for environmental, economic, social, and technical criteria to clarify the most sensitive criterion. The biggest changes are in the sensitivity analysis of social criteria and the smallest change is in the technical criterion.

*(a) Sensitivity analysis for environmental criteria*

*(b) Sensitivity analysis for economic criteria*

*(c) Sensitivity analysis for social criteria*

*(d) Sensitivity analysis for technical criteria*
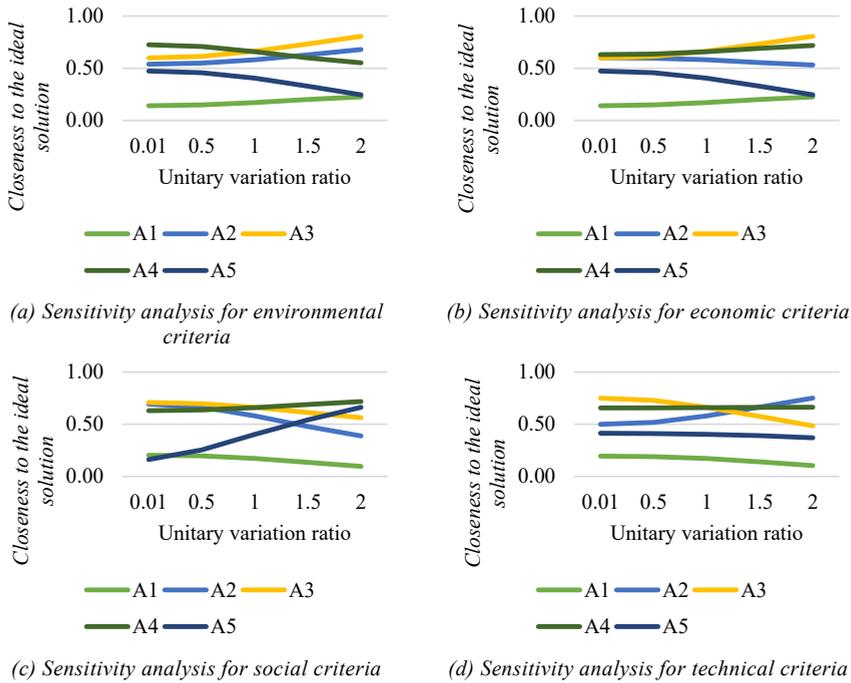
Figure 3.23. Utility value sensitivity analysis, TOPSIS results.

### 3.3.2. Utility value approach to the national industry sector

To clarify the possibilities of using existing and more environmentally friendly metal smelting furnace technologies in Latvia, a SWOT analysis was performed to clarify the strategic fit as an analysis of the efficiency of Latvian metallurgical enterprises and to determine the utility value of 8 smelting furnaces according to 11 criteria using the TOPSIS method.

To determine strategic fit, a literature analysis was conducted regarding technological processes, as well as interviews with industry representatives [205], [206]– [207]. Now, nationwide metal processing enterprises rely on their strength and resources received from local sellers. The enterprises use natural gas as fuel instead of coke (or the amount of coke is kept to a minimum, like in Hidrolats, Evan Group and Fonekss Metals companies). In this way, the amount of $CO_2$ emissions from the melting process can be reduced. The enterprises have developed a system for attracting experts. The hiring of young specialists and students is stimulated to improve the skills of employees and develop new ways to improve the efficiency of the enterprise. Ways are also being considered to obtain funding from EU funds, which could contribute to the development of factories.

The *strengths* of the scrap metal smelting industry in Latvia are the location of these companies and, consequently, which reduces logistics costs, as the company, manufacturer, seller and buyer are relatively close. Efficiency is improved, as outdated equipment is replaced with newer ones, improving production efficiency and reducing energy consumption. There is a reliable cooperation between all stakeholders involved in the production and sales sectors and good relations with customers have been established directly through sales processes and reliability. The possibility of recycling or remelting and reusing metals promotes sustainability and there are several scrap metal transfer points that encourage residents to hand over unnecessary metal and promote material reuse.

The *weaknesses* of this sector are the lack of qualified employees who would work and could operate and maintain the equipment, as well as the stagnation of technological processes due to the lack of technologies for the development of companies, which is also associated with the fact that sometimes there is not enough funding when new and more sustainable equipment appears to be purchased. This sector is very energy-intensive, so processing requires a lot of power and now it is difficult to find an alternative energy source. There is also an undiversified energy supplier and dependence on one supplier arises and demands for a more environmentally friendly company are increasing. There is also a relatively small sales market and therefore unstable financial changes may occur, and it is difficult to predict long-term financial benefits.

However, this sector also has *opportunity* related to attracting experts and cooperation partners from abroad and promoting the development of the company in technological and economic aspects, as well as using foreign markets for product sales. There are ample opportunities to promote the sustainability of the sector by installing carbon dioxide capture systems that will significantly reduce CO2 emissions during the metal smelting stage, as well as trying to use alternative energy sources. As well as finding opportunities to cooperate with foreign investors to introduce new technologies and equipment that will improve process efficiency and reduce energy consumption.

*Threats* are the aging of the existing workforce and the lack of new and qualified employees, as well as the high prices of raw materials, but the need to lower prices to meet the market demand for products, which leads to a decrease in profits and the company's illiquidity. Also, a changing economic and political environment contributes to instability in the market and established supply chains, as well as instability in the energy sector due to which it is necessary to change energy suppliers, which can potentially lead to an increase in financial costs. As well as instability with energy prices, which can cause sudden large expenses, which can affect the financial stability of the enterprise, and this can also affect the ability and ability of the company to develop with newer and more efficient equipment to meet environmental requirements.

Despite well-established supply chains and product distribution, businesses feel market instability due to political and economic influences. These fears force companies to reasonably assess all the risks associated with any changes – the expansion of production, modernization, etc. However, decisions of this kind carry with them the risks of another aspect – the environmental one. European Union directives require businesses to reduce emissions and use renewable energy sources. However, enterprises often cannot meet such requirements on their own. State financial assistance or temporary tax assistance could help enterprises develop, which in the future would contribute to the sustainable production of goods with increased added value and would contribute to the country's economy.

The modernization of production can be a strong step for the enterprise, although it is associated with risk. Potentially, efficiency gains could attract additional funding to support production. New markets can bring additional profit and stability, as a variety of buyers will be obtained. However, the main threats to enterprises are in the energy sector. The considered enterprises use mainly electric furnaces, and the metal melting process is an extremely energy-consuming stage and an increase in the price of electricity can be a critical or even decisive step in the functioning of the enterprise [205]. Diversifying energy providers can add stability to the process as it no longer depends on one energy seller. The use of alternative energy sources or already independent energy production will significantly secure both the melting process and the enterprise itself. Because enterprises use fuels with a lower carbon footprint, it can be assumed that the country's energy sector will reduce the amount of $CO_2$ emissions. As follows from the data of pollution permits [205] and from the pollutant release and transfer register [208], metalworking enterprises considered in the analysis in 2021 produced 8 % less $CO_2$ emissions than a year earlier.

To assess the utility value of various scrap metal melting furnaces, eight furnaces were defined and compared according to 11 technical and environmental criteria using the MCDA method TOPSIS, see Table 3.13. All values are referred to the production process and include either the consumption/emission per final product or amount of emission/waste in certain period. Uses data provided by enterprises in reports for the State Environmental Service [205], as well as interviews with representatives of enterprises.

Table 3.13

Input data for utility value comparison for metal melting furnaces [209]– [210]

| | Flash smelting/QSL | Ausmelt/ Isasmelt | Kaldo | Kivcet | EAF | Blast/Shaft | Short Rotary | Reverberator | Weight | Ideal solution |
|---|---|---|---|---|---|---|---|---|---|---|
| Maximum capacity, t/d | 2200 | 1150 | 900 | 1800 | 600 | 13000 | 3900 | 1000 | 9 % | MAX |
| $SO_2$ amount, year average, $mg/m^3$ | 700 | 850 | 400 | 400 | 90 | 100 | 350 | 560 | 9 % | MIN |
| $CO_2$, kg/t | 1700 | 1318 | 1500 | 2730 | 850 | 1214 | 9000 | 3000* | 9 % | MIN |
| Lead content in slag, % | 5 | 1 | 3 | 2.5 | 1.5 | 3 | 4 | 5 | 9 % | MIN |
| Energy consumption, MWh/t | 9 | 1.3 | 4.35 | 4.5 | 3 | 5.8 | 4.1 | 1.05 | 9 % | MIN |
| Oxygen, $Nm^3/d$ | 138889 | 41667 | 91667 | 11100 | 1528 | 2778 | 10278 | 1778 | 9 % | MIN |
| Gas, kWh/t | 275 | 1120 | 450 | 670 | 540 | 300 | 280 | 800 | 9 % | MIN |
| Amount of total lead production, t/year | 135000 | 120000 | 145000 | 130000 | 148000 | 110000 | 16000 | 110000 | 9 % | MAX |
| Amount of $H_2SO_4$, kg/t | 700 | 400 | 500 | 1100 | 670 | 0 | 390 | 830 | 9 % | MIN |
| Fuel consumption, kg/t | 110 | 405 | 100 | 110 | 12 | 720 | 710 | 25 | 9 % | MIN |
| Maximum temperature, °C/t | 1400 | 1370 | 1400 | 1400 | 1450 | 1400 | 1370 | 2000 | 9 % | MIN |

The results in Figure 3.24 show that, based on input data and after TOPSIS method assessment the electric arc furnace (EAF) is the most efficient. This result is consistent with the literature sources. This type of furnace is characterised by increased efficiency compared to the Blast furnace, as well as the ability to use electricity generated from renewable energy sources, which reduces the total amount of emissions created from the entire process [211]– [212]. A big advantage of EAF is the ability to work not only with raw metal, but also with scrap metal, which in no way affects the quality of the final product. As indicates [213], compared to Blast furnace, EAF can process up to 20 % more scrap metal, which contributes to the sustainability and circular economy of the sector.

Next comes the Blast/Shaft furnace. This type of furnace consumes a significant amount of coal/coke, which affects $CO_2$ emissions. However, modern furnaces are equipped with technologies to reduce this amount. For example, the use of technologies for capturing, storing and / or utilisation of carbon dioxide (CCUS), which can later be used to produce other valuable

materials / products [214], or by using alternative fuels (the so-called bioreducers) – syngas, torrefied biogas and etc [215]. The advantage of Blast Furnace is its large capacity – the maximum load can hold up to 13 000 tons per day, which allows producing a large amount of steel per year. Since the blast furnace can use low quality ore as fuel, this furnace can be considered cost-effective [216].

In turn, the worst result comparing to other observed furnaces was shown by flash smelting/QSL furnace. And although this process is characterised by a high degree of stability and productivity [217], at the moment, its performance is still inferior to more modern metallurgical furnaces, such as, for example, EAF. It should be noted that Ausmelt/Isasmelt furnaces also show excellent results. According to [218], [219], [220], [221], kilns of this type are especially remarkable for their high productivity and relatively low fuel costs. While Isasmelt stoves operate exclusively on solid fuels (coal, coke), Ausmelt can partially use electricity as fuel, which significantly reduces the amount of emissions created during fuel combustion. In the future, the Ausmelt process could eliminate the need for fossil fuels and become a greener technology [222].
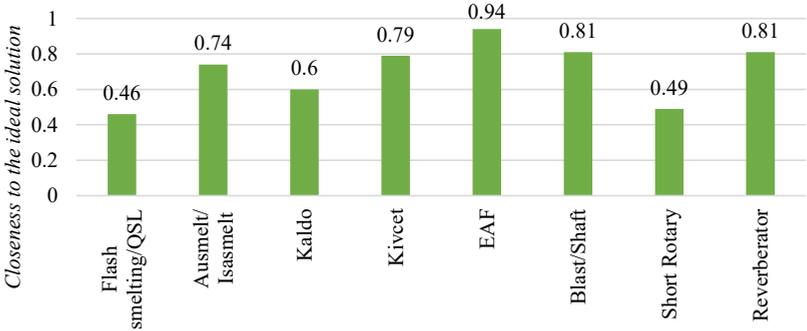


Figure 3.24. Utility value comparison for metal melting furnaces, TOPSIS result.

The strategic fit showed that the scrap metal smelting or recycling industry in Latvia is a place for growth, directly related to the high energy intensity of the industry and that it is necessary to find solutions to more environmentally friendly technologies and the use of renewable energy resources, and that the industry also needs to expand beyond the borders of the country to ensure financial stability. It is also necessary to think about growth in the field of employees and in the technological field.

The utility value showed that half of the metal melting furnaces examined are quite close to the ideal option. The main advantage of EAF is the ability to work with a large amount of scrap metal, as well as the relatively low amount of lead produced in the waste, low $SO_2$ and $CO_2$ emissions. Due to the ability to use electricity, this furnace is also characterised by low consumption of fossil fuels and given the ability to use electricity generated from renewable energy sources, EAF can be considered the most environmentally friendly among other analysed metal melting furnaces.

### 3.3.3. Utility value approach to the international energy sector

Strategic fit was assessed through quantitative and qualitative data analysis for selected EU countries, which were then compared using the TOPSIS ranking method according to defined quantitative criteria to determine GHG emissions performance.

For the comparison of GHG performance, eight EU countries have been selected, ensuring that different national environmental, economic and political backgrounds are covered. The

main point of reference for selecting countries for comparison was the GHG intensity of energy consumption. Latvia was chosen as the main focus of analysis, alongside Ireland and Slovenia, classified as medium GHG intensity. Estonia and Lithuania were selected as the countries with high GHG intensity, whereas Finland, Denmark and Sweden were chosen to represent countries with relatively low GHG intensity.

Eurostat data analysis from 2005 to 2015 indicates that Estonia had the highest average GHG emissions per capita (15,2 t $CO_2$ eq./capita), followed by Ireland (14,4 t $CO_2$ eq./capita), while the lowest GHG emissions were achieved by Latvia (5,7 t $CO_2$ eq./capita), Sweden (6,7 t $CO_2$ eq./capita) and Lithuania (7,1 t $CO_2$ eq./capita).

All countries have made improvements in the share of renewable energy but Sweden had the best performance regarding renewable energy consumption. Some countries such as Sweden, Finland and Denmark have made improvements by more than 10 % in a 10-year-period.

In terms of environmental taxes, Denmark had the highest performance. Denmark has the second highest tax rate in the EU energy sector. Slovenia has been approaching Denmark's environmental tax revenues since 2012, as Slovenia has higher tax rate on transport fuels than on fuels used for energy production – heating or electricity.

From all selected countries, Estonia has the highest $CO_2$ emissions, which is the second highest value in the EU after Luxembourg. The main reason for the high emissions in Estonia is electricity production from oil shale, which accounts for about 90 % of the total $CO_2$ pollution, and recently oil shale has also been used for liquid fuel (diesel) production [223]. However, Estonia has set ambitious goals to increase electricity production from biomass [224]. Ireland is also a significant source of $CO_2$ emissions with most of the emissions coming from industry and agriculture [225], and Finland, where emissions from energy sector are mainly generated by utilisation of natural gas and peat [226]. Overall, in a 10-year-period, emissions are decreasing periodically, except for Estonia where the trend is uneven.

The total consumption of solid fossil fuel is low in Estonia, Latvia and Lithuania in comparison to other selected countries. Generally, the consumption of solid fossil fuels is decreasing. Finland stands out with significantly high values for this indicator because over half of its heat is generated from solid fossil fuels.

Households hold an important position in the total energy consumption and represent the overall energy consumption image of a population. Household energy consumption per capita is the lowest in Lithuania, while Finland scores the highest. All the selected countries have reduced their household energy consumption over recent years.

Eurostat data indicates that the investment share of GDP was high during a period from 2005 to 2008 for all selected countries, and in 2009 it decreased by 10 % on average, which can be related to the global financial crisis. However, the investment share for all countries started to increase afterwards. The highest average investment share was in Estonia (28,5 %).

To assess the utility value of the international energy sector with aim to assess GHG emission indicators and compare eight countries. The SEG assessment considered the results of a literature review on the criteria to be used for cross-country comparisons, as well as the corresponding data from the Eurostat database for the period 2005–2015, which were normalised using the MIN-MAX method to ensure comparability of indicators.

The AHP method was used to determine the weights of the criteria, where the criteria were compared in pairs on a scale from 1 to 9, and the evaluation was done by 5 five experts. The criteria evaluated are GHG emissions per capita (as a primary measure of emission intensity); revenues from environmental taxes (reflecting the role of environmental policy in fiscal measures); household energy consumption per capita (indicating energy demand at the housing level); investment as a share of GDP (reflecting economic progress and sustainability); solid fossil fuel consumption (as a major source of GHG emissions); and renewable energy

consumption (indicating the transition to cleaner energy sources). The TOPSIS method was used to compare eight EU countries based on input data in Table 3.14.

Table 3.14

Input data for utility value comparison for countries according to GHG indicators

| | Denmark | Estonia | Ireland | Latvia | Lithuania | Slovenia | Finland | Sweden | Weight | Ideal solution |
|---|---|---|---|---|---|---|---|---|---|---|
| GHG emissions per capita, t $CO_2$ eq./capita | 0,481 | 0,613 | 0,760 | 0,602 | 0,472 | 0,559 | 0,741 | 0,517 | 32 % | MIN |
| Income from environmental taxes, % | 0,282 | 0,500 | 0,797 | 0,494 | 0,273 | 0,527 | 0,614 | 0,565 | 19 % | MAX |
| Household energy consumption per capita, kgoe | 0,552 | 0,432 | 0,575 | 0,632 | 0,615 | 0,558 | 0,411 | 0,573 | 15 % | MIN |
| Investment share of GDP, % | 0,420 | 0,470 | 0,442 | 0,419 | 0,355 | 0,412 | 0,466 | 0,319 | 13 % | MIN |
| Consumption of solid fossil fuels, thsd. tonnes | 0,475 | 0,469 | 0,382 | 0,615 | 0,484 | 0,696 | 0,435 | 0,612 | 13 % | MIN |
| Renewable energy consumption, % | 0,434 | 0,530 | 0,465 | 0,445 | 0,388 | 0,549 | 0,421 | 0,539 | 8 % | MAX |

Figure 3.25 shows the TOPSIS results for eight EU countries, ranked by their GHG emissions over the period 2005–2015. The TOPSIS results obtained are relatively similar, but Sweden is the best performer with low emissions per capita and high renewable energy consumption, although the worst performer is solid fossil fuel consumption. Ireland came in second place, mainly due to high environmental tax revenues and low fossil fuel consumption, despite having the highest GHG emissions per capita. However, Latvia came in last place, mainly due to high household energy consumption and heavy reliance on fossil fuels.
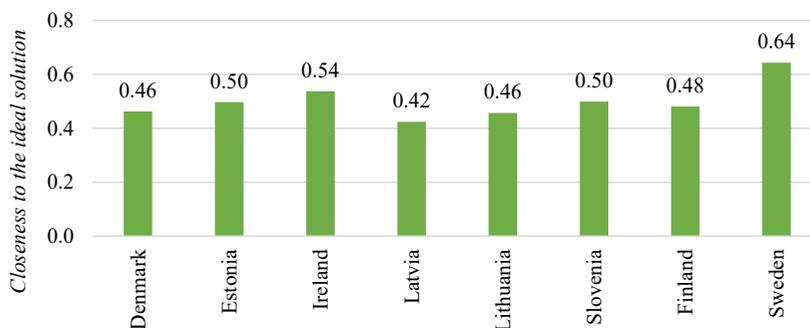


Figure 3.25. Comparison of utility values for countries according to GHG indicators, TOPSIS result.

Although countries were selected based on strategic fit, with different environmental, economic and political backgrounds, the resulting utility values are in a relatively similar range.

This means that countries can learn from each other some criteria that can improve their overall national GHG emissions performance.

### 3.3.4. Utility value approach to the municipal energy sector

Strategic feasibility and utility value of the use of renewable energy resources in one of the Latvian municipalities were determined, possible RES technologies were compared, as well as district (DH) and individual (IH) heating alternatives.

The Carnikava DH system consists of six interconnected boiler houses and heating networks. The total length of the heating networks is 2,837 m, of which 1,156 m is industrially insulated. All boiler houses have Viessmann natural gas boilers with different capacities, from 520 kW to 1,500 kW. Losses in heating networks range from 15 % to 17 %. The loss value indicates that the heat transmission infrastructure is inferior. The main reason is the preparation of hot water outside the heating season. As summer consumption is meagre, the percentage of heat losses is very high in the summer months.

According to 2019 data, the municipality has more than 9,500 inhabitants and six municipal buildings were analysed. Therefore, municipal buildings are very diverse in terms of their functionality and building characteristics, and they are not connected to the DH system.

Based on the average monthly heat and electricity consumption from 2019 to 2021 the largest energy consumers are the elementary school, preschool, and office building. The largest heat energy consumption is in the heating season, especially in winter. During the summer, the heat energy consumption is for preparing hot water. From September to April, electricity consumption is higher in the preschool and elementary school, but in other buildings the difference in electricity consumption between winter and summer is up to 1 MWh per month. The preschool and music and art school have the highest specific heat energy consumption, but the elementary school has the lowest. The preschool and primary school have the highest specific electricity consumption, while the music and art school have the lowest specific electricity consumption. On average, the specific electricity consumption is four times lower than the specific heat energy consumption. However, the most similar specific electricity and heat energy consumption is for the elementary school, but the biggest difference in the specific electricity and heat energy consumption is for the music and art school.

Six possible alternatives were defined for increasing the share of RES in DH. Alternatives can be introduced at the same time as the implementation of IH development scenarios. They mainly involve the combination of separate systems and heat networks.

Different RES alternatives for consumer scenarios were analysed – two cases of DH development as the five boiler houses and the DH system contained were combined into a whole, and two DH were combined according to their distance from each other. Since the DH in Carnikava is also used for hot water production, which means that there is also a summer load, the scenarios of installing heat pumps and solar collectors were also analysed. For the created large gas boiler plant, the scenario of installing a wood chip boiler was analysed, while in the case of the two smaller created plants, the installation of pellet boilers was evaluated as a basic alternative. The heat pump and solar collector scenarios are each supplemented by the fuel boiler used for each system—wood chips for the large system and pellets for the two smaller systems.

Woodchip boiler is combining the five existing DH plants of Carnikava into one and connecting the municipal buildings, the construction of a woodchip boiler house is considered.

Pellet boiler that proposes to combine Carnikava's five existing DH systems into two separate systems and connect municipal buildings to them. By creating two separate systems, the consumer load is slightly too low for using a wood chip boiler.

Woodchip boiler + solar collectors with storage is considering that the number of consumers in Carnikava is small and distributed over a large area, the scenario where solar collectors with storage are installed to cover the summer load. They should be placed closer to the consumers. A woodchip boiler will be used to cover the heating load in the case of a combined CSA system.

Pellet boiler + solar collectors with storage is considering that the number of consumers in Carnikava is small and spread over a large area, it is planned to study the scenario where PV panels are installed in combination with an air source heat pump to cover the summer load. They will be placed closer to the consumers. In the case of two separate DH systems, pellet boilers will be used to cover the heating load.

Four possible alternatives were defined for increasing the share of RES in IH in municipality buildings, replacing natural gas boilers Alternatives can be introduced at the same time as the implementation of DH development scenarios.

Pellet boilers is one of the alternatives is to replace natural gas boilers with a pellet boiler that provides heating and hot water: solar panels and a heat pump. The building has a summer heat load, so one alternative is solar panels, which would generate electricity for the heat pump during the summer months. Solar collectors are assuming the roof of the building is suitable for installing solar panels, solar panels can be considered another heat energy alternative. Thus, the necessary summer heat load can be met with solar collectors.

One of the alternatives is to replace the natural gas boilers with a pellet boiler that provides heating and hot water. The provision of thermal energy with solar panels and a heat pump was analysed as another technological solution since the heat pump does not require a large area, and the building has a large roof area that can be effectively used for solar panels. The electricity consumption of the heat pump can be covered in the summer months by using electricity from solar collectors. Therefore, this alternative evaluates the installation of both an air source heat pump and a solar power plant. In these scenarios, solar panels are considered to meet the summer load and the existing natural gas system or its replacement with a pellet boiler to meet the remaining heat load. Solar collectors could meet the summer load of the building's hot water consumption, provided the building's roof is suitable for solar collector installation. The installation of solar collectors is not considered for buildings that have low summer hot water consumption or are heavily shaded. In addition to the solar collectors, a suitable buffer tank should be integrated to cover 2–3 days of consumption.

With utility value is assess the economic and environmental sustainability of district (DH) and IH alternatives, promote the use of RES resources and replace the use of natural gas, input data are in. A case study of a village in Latvia, which includes 28 residential, six municipal and five commercial buildings. Six DH alternatives and four IH scenarios are defined:

**DH1**_Wood Chip Boiler with Flue Gas Condenser
**DH2**_Wood Chip Boiler+ PV Panels + Heat Pump Solution
**DH3**_Wood Chip Boiler+Solar Collectors with Thermal Energy Storage
**DH4**_ Pellet Boiler
**DH5**_Pellet Boiler+ PV Panels + Heat Pump Solution
**DH6**_Pellet Boiler+Solar Collectors with Thermal Energy Storage

**IH1**_Pellet Boiler
**IH2**_Heat Pump Solution + PV Panels
**IH3**_Solar Collectors with Thermal Energy Storage Natural Gas Boiler
**IH4**_Solar Collectors with Thermal Energy Storage Pellet Boiler

Table 3.15

Input data for utility value comparison for RES technology in heating supply in municipal public and residential buildings

| | DH1 | DH2 | DH3 | DH4 | DH5 | DH6 | IH1 | IH2 | IH3 | IH4 | Weight | Impact |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Consumption of fuel energy, MWh/MWh | 0.99 | 0.82 | 0.82 | 1.18 | 0.95 | 0.97 | 1.11 | 0.36 | 0.93 | 1.04 | 12,5 % | MIN |
| Specific NOx emissions, g/MWh | 321 | 228 | 238 | 343 | 242 | 254 | 351 | 0.000001 | 41 | 187 | 12,5 % | MIN |
| Specific PM emissions, g/MWh | 36 | 28 | 29 | 42 | 30 | 31 | 206 | 0.000001 | 0.00001 | 110 | 12,5 % | MIN |
| Costs of $CO_2$ reduction, EUR/t $CO_2$ | 592 | 832.8 | 1385.7 | 380.8 | 684.5 | 1145.8 | 587.9 | 19.4 | 5410.8 | 957.6 | 12,5 % | MIN |
| Investments, 1000 EUR/MWh | 0.13 | 0.19 | 0.31 | 0.09 | 0.15 | 0.26 | 94.62 | 284.48 | 126.53 | 193.43 | 12,5 % | MIN |
| Internal rate of return, % | 34.45 | 25.74 | 9.4 | 7.75 | 7.29 | −11.57 | 0.01 | 0.4 | −0.1 | 0.03 | 12,5 % | MAX |
| Production costs, EUR/MWh | 59.6 | 52.7 | 54.2 | 106.5 | 94.5 | 97.9 | 86.9 | 291.1 | 110.6 | 95.2 | 12,5 % | MIN |
| Opportunities for diversification of utilised energy resources (technology is not limited only to one type of energy resource supply, count of resources | 2 | 3 | 3 | 2 | 3 | 3 | 2 | 3 | 3 | 3 | 12,5 % | MAX |

In Figure 3.26 the TOPSIS results on utility value are shown. The results is wide-ranging, since all criteria were given equal weight, better and not-so-better alternatives clearly appear. Two better alternatives are DH systems with wood chip piles, but less suitable alternatives are IH solar collectors with heat accumulation and natural gas boilers, as well as DH and IH systems with pellet boilers.
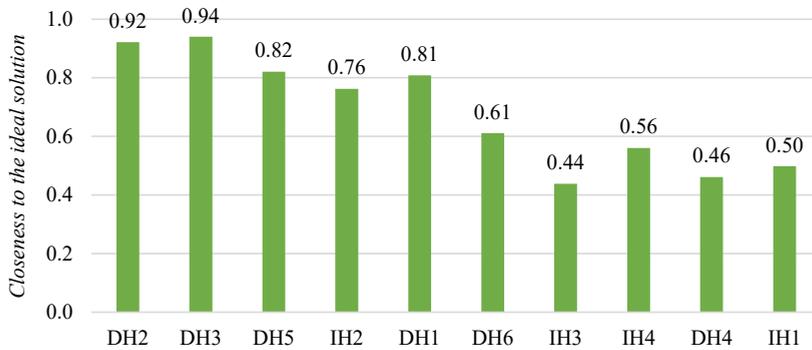


Figure 3.26. Comparison of the utility value of RES technology in heating supply in municipal public and residential buildings, TOPSIS result.

Taking into account the analysis of the case study and the strategic relevance of promoting the use of renewable energy sources in heating, as well as evaluating alternatives according to utility value, where environmental, economic and social criteria were taken into account, a relatively broad assessment of alternatives was obtained, which will help decision-makers understand in which direction to continue and implement the initiated plan.

### 3.3.5. Utility value approach to the agriculture sector

Traditionally, bran by-products from agriculture are used as waste or added to livestock feed. However, they can be used as a resource for analysis. With strategic relevance, product groups are obtained from the literature review with qualitative data analysis, where various wheat by-products are used. However, with the utility value TOPSIS method, the possibilities of using bran by-products are compared according to environmental, social, economic and technical criteria.

By reviewing the available scientific literature, strategic fit was determined, and around 30 products were obtained where wheat by-products can be used. Products were obtained from four wheat byproducts – bran, straw, husk, and dust. Wheat is also the most common type of cereal in Latvia and the world [227,228]. Of these byproducts, bran is the most widely used, while dust is used to produce only one product, bio-based packaging [229]. Products were divided into six groups: packaging materials, building materials, adsorbents, fuels, thermal insulation materials and chemicals.

Bran, straw, dust and husks are most commonly used as wheat by-products in packaging materials, resulting in products such as bio-based composite with polypropylene (PP) [230,231], food film with antioxidant properties [232], bio-based food packaging [229], biocomposite – film for fresh food packaging [233], thermoplastic [234].

In construction materials, straw and husk are most often used as wheat by-products, resulting in products such as concrete [235], lightweight concrete [236,237].

The most common adsorbent used is bran, straw and husk, which are wheat by-products, resulting in products such as siliceous lignin microparticles as an adsorbent [238], adsorbent

for Reactofix golden yellow 3 RFN dye [239], carbon microspheres [240], and absorbent for eliminating dyes and other toxic effluents from the textile industry [241].

Wheat by-products such as bran and straw are used in fuel production, resulting in products such as fuel pellets [242], phenolic bio-oil and biochar [243], biofuel [244,245].

Thermal insulation materials are produced from wheat by-products such as bran, straw and husk, which results in products such as thermal insulation biocomposite [246], clay bricks [247], mycelium-based composite [248], polyurethane foam [249].

In the production of chemicals, bran, straw and husk are used from wheat by-products, resulting in products such as silicon [250], hydrogen [251], organic acids – ferulic acid, lactic acid, itaconic acid and fumaric acid [245,252], enzymes [245], protein [245], medicines and vitamins [245], cosmetics [245], single cell oil [253], antioxidant and antimicrobial extracts [254], xylanase [255], lignin [256], mesoporous biogenic silica nanoparticles [257].

To determine the utility value of sustainable use of bran by-products, a literature analysis of potential products was conducted and defined 30 innovative products derived from four wheat byproducts—bran, straw, husk, and dust—with wheat bran being the most used material. These products were grouped into six categories: packaging materials, construction materials, adsorbents, fuels, thermal insulation materials and chemicals, but due to their relatively low added value, fuels and construction materials were excluded from further analysis.

The TOPSIS method compared seven products, which were compared according to their commercialisation potential based on environmental, social, economic and technical criteria. The criteria were assessed by experts according to a 5-point scale: 1 – does not meet the requirements; 5 – meets the requirements, except for the criterion of product price comparison, which is evaluated as a percentage. Using the TOPSIS method a comparison of potential products was performed according to environmental, economic, social and technical criteria, the input data is summarized in Table 3.16.

Table 3.16

Input data for utility value comparison for use of bran by-products

| | Mycelium-based composite | Adsorbent | Bio-based PP composite | Bio-based film | Enzymes | Lactic acid | Single-cell oil | Weight | Best solution |
|---|---|---|---|---|---|---|---|---|---|
| Availability of technologies, five-point scale | 3 | 4 | 3 | 3 | 4 | 4 | 3 | 15 % | MAX |
| Sustainability, five-point scale | 5 | 4 | 4 | 4 | 5 | 5 | 5 | 5 % | MAX |
| Product price comparison, % | 92,5 | 92,6 | 14,2 | 0,01 | 50 | 32,6 | 37,9 | 25 % | MIN |
| Market demand, five-point scale | 4 | 2 | 4 | 2 | 2 | 3 | 5 | 20 % | MAX |
| Environmental impact, five-point scale | 4 | 5 | 3 | 2 | 3 | 4 | 5 | 20 % | MAX |
| Social aspects, five-point scale | 5 | 4 | 5 | 5 | 3 | 3 | 4 | 15 % | MAX |

The TOPSIS results in Figure 3.27 show that the most sustainable option for bran by-products is bio-composite production due to the favourable product price. However, if price were excluded as a criterion, single-cell oil would be ranked highest. Another good result was

achieved by producing an absorbent from a bran by-product due to its lower cost and environmental impact compared to conventional adsorbents.
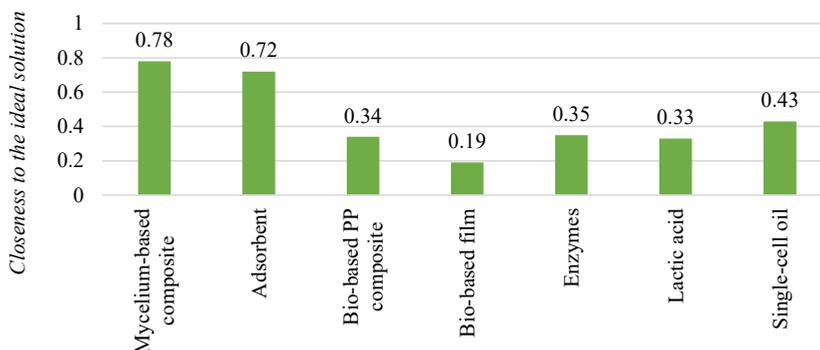


Figure 3.27. Comparison of utility value for the use of bran by-products, TOPSIS result.

As can be seen from the strategic fit, there are several sectors where it is possible to sell wheat by-products from agriculture and these products can then be used in various sectors. However, after determining the utility value, a large difference is shown between the analysed options, which, of course, makes decision-making easier.

### 3.3.6. Utility value approach to the international industry sector

The increase in the amount of infectious healthcare waste and the requirement to reduce the amount of waste deposited in landfills and the move towards a circular economy create a need for effective management of this type of waste. Consequently, the strategic fit of treatment technology was examined, so that infectious healthcare waste could then be recycled, and management technologies were compared according to environmental, technical and social criteria using a cost-benefit approach.

For healthcare waste treatment technology comparison for strategi fit was selected seven waste treatment technologies. As thermal technologies were selected vacuum autoclaves, autoclaves with integrated shredding, batch wise microwaves, continuous microwave, frictional heat treatment and incineration technologies. As chemical treatment technology is sodium hypochlorite-based technology. Some type of healthcare waste needs to be treated with higher temperature because of waste hazardous nature, but other healthcare waste, like infectious waste can be disinfected if a certain level of microbiological inactivation efficiency is achieved [258].

Autoclaves were originally used for medical instrument sterilization but in lase few decades healthcare waste treatment is possible with this technology [259]. The process temperature of the autoclave technology is 120–150 ºC and operates with a pressure of 2-5 bar [260]. Autoclaves can be used for wide range of healthcare waste treatment but it is not suggested to use autoclave for volatile and semi-volatile organic compounds, chemotherapy waste, mercury and other hazardous chemical waste, as well as radiological waste [259]. Low-heat waste treatment technologies, like autoclaves makes less air pollution [261].

Vacuum autoclaves take less time to disinfect because they are more efficient at removing air and disinfecting waste [259]. Capacity for vacuum autoclave is 5 to 3000 kg/hour and technology advantages are low impact to environment and waste residues after treatment is non-hazardous and even is possibility to recycled them [261].

Autoclaves with integrated shredding is as hybrid autoclave and has improved heat transfer into waste and has high disinfection level at shorter time [259]. Capacity is 5 to 3000 kg/hour and using this technology impact to environment is low, has no hazardous residues but they are unrecognisable after treatment and reduce waste amount [261].

Microwaves technology typically uses 2450 ± 50 MHz and 915 ± 25 MHz for disinfection [262]. Using this waste treatment technology is possible to treat wide range of healthcare waste, but volatile and semi-volatile organic compounds, chemotherapy waste, mercury and other hazardous chemical waste and radiological waste are not suggested for this waste treatment technology [259]. Microwaves technology does not have a significant impact on the environment because wastewater is treated and there are minimal air emissions from technology [261]. Microwave technology has complex influencing factors of disinfection and for healthcare waste and especially for hazardous healthcare waste it is important indicator [263].

Batch wise microwaves technology advantages are low environmental impact and after treatment waste is no hazardous un technology capacity is 1 to 210 kg per hour [261].

Continuous microwave technology capacity is 100 to 800 kg per hour and after treatment healthcare waste is unrecognisable and no hazardous, amount has reduced and is low environmental impact [261].

Frictional heat treatment technology heats waste to 150ºC and shreds waste into powder and for waste disinfection is used temperature 135°C up to 151°C [259]. With frictional heat technology is possible to take care of infectious healthcare waste - glass, plastic, metal, liquids and pathological waste [259]. Capacity is10 to 600 kg per hour and using frictional heat treatment technology there is low impact to environment and after treatment waste is no hazardous and unrecognisable and waste reduction is also advantage of this technology [261].

Sodium hypochlorite-based technology is alkaline hydrolysis or alkaline digestion process which in decontaminated aqueous solution turns anatomical parts [259]. This healthcare waste treatment technology is used for pathological and biological waste treatment, but is not suggested for waste which contain aluminium, tin, zinc, magnesium, copper or galvanized iron as well as concentrated acids, flammable liquids and organ halogen compounds and nitromethane and similar nitro compounds [259]. Advantages of sodium hypochlorite-based technology is amounting reduction, unrecognisable and no hazardous waste and technology capacity is 600 to 3000 kg per hour [261].

Incineration with dual chamber technology is knows as starved-air incinerators, pyrolytic incinerators, two-stage incinerators or modular combustion units [259]. In incarnation technology can be treated wide range of healthcare waste and is specially made for pathological waste, but it is not suggested for pressurized gas containers, large amounts of reactive chemical waste, radiographic wastes (silver, salts and photographic), as well as wastes which contains mercury, cadmium or other heavy metals from broken thermometers, used batteries and sealed ampoules or vials that may burst and radioactive waste [259]. Incineration capacity is 5 to 500 kg per hour and advantages is waste amount reduction and waste is unrecognisable and as disadvantages for this technology is high impact to environment because of possibility to hazardous ash, air pollution and risk of burns [261].

To assess waste treatment technology is used utility value approach and indicators must reflect sustainability with environmental, technical and economic aspects [264]. Indicators are delineated as data from technology and as evaluation from literature analysis.

As environmental aspect is energy consumption (kWh/kg) and water consumption (l/kg) data for each technology and it represents how much energy and water is used to treat kg of healthcare waste. Also, as environmental aspect are criteria about water connection, quality and wastewater, as well as environmental impact criteria and hazardous residues criteria.

For technical aspect were chosen technology capacity which is represented by how wide the technology capacity range is and what type of healthcare waste can be treated with technology because each technology has defended what kind of waste can be treated. Also, as criteria is temperature for waste treatment process, how effective is waste disinfection and for hazardous healthcare waste it is very important criteria. For circular economy aspect important technical aspect is criteria if waste can be recycled after treatment with technology.

For economic aspect was selected costs and maintenance criteria for technology. In this research focus is to technical and environmental indicators for waste treatment technologies.

Experts evaluated criteria and give it weight which is in Table 3.17 and for environmental criteria (C1-C5) weight is 0,4 which was divide to sub-criteria, for technical criteria (C6-C10) weigh is 0,4 which was also divided to sub-criteria and economic criteria (C11) is with 0,2 weight. Also, in Table 3.17 are defended each criteria ideal solution – minimal (MIN) or maximal (MAX) and it depends on each criterion qualitative or quantitative data.

Table 3.17

Input data for utility value comparison for iHCW treatment technology

| Criteria | Vacuum autoclaves | Autoclaves with integrated shredding | Batch wise microwaves | Continuous microwave | Frictional heat treatment | Sodium Hypochlorite based technology | Incineration | Weight | Ideal value |
|---|---|---|---|---|---|---|---|---|---|
| C1_Energy consumption, kWh/kg | 0,142 | 0,036 | 0,251 | 0,215 | 0,785 | 0,210 | 0,175 | 10 % | MIN |
| C2_Water consumption, l/kg | 2,996 | 0,361 | 0.152 | 0 | 1,100 | 1.000 | 0 | 10 % | MIN |
| C3_Water connection, quality and wastewater, yes/no | 3 | 3 | 3 | 1 | 2 | 2 | 1 | 2 % | MIN |
| C4_Environmental impact, high/low | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 9 % | MIN |
| C5_Hazardous residues, yes/no | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 9 % | MIN |
| C6_Capacity interval, kg/hour | 1 | 1 | 3 | 2 | 2 | 1 | 3 | 8 % | MIN |
| C7_Infectivity removal efficiency, ranking | 1 | 2 | 4 | 4 | 2 | 2 | 1 | 9 % | MIN |
| C8_Temperature, °C | 127,5 | 0 | 100 | 100 | 150 | 0 | 1150 | 8 % | MIN |
| C9_Waste sorting after treatment, recognisable/unrecognisable | 1 | 0 | 0 | 2 | 2 | 2 | 2 | 12 % | MIN |
| C10_Types of waste treated, narrow/wide range | 3 | 3 | 2 | 2 | 3 | 1 | 3 | 3 % | MAX |
| C11_Costs and maintenance, high/low | 0 | 2 | 2 | 2 | 2 | 2 | 0 | 20 % | MIN |

In Figure 3.28 the utility value results from the MCDA method TOPSIS are shown, and the highest evaluations has an autoclave with integrated shredding waste treatment technology with a value 0.82 and the second best technology after the criterion is chemical treatment technology – sodium hypochlorite-based technology with 0.73 value.

Vacuum autoclaves technology was the only one technology which after healthcare waste treatment could be possible to recycle waste and this indicator was one of the most important, but in other criteria technology was not quite good and is not one of the top technologies in this case.
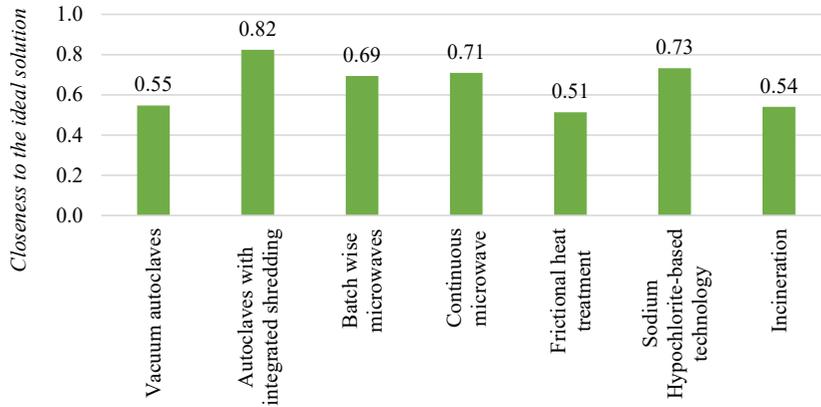


Figure 3.28. Utility value comparison for iHCW technologies, TOPSIS results.

Depending on the strategic relevance, infectious healthcare waste management is possible with several treatment technologies, but each of the technologies has its own advantages and disadvantages. Especially when considering the use of waste as a resource and its recycling into a valuable product. The utility value determination of treatment technologies shows how some technologies are of similar importance, although their characteristics are different.

# 4. CONCLUSIONS

This Doctoral Thesis introduces a thorough, yet flexible multi-factorial decision-making methodological framework aimed at improving sustainable decision-making within resource value chains. The formulated methodology is based on an incremental complexity framework that merges three vital decision-making levels – strategic fit, sustainability assessment and utility value – and is relevant at international, national, municipal and sectoral levels in the energy, waste, industry and agriculture domains.

In contrast to conventional methods, the methodology supports multi-factorial analysis using both qualitative and quantitative data. This guarantees that decisions are not limited in data type, while are consistent with the solved problem nature, for example, compliance with environmental, economic and social standards, fostering sustainable and coherent results across various governance levels. Notably, the framework can be used independently at each level, while also promoting cross-sectoral integration, allowing for the alignment of international objectives with local or municipal requirements and *vice versa*, without overcomplicating the decision-making process.

The methodology was adapted to nine varied case studies, each requiring the identification of the most sustainable solutions across different segments of the resource value chain. These applications substantiated the Thesis hypothesis: a multi-factorial methodology founded on incremental complexity can successfully steer decision-making across multiple governance levels and resource sectors while pinpointing the most suitable sustainable outcomes.

At the strategic fit level, the methodology facilitates initial evaluation of possible solutions – either qualitatively or quantitatively – based on their alignment with strategic objectives. It aids in recognising critical points in the resource value chain, enhancing systemic coherence. For example, case studies on energy consumption in Latvian agricultural sub-sectors highlighted the necessity for the development of region- and sector-specific development and action strategies to achieve sustainability goals.

The sustainability assessment level offers a deeper analysis of environmental, economic or social impacts, tailored to the specific context. This was adapted in case studies from the national waste sector (particularly, infectious healthcare waste, as well as used fishing nets and fishing nets production scraps) and where various waste valorisation scenarios were evaluated using life cycle assessment, environmental damage cost assessment and social life cycle assessment, providing a robust foundation for sustainability-oriented decision-making.

The utility value level expands the decision-making viewpoint by facilitating unidimensional or multidimensional evaluations tailored to specific contextual needs *via* multi-criteria decision-making analysis. This phase is crucial for comparing alternative solutions and ensuring well-rounded decisions. The applicability of MCDA methods showed similar, but not identical, results, indicating that the choice of MCDA methodology is also important for decision-making outcomes. For example, in the fish feed case study, the complete methodology was employed – from the strategic relevance of agricultural by-products to environmental, economic, and, social evaluations (*via* LCA, LCCA, S-LCA) and technical assessment – resulting in a comprehensive utility value judgment. Utility value evaluations were also implemented in other case studies, such as prioritization of scrap metal melting technologies in Latvia, comparative ranking of eight European countries based on greenhouse gas emission metrics, assessment of renewable energy technologies in municipal infrastructures, evaluation of bran by-product utilisation and global comparisons of healthcare waste treatment technologies – in all highlighting the adaptability of the multi-criteria decision making analysis to various resource value chain problems and decision scopes (international, national, municipal and sectoral).

In summary, the developed methodology makes a significant contribution to sustainable and intelligent resource value chain management. It empowers stakeholders (policymakers, municipality officers, company owners, investors, etc.) to make strategic, sustainability-focused and value-driven decisions, facilitating the systemic transformation of resource value chains. This aligns with and propels the objectives of the European Green Deal, fostering a circular, inclusive and climate-resilient economy.

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# ANNEXES

**Doctoral Thesis publications**

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# Multi-Criteria Decision Analysis Methods Comparison

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*Abstract* – **Multi-criteria decision analysis (MCDA) is widely used to solve various decision problems through alternative evaluation. MCDA methods can be used in every field that can define a problem, alternatives and criteria. However, finding the appropriate method can influence the results, in this research five MCDA methods have been tested on the renewable energy sector in Latvia to find the best alternative. The main results showed that TOPSIS, VIKOR and PROMETHEE-GAIA have similar priority selection and the highest ranking was selected for hydropower plant, but MULTIMOORA and COPRAS results were beneficial to Solar PV.**

*Keywords* – **COPRAS; MCDA; MULTIMOORA; PROMETHEE-GAIA; renewable energy; TOPSIS; VIKOR.**

## 1. INTRODUCTION

Multi-criteria decision analysis (MCDA) is a multi-step process consisting of a set of methods to structure and formalise decision-making processes in a transparent and consistent manner [1]. Over the years, MCDA has developed many methods and software to resolve the defined problems. To use the methods, it is important to define the problem, alternatives, and criteria that may be different types of costs, environmental impact indicators, social indicators, energy efficiency, quality and other specific criteria that are relevant to the problem. When there are many alternatives for one problem, it is important to find the most suitable alternative with the best cost criteria, lowest impact on environment, and good energy efficiency. This can be achieved by using the MCDA method as a tool for comparing alternatives.

There are many methods that can be used for solving problems and they can be arranged according to different parameters. Each MCDA method has its own calculation method by which alternatives are queued and it is not possible to claim that using specific methods with the same input data will lead to the same final result. Methods can be selected by the type of result [2]. If the result is required as a comparison of values, AHP, MULTIMOORA, MAUT, Weighted Sum Method, Weighted Product Method and other methods can be used. Using AHP, TOPSIS, and VIKOR, COPRAS, STEP and other methods can be used to reach the defined goal and to find the best alternative from the provided options. PROMETHEE and ELECTRE methods are based on pairwise comparison and conformity assessment for the desired purpose.

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There is a possibility to get the same results using different methods: TOPSIS and VIKOR [3], VIKOR and PROMETHEE [4] methods lead to quite similar results, TOPSIS and COPRAS results are practically the same except for two alternatives [5], MULTIMOORA, TOPSIS and VIKOR [6], VIKOR, COPRAS and PROMETHEE [7], COPRAS and VIKOR [8] method lead to the same results. But there might be results that do not match, for example, VIKOR, COPRAS and TOPSIS results [9] and MULTIMOORA and PROMETHEE [10] ranking results.

There are many MCDA methods and each method has its own definition of best alternative and it is not determined if using same input data in different MCDA methods will give the same results. To see how similar or different results might evolve from five MCDA methods – a comparison of TOPSIS, VIKOR, COPRAS, MULTIMOORA, and PROMETHEE-GAIA methods are made, using data about renewable energy technologies alternatives in Latvia. The alternatives applied are solar photovoltaic (Solar PV), wind power plants (WPP), hydropower plants (HPP) and biomass, and biogas combined heat and power (CHP) (Bio-energy CHP). To compare the methods, seven criteria are used about cost, $CO_2$ emissions and electrical capacity. After this comparison, it will be possible to see what results the MCDA methods provide, similar or different, and which renewable energy technologies are best for Latvia.

## 2. METHODS

MCDA methods can be selected by their properties and requirements. A summary of properties applies through the TOPSIS, VIKOR, COPRAS, MULTIMOORA, PROMETHEE-GAIA and AHP methods to select the most appropriate method by data and ranking type, software, input and output data are provided in Table 1. This comparison was done to see similarities and differences between methods.

In the Analytical Hierarchy Process (AHP) method, alternatives are listed and then compared pairwise according to their contribution to reaching each objective or criterion [1]. This method was developed by Thomas L. Saaty and is one of the popular methods to find weight of criteria.

For all selected methods subjective data are criteria weights. The TOPSIS method requires minimal input data and results are easy to understand and it is with shortest geometrical distance to ideal result [2]. The VIKOR method focuses on alternative ranking by closeness to best solution and the maximum and minimum values of the criteria give impact to result [3]. COPRAS method takes into account performance of the alternatives with best and worst values which affect the result [4]. With MULTIMOORA method it is possible to determine the objectives of conflicting criteria and it has a ratio system and reference point calculation method [5]. PROMETHEE-GAIA method is based on the computation of preference degrees and it shows which alternative would be more appropriate to solve the problem and how criteria weight impact alternative position [2].

TABLE 1. SUMMARY OF MCDA METHODS

| | TOPSIS | VIKOR | COPRAS | MULTIMOORA | PROMETHEE-GAIA | AHP |
|---|---|---|---|---|---|---|
| **Type of normalization** | Vector normalisation (square root of sum (L2 normalization) | Linear normalization (L1 normalization) | Vector normalization (sum) | Vector normalization (square root of sum) | Normalization is performed automatically | Vector normalisation (sum) |
| **Suitability** | Choice problems, ranking problems | Choice problems, ranking problems | Choice problems, ranking problems | Choice problems, ranking problems | Choice problems, ranking problems, description problems (GAIA) | Choice problems, ranking problems, sorting problems (AHPsort) |
| **Inputs** | Ideal and anti-ideal option weights | Best and worst option weights | Best and worst option weights | Best and worst option weights | Indifference and preference thresholds weights | Pairwise comparison on ratio scale (1–9) |
| **Outputs** | Complete ranking with closeness score to ideal and distance to anti-ideal | Complete ranking with closeness score to best option | Complete ranking | Complete ranking | Partial and complete ranking (pairwise outranking degrees) | Complete ranking with scores |
| **Preference function** | Distance metric (Euclidean distance, Manhattan distance, Tchebycheff distance) | Distance metric (Manhattan distance) | Min Max | Min Max | Usual, Linear, U-shape, V-shape, Level, Gaussian | |
| **Approach** | Qualitative and/or quantitative | Quantitative | Quantitative | Quantitative | Qualitative and/or quantitative | Qualitative |
| **Ranking scale** | 0 to 1 | Positive values | Positive values | Positive values | −1 to 1 | 0 to 1 |
| **Best alternative** | Max value | Min value | Max value | Max value | Max value | Max value |
| **Consistency levels** | no restrictions | no restrictions | no restrictions | no restrictions | 7±2 | 9 |
| **Software** | MS Excel, Matlab, Decerns | MS Excel | MS Excel | MS Excel | Visual Promethee, Decision Lab, D-Sight, Smart Picker Pro | MS Excel, MakeItRational, ExpertChoice, Decision Lens, HIPRE 3+, RightChoiceDSS, Criterium, EasyMind, Questfox, ChoiceResults, 123AHP, DECERNS |

### 2.1. INPUT DATA

Input data – criteria with values and alternatives – have been taken from 'Progress in renewable energy technologies: innovation potential in Latvia' [6] and are presented in Table 2. These data are used to find the best alternative for renewable energy production. In each method, data are the most important element to rank alternatives because these values are used in the calculation process.

TABLE 2. INPUT DATA

| Criteria | | Alternatives | | | |
|---|---|---|---|---|---|
| | | **Solar PV** | **WPP** | **HPP** | **Bio-energy CHP** |
| C1 | Installed electrical capacity, MW | 1 | 77 | 1565 | 155 |
| C2 | Investment cost, €/kW | 1238 | 3565 | 1388 | 1113.5 |
| C3 | Operation and maintenance cost, €/kW | 12.37 | 26.7 | 2.67 | 0.00446 |
| C4 | RES equipment prices by manufacturer, €/kW | 430 | 1380 | 1290 | 3787.5 |
| C5 | Levelled cost of electricity, €/kW | 0.08 | 0.06 | 0.09 | 0.075 |
| C6 | Life-cycle $CO_2$ emissions, $gCO_2eq/kWh$ | 200 | 150 | 150 | 200 |
| C7 | Job creation, thousands | 3095 | 1155 | 865 | 528 |

Data about installed electrical capacity (C1) shows maximum net production capacity of power plants in Latvia and are taken from the IRENA report on Renewable Capacity Statistics [7]. From Data for investment cost (C2) are from IRENA report on Renewable Power Generation Costs [8] and depend on alternative capacity and criteria levelled cost of electricity (C5) data which are average values for each alternative in Europe. The criteria operation and maintenance cost (C3) and RES equipment prices by manufacturer (C4) data are from the IRENA report on Renewable Power Generation Costs [8] and from Energy Outlook [9] and concern Europe. Life-cycle $CO_2$ emissions (C6) data are on Europe and are from the European Environment Agency (EEA) report on Renewable energy in Europe-2017 [10] and World Nuclear Association report data [11]. Job creation (C7) criteria data are from the IRENA review on Renewable Energy and Jobs [12] and pertain to alternatives in Europe.

For some MCDA methods it is important to know if it is better for the value of the criteria to be maximizing or minimizing. In this study, most criteria values are better to be minimizing and only electrical capacity and job possibilities are better to be maximising.

### 2.2. AHP

In the AHP method an important indicator is the number of criteria and it affects result consistency because more than seven criteria lead to an increase in inconsistency [22].

The AHP model facilitates the organization of the various variables in levels of hierarchy and it helps experts to evaluate criterion against criterion [23].

The AHP method equations (1) and (2) are [22]:
–  Define and value criteria (scale 1–9).
–  Calculate normalized matrix using Eq. (1):

$$X_{ij} = \frac{C_{ij}}{\sum C_{ij}} \; , \tag{1}$$

where
   $C_{ij}$    criteria value;
   $\sum C_{ij}$  column sum.
   Calculate priority vector from Eq. (2):

$$W_{ij} = \frac{\sum X_{ij}}{n} \; , \tag{2}$$

where
   $\sum X_{ij}$  normalized matrix column sum;
   $n$      number of criteria.
   In application of this AHP method to calculate weight it is important to use experts to evaluate criteria because this affects the alternative's values in the future when MCDA methods are using criteria weight.

When weights are calculated using the AHP method, these values can be used in every MCDA method. Also, after the AHP method, results can make conclusions about the indicated values and which indicator can solve the problem.

## 2.3. TOPSIS

The full name of the method is Technique for Order Preference by Similarity to Ideal Solutions. This method evaluates the distance of alternatives to ideal and anti-ideal point and alternative with shortest distance to ideal point is the best alternative. There are three distances in the TOPSIS method – Manhattan distance, Tchebycheff distance and Euclidean distance, which were all used in this study Eq. (1).

TOPSIS method Eq. (3), (4), (5), (6) and (7) are from [3]. Method described:

  – Calculate normalized matrix using Eq. (3):

$$R = \frac{X}{\sqrt{\sum X^2}} \; , \tag{3}$$

where
   $X$    criteria value;
   $\sum X$  sum of criteria value.

  – Calculate normalized weight matrix from Eq. (4):

$$V = R \times W \; , \tag{4}$$

where
   $R$    normalized matrix value;
   $W$   criteria weight.

  – Define the best and worst values of criteria: best values $V^+$= max and worst values $V^-$= min; best values $V^+$= min and worst values $V^-$= max.

– Use of formulas as shown in Eq. (5) and (6) to difference value from best or worst value:

$$d_a^+ = \sqrt{\Sigma(V^+ - v_a)^2} \, , \tag{5}$$

where
$V^+$    ideal or best value;
$v_a$    normalized weighted matrix value,

$$d_a^- = \sqrt{\Sigma(V^- - v_a)^2} \, , \tag{6}$$

where
$V^-$    non-ideal or worst value;
$v_a$    normalized weighted matrix value.

– Find the relative closeness and rank the alternatives using Eq. (7):

$$C_a = \frac{d_a^-}{d_a^+ - d_a^-} \, , \tag{7}$$

where
$d^-_a$    non-ideal or worst value;
$d^+_a$    ideal or best value.

The main difference between this and other methods is that TOPSIS uses best and worst value for each criterion and calculates the value of alternatives using gap between best and worst criteria. The smallest difference between best and worst values are the closer values for results of alternatives will be.

## 2.4. VIKOR

The full name of the method in Serbian is VlseKriterijumskaOptimizacija I KompromisnoResenj. In this method, an important factor is alternative closeness to the ideal solution and after that alternatives are ranked [13]. The Euclidean distance[14] is used in this method.
Eq. (8) and Eq. (9) are from [26]. Method described:

– Define best and worst value of criteria.
– Find values for best and worst values matrix using Eq. (8):

$$S = w \frac{f^* - f}{f^* - f^-} , \tag{8}$$

where
$w$    criteria weight;
$f$    criteria value;
$f^*$    best value of criteria (max or min);
$f^-$    worst value of criteria (min or max).

– Find values $S$, $R$ and $Q$ for each alternative:

$$Q = v\frac{S_j - S^*}{S^- - S^*} + (1 - v)\frac{R_j - R^*}{R^- - R^*},\tag{9}$$

where $v$ is decision making factor (if major agreement than $v \geq 0.5$, if consensual agreement than $v = 0.5$, if agreement with veto than $v \leq 0.5$), in this case $v = 0.5$;

$S_j = \sum w\frac{f^* - f_i}{f^* - f^-}$, $S^* = \min S_j$, $S^- = \max S_j$; $Rj = \max\left[w\frac{f^* - f_i}{f^* - f^-}\right]$, $R^* = \min R_j$, $R^- = \max R_j$.

In this method, there is not a normalized and normalized weights matrix as in the TOPSIS, COPRAS and MULTIMOORA methods.

### 2.5. COPRAS

The full name of the method is Complex Proportional Assessment. This method applies stepwise sorting and utility degree calculation which helps when there are conflicting criteria [4]. In order to achieve alternative sequencing after utility degree, the alternatives needs to be sorted in descending order [5].

The COPRAS method equations (10), (11), (12), (13), (14) and (15) are from [15].

Method described:

– Find normalized matrix from Eq. (10):

$$\overline{x_{ij}} = \frac{x_{ij}}{\sum x_{ij}},\tag{10}$$

where

$x_{ij}$     criteria values;
$\sum x_{ij}$     sum of criteria values.

– Find normalized weighted matrix from Eq. (11):

$$\widehat{x_{ij}} = \overline{x_{ij}} \times w,\tag{11}$$

where

$\overline{x_{ij}}$     normalized matrix values;

$w$     criteria weight.

– Determination of the maximizing index Eq. (12) and minimizing index Eq. (13):

$$P_j = \sum \widehat{x_{ij}},\tag{12}$$

$$R_j = \sum \widehat{x_{ij}},\tag{13}$$

where

$P_j$     maximizing index;
$R_j$     minimizing index;
$\widehat{x_{ij}}$     weighted normalized matrix.

– Using Eq. (14) find relative weights for every alternative:

$$Q_j = P_j + \frac{\sum R_j}{R_j \sum \frac{1}{R_j}},$$ (14)

where

$P_j$     maximizing index;
$R_j$     minimizing index.

– Calculate utility degree using Eq. (15):

$$N = \frac{Qi}{Q\max} \times 100\%.$$ (15)

In this method criteria value and all alternative sums are used to find values of normalized matrix, but in other methods, like TOPSIS, the criteria value and square root from sum of square is used to calculate values of alternatives.

### 2.6. MULTIMOORA

Full name of method is Multi-Objective Optimization on the basis of Ratio Analysis. MULTIMOORA is a system that optimizes conflicting alternatives to find the best result and is easy to apply to solve various problems [5].This method has an extended version where it is possible to work with a value interval [16].

Equations (16), (17), (18) and (19) for MULTIMOORA method are from [17]. Method described:

– Normalized matrix in Eq. (16):

$$X^* = \frac{x_i}{\sqrt{\sum x_i^2}},$$ (16)

where $x_i$ is criteria value.

– Calculate normalized weight matrix using Eq. (17):

$$Y = x_i \times w,$$ (17)

where:

$x_i$     normalized matric value;
$w$     criteria weight.

– Difference between max and min values for each alternative using Eq. (18):

$$y_i = \sum \max x_{ij}^* - \sum \min x_{ij}^*.$$ (18)

– Find alternatives values from Eq. (19):

$$U_i = \frac{\sum \max X_{ij}^*}{\sum \min X_{ij}^*}.$$ (19)

In this method, it is possible to use inverse formula of Eq. (19) and use the minimum value as the best alternative, if it is needed to compare with other methods where minimum values are the best alternatives as in case of the VIKOR method.

In this method it is quite important to calculate the difference between minimum and maximum values of criteria and the value of alternative

### 2.7. PROMETHEE-GAIA

PROMETHEE stands for Preference Ranking Organization Method for the Enrichment of Evaluations and GAIA stands for Graphical Analysis for Interactive Aid [30].

In the PROMETHEE method, criteria weight gives more impact than the values of the preference function threshold [30]. It is possible to choose preference functions and software can be used to arrange the criteria and their weights [30]. Calculations are made in the program Visual PROMETHEE academic.

## 3. RESULTS AND DISCUSSION

The AHP method pairwise comparison is made by assessing the importance of the criterion over the other criterion and the results are illustrated in Table 3. In pair comparison value 1 represents that both criteria are equally important, value 5 represents that one criterion is very important compared to other criteria and value 9 represents that one criterion is absolutely most important than other criteria. And for opposed criteria comparison values are proportionally opposed. This pairwise comparison was made by three experts from the field of environmental science.

After calculation criteria weight very important is to verify if $\sum W_{ij} = 1$ and consistency values, for this AHP consistency index (CI) is 0.127 and consistency ratio (CR) is 0.097. If CR > 10% then pairwise comparisons are inconsistent [2].

Table 4 contains all criteria and their weights. The most important criteria are installed electrical capacity with a weight 27 % and the next is job creation criteria with 22 % weight. The lowest impact on alternatives is from the criteria about levelled cost of electricity and on life-cycle $CO_2$ emissions.

Important value in the TOPSIS method is alternative closeness indicator which are final value for alternative and are in Table 5. Based on the results of the TOPSIS method, the best alternative is the hydroelectric power plant (HPP) followed by biomass and biogas CHP (Bio-energy CHP).

In accordance with the VIKOR method, the best alternative is that with the minimal value. Results of this method are in Table 6 and the best alternative is hydroelectric power plant (HPP) then solar PV. To compare VIKOR and other methods it is important to remember that in this method an important step is to minimize all criteria to make comparisons.

The COPRAS method is simple and most impact for best alternative is from criteria weight and index values. Based on this method, the best alternative is solar photovoltaic (Solar PV) and hydroelectric power plant (HPP). The values of alternatives are presented in Table 7. Best alternative in this method is Solar PV and worst alternative is wind power plants (WPP) and both alternatives have large difference in their final values and this might be because of these alternative values for each criterion.

TABLE 3. CRITERIA PAIRWISE COMPARISON

| | | C1 | C2 | C3 | C4 | C5 | C6 | C7 |
|---|---|---|---|---|---|---|---|---|
| | | Installed electrical capacity, MW | Investment cost, €/kW | Operation and maintenance cost, €/kW | RES equipment prices by manufacturer, €/kW | Levelled cost of electricity, €/kW | Life-cycle $CO_2$ emissions, $gCO_2eq/kWh$ | Job creation, thousands |
| C1 | Installed electrical capacity, MW | 1 | 6 | 5 | 2 | 3 | 2 | 0.5 |
| C2 | Investment cost, €/kW | 0.17 | 1 | 1 | 1 | 2 | 2 | 0,5 |
| C3 | Operation and maintenance cost, €/kW | 0.2 | 0.5 | 1 | 2 | 2 | 3 | 0.5 |
| C4 | RES equipment prices by manufacturer, €/kW | 0.5 | 1 | 0.5 | 1 | 2 | 2 | 0.5 |
| C5 | Levelled cost of electricity, €/kW | 0.33 | 0.5 | 0.5 | 0.5 | 1 | 2 | 0.5 |
| C6 | Life-cycle $CO_2$ emissions, $gCO_2eq/kWh$ | 0.5 | 0.5 | 0.33 | 0.5 | 0.5 | 1 | 0.5 |
| C7 | Job creation, thousands | 2 | 2 | 2 | 2 | 2 | 2 | 1 |

TABLE 4. CRITERIA VALUES AND WEIGHTS

| | |
|---|---|
| Installed electrical capacity, MW | 27 % |
| Investment cost, €/kW | 12 % |
| Operation and maintenance cost, €/kW | 13 % |
| RES equipment prices by manufacturer, €/kW | 11 % |
| Levelled cost of electricity, €/kW | 8 % |
| Life-cycle $CO_2$ emissions, $gCO_2eq$/kWh | 7 % |
| Job creation, thousands | 22 % |

TABLE 5. TOPSIS RESULT AND RANK

| A1 | A2 | A3 | A4 |
|---|---|---|---|
| Solar PV | WPP | HPP | Bio-energy CHP |
| 0.33 | 0.16 | 0.77 | 0.28 |
| 2 | 4 | 1 | 3 |

TABLE 6. VIKOR RESULTS AND RANK

| A1 | A2 | A3 | A4 |
|---|---|---|---|
| Solar PV | WPP | HPP | Bio-energy CHP |
| 0.67 | 0.92 | 0 | 0.81 |
| 2 | 3 | 1 | 4 |

TABLE 7. COPRAS RESULTS AND RANK

| A1 | A2 | A3 | A4 |
|---|---|---|---|
| Solar PV | WPP | HPP | Bio-energy CHP |
| 1.94 | 0.86 | 1.47 | 0.93 |
| 1 | 4 | 2 | 3 |

Results from the MULTIMOORA method is in Table 8 and the best alternative is solar photovoltaic (Solar PV) and hydroelectric power plant (HPP). Final values have large range and it's because final values are calculated from difference between the minimum and maximum values

TABLE 8. MULTIMOORA RESULTS AND RANK

| A1 | A2 | A3 | A4 |
|---|---|---|---|
| Solar PV | WPP | HPP | Bio-energy CHP |
| 3.25 | 0.47 | 1.93 | 0.28 |
| 1 | 3 | 2 | 4 |

Table 9 contains results from the PROMETHEE-GAIA method and the complete ranking is based on net preference flow (Phi) which is a balance between positive preference flow (Phi+) which

measures strength and negative preference flow (Phi−) that represents weakness. In this case, the preference function is linear and thresholds are absolute. In accordance with this method, the best alternative is the hydroelectric power plant (HPP) and solar photovoltaic (Solar PV).

TABLE 9. COMPLETE RANKING

|      | A1       | A2      | A3      | A4             |
| ---- | -------- | ------- | ------- | -------------- |
|      | Solar PV | WPP     | HPP     | Bio-energy CHP |
| Phi  | 0.0100   | −0.2567 | 0.2833  | −0.0367        |
| Phi+ | 0.4533   | 0.3200  | 0.5900  | 0.4300         |
| Phi− | 0.4433   | 0.5767  | 0.3067  | 0.4667         |

PROMETHEE rankings results can be displayed as PROMETHEE Diamond in Fig. 1. In the PROMETHEE Diamond, each alternative has point on the (Phi+, Phi−) plane and the vertical dimension (green-red axis) corresponds to the Phi net flow which is a balance point [18].
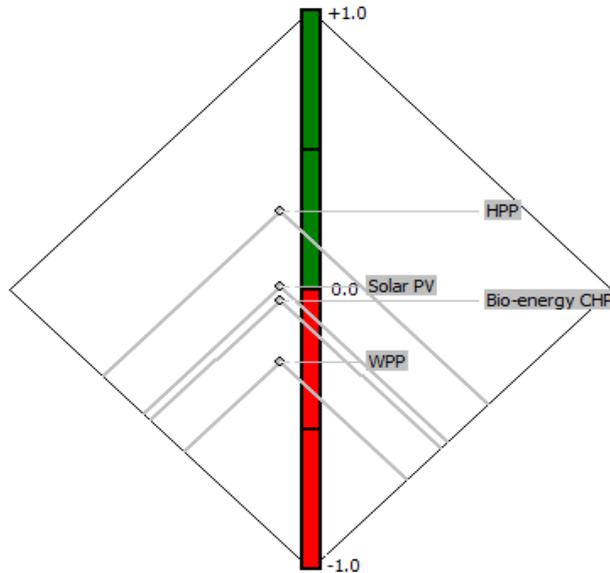


Fig. 1. PROMETHEE Diamond.

Fig. 2 illustrates the PROMETHEE Network and shows which alternative is better and helps to compare alternatives. The network representation is like a close-up of the Diamond view where the distances between the alternatives are displayed [30].
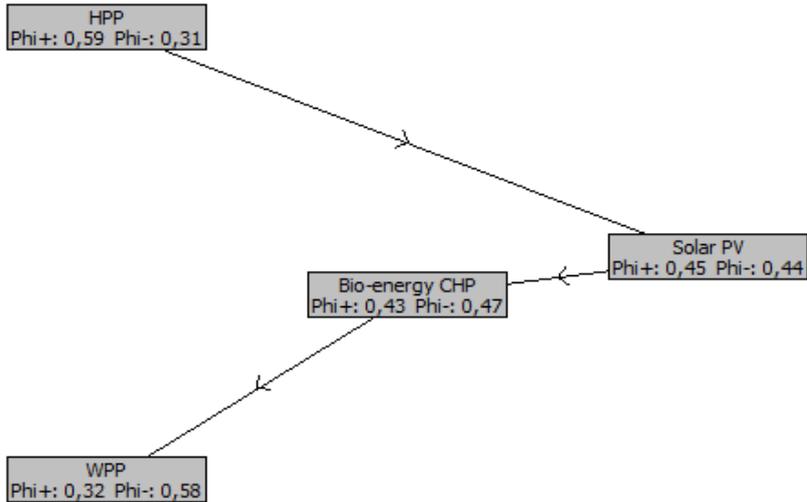
Fig. 2. PROMETHEE Network.

The PROMETHEE Rainbow is shown in Fig. 3 where every alternative's strong and weak criterion is depicted. Positive (upward) slices represents criteria that positively affects the alternative and negative (downward) slices represent criteria that give a negative effect to the alternative [18].
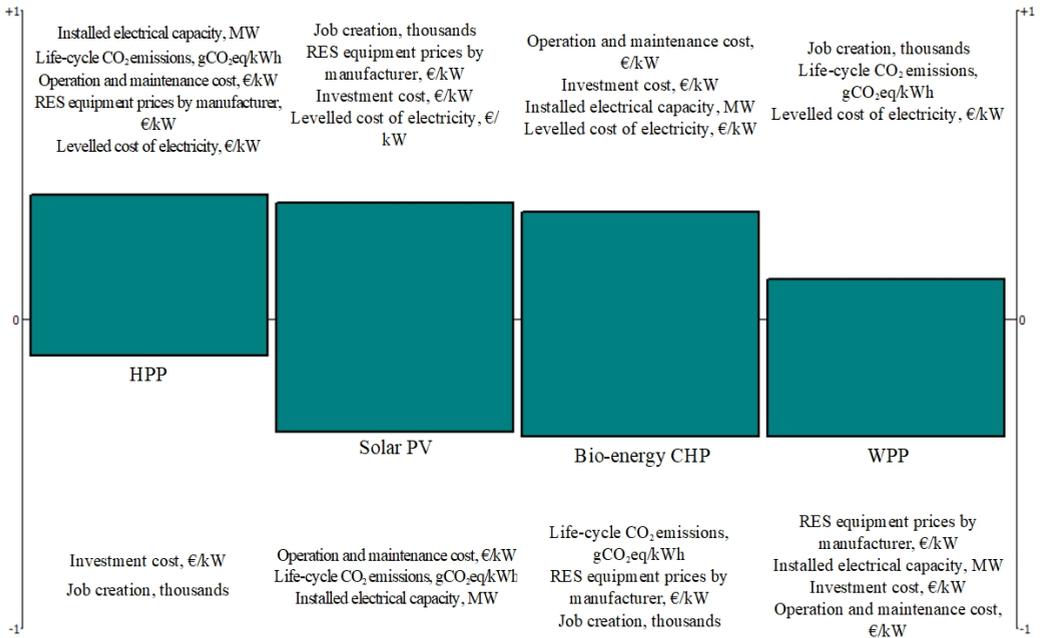


Fig. 3. PROMETHEE Rainbow.

For the hydroelectric power plant (HPP) alternative, weakness stems from investment cost and job creation and after this method it is the best alternative. For wind power plants (WPP) which are the worst alternative, there are only three good criteria – job creation, life-cycle $CO_2$ emissions and levelled cost of electricity.

After five Multi-criteria decision analyses – TOPSIS, VIKOR, MULTIMOORA, COPRAS and PROMETHEE-GAIA, Table 10 provides a summary of all final values for each alternative. For TOPSIS, VIKOR and PROMETHEE-GAIA methods the best alternative is hydroelectric power plant (HPP) and in accordance with the other 2 methods, HPP is ranked second. But in COPRAS and MULTIMOORA methods, the best alternative is solar photovoltaic (Solar PV). The most impact for the final results is from criteria weights and methods definition of best alternative - closeness indicator to ideal distance, closeness score to best option, pairwise outranking or ranking with scores. The best value of the criteria – minimum or maximum – is also an important indicator.

TABLE 10. ALTERNATIVE VALUES AND RANKING

|  | Solar PV | WPP | HPP | Bio-energy CHP |
|---|---|---|---|---|
| **TOPSIS** | 0.33 | 0.16 | 0.77 | 0.28 |
|  | 2 | 4 | 1 | 3 |
| **VIKOR** | 0.67 | 0.92 | 0 | 0.81 |
|  | 2 | 3 | 1 | 4 |
| **COPRAS** | 1.94 | 0.86 | 1.47 | 0.93 |
|  | 1 | 4 | 2 | 3 |
| **MULTIMOORA** | 3.25 | 0.47 | 1.93 | 0.28 |
|  | 1 | 3 | 2 | 4 |
| **PROMETHEE-GAIA** | 0.01 | −0.26 | 0.28 | −0.04 |
|  | 2 | 4 | 1 | 3 |

The results from MCDA methods are reflected in Fig. 4 and they are ranked from best to worst alternative. After this result is displayed in the diagram, it is easier to see the trend in terms of which alternatives are ranked higher than others. The best alternative would be hydroelectric power plant (HPP) and then solar photovoltaic (Solar PV) because these alternatives are in first or second position in comparison with most of the other alternatives.
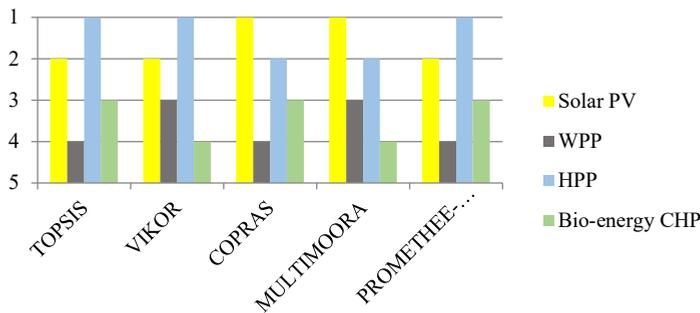


Fig. 4. Result rank of MCDA methods.

The lowest rank is for the wind power plants (WPP) alternative because in 3 out of 5 methods it is in the last place. For this alternative minimal and maximal criterion values are lowest rates which impact final ranking.

## 4. CONCLUSION

The aim of this paper was to use same input data for five MCDA methods and to see if alternatives ranking would be the same or different for each method and of course to see which is the best renewable energy technology for Latvia. Five MCDA methods – TOPSIS, VIKOR, COPRAS, MULTIMOORA and PROMETHEE GAIA have been chosen because they have different approaches on how to calculate alternatives values and there it was possible to use criteria which can be definite minimum or maximum as best value.

The same results were not obtained for all methods but in all methods two alternatives were in the first two places as best alternatives - hydroelectric power plant (HPP) and solar photovoltaic (Solar PV). On the basis of seven criteria, the best renewable energy technology for Latvia is hydroelectric power plant (HPP) and it is because in the most valuable criteria installed electrical capacity (27 %) in this alternative had best results from all energy alternatives.

The results of five MCDA methods have produced different results, but with a similar trend to best alternative. It's not really objective to compare the results obtained by different methods because results are similar but not the same. To get more reliable results and for comparison use one methodology for problem and sub-problem. MCDA methods are developing with new modules and software's which are more specific and helpful to solve problems. Methods can be chosen after goal of result, method approach, input and output type, used software and suitability for the problem.

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# GHG Performance Evaluation in Green Deal Context

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*Abstract* – **Recently introduced European Green Deal has set a target for Europe to become the first climate-neutral continent by 2050. This ambitious commitment will bring a serious challenge for the EU. However, the degree of this challenge will not be the same to all EU member states. In this paper, the multi-criteria decision analysis is applied to rank eight selected EU countries (Denmark, Estonia, Ireland, Latvia, Lithuania, Slovenia, Finland and Sweden) regarding GHG performance, and thus illustrate different starting points of the transition to carbon-neutrality. In parallel to the widely used indicator of GHG emissions per capita, evaluation incorporates various other criteria covering energy consumption, population size, and the use of renewable energy and fossil fuel, as well as investment and tax rates. TOPSIS analysis shows that the best GHG performance is achieved by Sweden, while Latvia ranks the lowest. The presented evaluation method could be a useful tool in planning implementation of policies to reach Green Deal settings on European, as well as on a national level.**

*Keywords* – **Country ranking; European Green Deal; greenhouse gas (GHG) emissions; TOPSIS.**

## 1. INTRODUCTION

The newly introduced European Green Deal has set a particularly ambitious target for Europe to become climate-neutral by 2050. It requires to reduce GHG emissions by 50–55 % by 2030 in comparison to the levels of 1990, and to reach net-zero GHG emissions by 2050 [1]. To clearly illustrate the ambitious extent of this target, it can be mentioned that the EU GHG emissions were reduced by 22 % in 2017, compared to 1990 levels. In order to achieve full reductions up to 100 % by 2050, EU must reduce its GHG emissions by additional 78 % throughout the next 30 years. Although it is determined, that emissions not mitigated by 2050 will be removed, e.g. via natural carbon sinks such as forests and carbon capture and storage technologies [2], there are still uncertainties concerning carbon storage in geological structures related to long-term leakage and safety, as well as storage in oceans due to possible negative impacts on ecology [3]. In addition, carbon storage technologies can be expensive [4]. Meanwhile, the possibilities for increasing natural carbon sequestration are ambiguous, taking into consideration the growing demand for bio resources. This confirms that the primary focus must be on reducing emissions to the maximum already at the production stage. Considering the past progress in emission reduction, introduction of the Green Deal will demand a completely new approach to the economy and quite drastic

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measures in all sectors of economy. It is clear it will possess serious challenge for all EU countries. However, it is also obvious that the starting point differs widely, bringing variations in the degree of challenge.

In this paper multi-criteria decision analysis (MCDA) is applied to determine the present position of eight selected EU countries (Denmark, Estonia, Ireland, Latvia, Lithuania, Slovenia, Finland and Sweden) in terms of GHG performance. Various indicators are applied, along with GHG emissions considering economic, political, and social and energy consumption factors. This comparison allows determining what the starting points for various countries are and which could take the lead in reaching carbon neutrality. Moreover, taking into account that countries influence each other's energy, environment and economic conditions [5], such comparison can be useful in researching the links between countries. Regarding Latvia, it gives the opportunity to detect its position compared to other EU countries and to judge on the required intensity of the necessary measures. For countries at worse GHG positions, this comparison shows the roadmap for the implementation of successful policies.

## 2. EVALUATION OF GHG PERFORMANCE

Greenhouse gas inventory, prepared by the European Environment Agency (EEA), ranks the EU countries according to the total amount of their GHG emissions. On the EU level, progress in GHG emission reduction is mainly measured by the annual changes of the total GHG amount, changes since 1990 and (or) regarding the achievement of national targets [6]. Although, the criterion regarding carbon-neutrality achievement is net GHG emissions, implementation of various indicators allows determining how advantageous countries are in terms of GHG emission reduction.

GHG performance is often evaluated as a part of a broader environmental performance and sustainability assessments [7]–[9]. Along with direct GHG indicators, such as the total GHG emissions per country or GHG emissions per capita, such evaluations often include factors, which do not directly express the GHG emissions while still being closely related. Such factors include: the share of renewable energy [7]–[12], energy consumption [7], [8], [10], [11], environmental or energy taxes [7], [9], [10], [12], environmental protection expenditure [12] and others.

There are few studies investigating environmental indicators with the aim to evaluate GHG performance. Some are discussed below. Also, many studies have focused on the drivers of GHG emission reduction. Arguably, the most important are the increase of energy efficiency [13]–[15] and renewable energy [9], [13]. Although, [15] reported that the impact of the share of renewable energy was insignificant in GHG emission reduction, while policies to increase energy efficiency were assessed to have a greater impact.

Lately countries are often grouped into categories according to their GHG performance as an attempt to give a general demonstration of similarities and differences and search for correlations. For example, [16] established a method of four quadrants to compare the countries' performance in emission intensity, carbon removal rate, and net reduction rate of GHG emissions from 1991 to 2012. Such division is based on absolute emission quantity, as well as relative emission quantity (the ratio of GHG emissions and GDP) and trends in GHG emissions (the annual net reduction of GHG emissions). According to [16] related calculations, Latvia was the only country in the EU28 to report net GHG removal in 2012. Latvia along with other countries, including Lithuania and Estonia, was grouped in Quadrant I, representing countries with high emission intensities and high carbon removal rates. On the contrary, Germany stood out with significantly high net GHG emissions. However, due to Germany's low emission intensity it was located in Quadrant III representing countries with low emission intensities and low carbon removal rates. Quadrant II

grouped countries representing low emission intensities and low carbon removal rates (for instance, Sweden), while Quadrant IV grouped countries with high emission intensities and low carbon removal rates (e.g. Poland).

Meanwhile, [17] grouped the EU countries into clusters according to their similarities in emissions of four types of GHG to examine the diversity of European countries in terms of GHG emissions. Four clusters regarding the application of k-means algorithm and Euclidian distance have been developed. The clusters were classified according to the amount of emissions. In this evaluation, two approaches were used – the total GHG emissions per country and the GHG emissions per capita. Grouping of the total emissions and grouping of the emissions per capita resulted in different sizes of clusters, which highlighted the question of whether countries should be evaluated by their total emissions or emissions per capita. A similar study [18] grouped countries into clusters by applying agglomeration algorithm. In other investigations [15], [16], [18] countries were evaluated by a narrow set of indicators, and the purpose of such evaluations was to group countries rather than to compare to each other in order to assess the best and the worst performances. The aim of this paper is to rank the selected EU countries according to their GHG performance by offering a set of economic, political, and social indicators.

## 3. GHG EMISSION PROFILE OF THE SELECTED EU COUNTRIES

For the comparison of GHG performance, eight EU countries have been selected, ensuring that different national environmental, economic and political backgrounds are covered. The main point of reference for selecting countries for comparison was the GHG intensity of energy consumption. Latvia was chosen as the main focus of analysis, alongside Ireland and Slovenia, classified as medium GHG intense. Estonia and Lithuania were selected as the countries with high GHG intensity, whereas Finland, Denmark and Sweden were chosen to represent countries with relatively low GHG intensity.

Eurostat data analysis from 2005 to 2015 indicates that Estonia had the highest average GHG emissions per capita (15.2 t $CO_2$ eq./capita) (Fig. 1), followed by Ireland (14.4 t $CO_2$ eq./capita), while the lowest GHG emissions were achieved by Latvia (5.7 t $CO_2$ eq./capita), Sweden (6.7 t $CO_2$ eq./capita) and Lithuania (7.1 t $CO_2$ eq./capita).
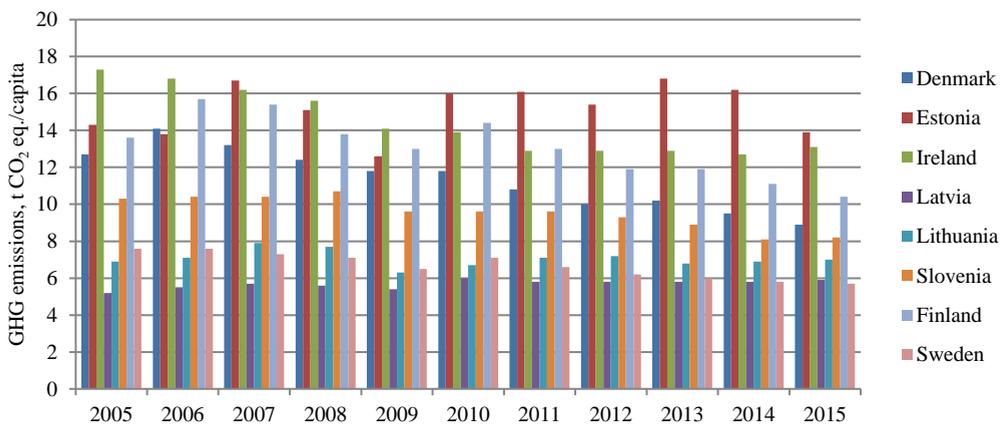


Fig. 1. GHG emissions per capita.

During the studied period, Sweden had the best performance regarding renewable energy consumption. All countries have made improvements in the share of renewable energy. Some countries such as Sweden, Finland, and Denmark have made improvements by more than 10 % in a 10-year-period.

In terms of environmental taxes, Denmark had the highest performance. Denmark has the second highest tax rate in the EU energy sector. Slovenia has been approaching Denmark's environmental tax revenues since 2012, as Slovenia has higher tax rate on transport fuels than on fuels used for energy production – heating or electricity.

From all selected countries, Estonia has the highest $CO_2$ emissions, which is the second highest value in the EU after Luxembourg. The main reason for the high emissions in Estonia is electricity production from oil shale, which accounts for about 90 % of the total $CO_2$ pollution, and recently oil shale has also been used for liquid fuel (diesel) production [19]. However, Estonia has set ambitious goals to increase electricity production from biomass [20]. Ireland is also a significant source of $CO_2$ emissions with most of the emissions coming from industry and agriculture [21], and Finland, where emissions from energy sector are mainly generated by utilization of natural gas and peat [22]. Overall, in a 10-year-period, emissions are decreasing periodically, except for Estonia where the trend is uneven.

The total consumption of solid fossil fuel is low in Estonia, Latvia and Lithuania in comparison to other selected countries. Generally, the consumption of solid fossil fuels is decreasing. Finland stands out with significantly high values for this indicator because over half of its heat is generated from solid fossil fuels.

Households hold an important position in the total energy consumption and represent the overall energy consumption image of a population. Household energy consumption per capita is the lowest in Lithuania, while Finland scores the highest. All the selected countries have reduced their household energy consumption over recent years.

Eurostat data indicates that the investment share of GDP was high during a period from 2005 to 2008 for all selected countries, and in 2009 it decreased by 10 % on average, which can be related to the global financial crisis. However, the investment share for all countries started to increase afterwards. The highest average investment share was in Estonia (28.5 %).

## 4. METHODOLOGY

### 4.1. Methodology Algorithm

The evaluation process consisted of four main steps (Fig. 2). First, eight EU countries for the comparison have been selected. Next, criteria for GHG performance evaluation have been chosen, followed by the determination of their importance with the application of AHP (Analytic hierarchy process). Lastly, the ranking of countries' GHG performance was made using the TOPSIS method.



Fig. 2. Methodology algorithm.

MCDA (Multi-criteria decision analysis) is a set of processes by which problems are solved, when problems, alternatives and criteria are defined. There are dozens of methods for calculating the best alternatives, according to a set of criteria. Because of the opportunity to easily compare different alternatives, TOPSIS (Technique for Order Preference by Similarity to Ideal Solutions) method was chosen for this evaluation. The basic principle is that the best alternative is at the shortest distance to the ideal solution and at the furthest distance to the negative-ideal solution [23]. As far as the TOPSIS method is concerned, it is important to define the best and the worst values for criteria. The best alternative is the one with the highest value.

AHP (Analytic hierarchy process) was developed by Thomas L. Saaty. It is one of the most popular methods used for finding criteria weight. With this method, all criteria are listed and then compared pair-wise according to their importance (contribution to reaching an objective) [24]. All criteria are compared to each other assigning values from 1 to 9. After calculations, each criterion has a weight and is further used in ranking alternatives.

### 4.2. Selection of Criteria

Based on the information provided in literature, as well as considering the available data, six criteria were chosen for the evaluation of GHG performance (Fig. 3). GHG emissions per capita were chosen as a widely used indicator in many studies and EU reports, as well as a basic representative factor of countries' emissions level. Income from environmental taxes was selected as an indicator representing the overall role of environmental protection in the national tax system, expressed as a percentage of the total income from taxes. Household energy consumption per capita was expressed as kg of oil equivalent, and it allowed to easily compare the energy needs of population.

Investment share of GDP is an indicator used to monitor progress towards EU Sustainable Development Goals and represents the level of economic productivity. Consumption of solid fossil fuels was chosen as a basic representative of the amount of the main GHG generating fuels, and was expressed in absolute values of thousand tonnes. Last, renewable energy consumption represents the achievements towards clean energy, and was expressed as a share of consumed renewable energy in gross final energy consumption.
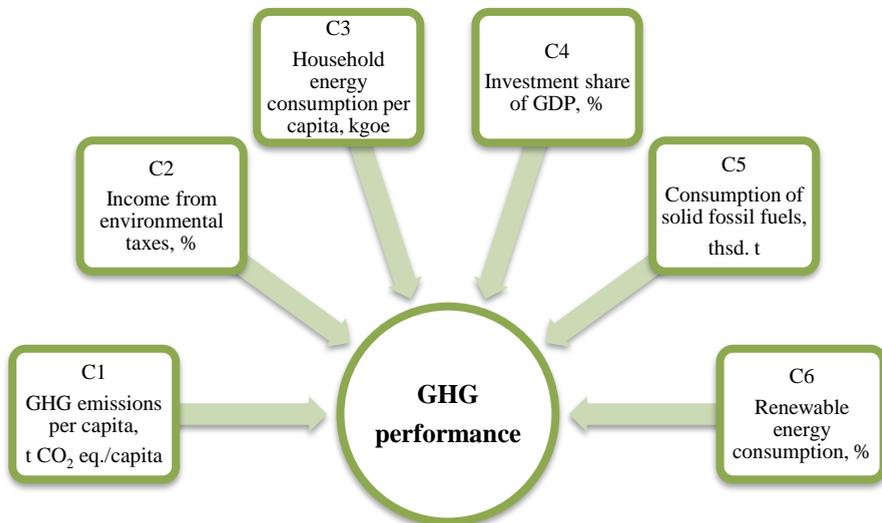


Fig. 3. GHG performance criteria.

### 4.3. *Evaluation of Criteria Weight*

After defining criteria, their weight was evaluated. All criteria were compared in pairs and attributed with values on a scale from 1 to 9, where 1 means that the criteria are equally important and 9 means that one criterion is absolutely more important than the other comparable criterion. Criteria weights were determined with expert judgement method. Two experts of the environmental science participated in the evaluation process. The mean values from expert judgements can be seen in Table 1.

Criterion with the highest attributed importance was GHG emissions per capita (32 %), while all other criteria were significantly less important. In addition, Table 1 indicates the desired direction for criteria values. Minimal values are desired for GHG emissions, energy consumption, investment from GDP and solid fuel consumption criteria, while the maximal values are desired for income from environmental taxes and renewable energy consumption. AHP analysis gave a consistency index (CI) of 0.118 and consistency ratio (CR) of 0.095 indicating that the pair-wise comparisons are consistent.

TABLE 1. CRITERIA WEIGHTS

| Criteria | | Weight | Best values |
|---|---|---|---|
| C1 | Greenhouse gas (GHG) emissions per capita | 32 % | MIN |
| C2 | Income from environmental taxes | 19 % | MAX |
| C3 | Household energy consumption per capita | 15 % | MIN |
| C4 | Investment share of GDP | 13 % | MIN |
| C5 | Solid fuel consumption | 13 % | MIN |
| C6 | Renewable energy consumption | 8 % | MAX |

The statistical indicator values for each country were obtained from Eurostat database for a time period from 2005 to 2015. Data were normalised after MIN-MAX normalisation. Input data for TOPSIS is presented in Table 2.

TABLE 2. TOPSIS INPUT DATA

| | | A1 | A2 | A3 | A4 | A5 | A6 | A7 | A8 |
|---|---|---|---|---|---|---|---|---|---|
| | | **Denmark** | **Estonia** | **Ireland** | **Latvia** | **Lithuania** | **Slovenia** | **Finland** | **Sweden** |
| C1 | Greenhouse gas (GHG) emissions per capita | 0.481 | 0.613 | 0.760 | 0.602 | 0.472 | 0.559 | 0.741 | 0.517 |
| C2 | Income from environmental taxes | 0.282 | 0.500 | 0.797 | 0.494 | 0.273 | 0.527 | 0.614 | 0.565 |
| C3 | Household energy consumption per capita | 0.552 | 0.432 | 0.575 | 0.632 | 0.615 | 0.558 | 0.411 | 0.573 |
| C4 | Investment share of GDP | 0.420 | 0.470 | 0.442 | 0.419 | 0.355 | 0.412 | 0.466 | 0.319 |
| C5 | Solid fossil fuel consumption | 0.475 | 0.469 | 0.382 | 0.615 | 0.484 | 0.696 | 0.435 | 0.612 |
| C6 | Renewable energy consumption | 0.434 | 0.530 | 0.465 | 0.445 | 0.388 | 0.549 | 0.421 | 0.539 |

## 5. RESULTS

Results of the TOPSIS analysis indicate that the best GHG performance is reached by Sweden, which achieved a coefficient of 0.64 (Table 3). Sweden was expected to rank first, as it has showed high performance in other studies evaluating sustainability and environmental performance (e.g. [9] and [11]). Also, it has one of the lowest GHG emissions per capita and the share of renewable energy is one of the highest as well. Regarding other indicators, Sweden reached average score, except for solid fossil fuel consumption, where it takes the second worst place. Although, it is noteworthy that solid fossil fuel consumption is an absolute value, and therefore Sweden's poor performance for this indicator may be explained by the size of its population and industry or other factors related to consumption of resources.

TABLE 3. RESULTING COUNTRY COEFFICIENTS

| Denmark | Estonia | Ireland | Latvia | Lithuania | Slovenia | Finland | Sweden |
|---------|---------|---------|--------|-----------|----------|---------|--------|
| A1 | A2 | A3 | A4 | A5 | A6 | A7 | A8 |
| 0.463 | 0.497 | 0.538 | 0.424 | 0.457 | 0.499 | 0.481 | 0.644 |
| 6 | 4 | 2 | 8 | 7 | 3 | 5 | 1 |

Despite the highest GHG emissions per capita, Ireland ranks second in GHG performance evaluation (Fig. 4). Ireland's relatively good performance can be explained by its outstandingly high score for the income from environmental taxes, which was the second most important criterion, as well as the significantly low consumption of solid fossil fuels.

Meanwhile, Latvia showed the lowest GHG performance. The main reason for that could be the significantly high score for household energy consumption per capita, where Latvia holds the worst position. Consumption of solid fossil fuels plays a relatively important role as well, while other indicator values were considered rather average.
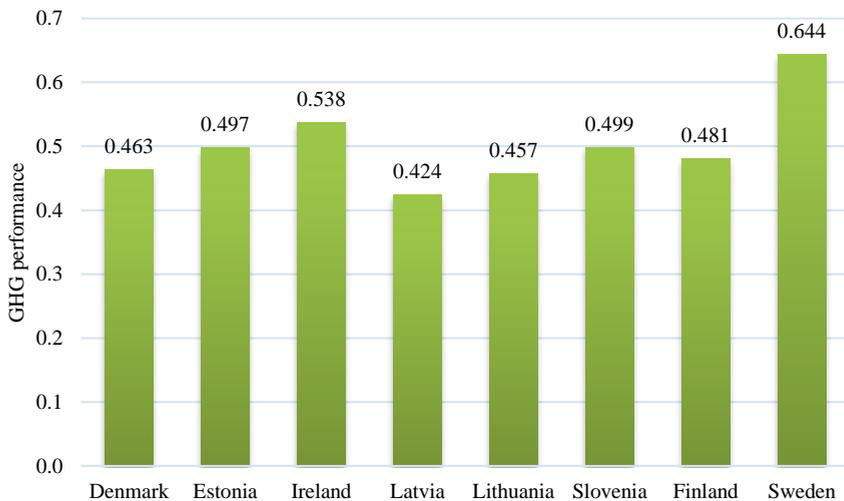


Fig. 4. Ranking of countries' GHG performance.

However, it is important to consider that evaluations were made from the average values for a period from 2005 to 2015, therefore, development trends of indicator values were not considered.

For example, the share of income from environmental taxes in Latvia has a lower indicator value than Ireland, while, in 2015, Latvia had a share of environmental taxes of 3.52 % and Ireland had a share of 1.88 % from GDP.

Denmark ranks nearly the second worst in GHG performance ranking. Denmark had average values for most of the criteria, without taking any top or bottom positions. However, its score decreased because of the low share of income from environmental taxes.

The results indicate that Estonia and Slovenia perform almost equally in terms of GHG performance. Both countries have similar values for most indicators. Nevertheless, Slovenia has higher household energy consumption and solid fossil fuel consumption, while Estonia has the second lowest household energy consumption per capita.

In the performed GHG ranking, Lithuania takes the second worst place, achieving slightly higher coefficient than Latvia. This result is somewhat surprising, considering that Lithuania had the best score for GHG emissions per capita, which is an indicator of significantly high importance. Still, Lithuania performs the worst for the share of income from environmental taxes and renewable energy consumption which arguably results in the low overall GHG performance.

## 6. CONCLUSION

The aim of the paper was to rank selected EU countries according to their GHG performance. Several indicators were implemented, covering aspects of energy consumption, as well as considering political (environmental taxes), economic (investment) and social (population size) factors. The ranking was performed with TOPSIS method, which allowed a simple comparison of the criteria.

Results indicate that from all the compared countries Sweden is at the most desired position in terms of GHG performance and has the most promising starting point to achieve carbon-neutrality by 2050. Sweden had relatively good values for the most of the selected criteria, and therefore its implemented policies could work as an example for other countries.

Despite the fact that Latvia performs rather well in many environmental and sustainability assessments of the EU countries (e.g. [10] and [15]), results show that it holds the lowest position in terms of GHG performance in comparison to the other selected EU countries. This indicates that achievement of carbon neutrality by 2050 will be a particular challenge to Latvia. Results suggest that one of the focus points for Latvia should be reducing its energy consumption, which, arguably, can be achieved by increasing energy efficiency.

Although some countries perform better than others in terms of GHG performance, it has been highlighted that the current policies will only reduce EU's GHG emissions by 60 % by 2050 [1], therefore, all countries need to take drastic measures in reorganizing their policies to achieve clean energy and sustainable economy.

Further studies should arguably focus on:
- Implementation of additional indicators to arrive at a more precise countries' ranking;
- Application of quantitative data for the determination of criteria weights;
- Application of methods that allow to investigate connections between indicators, thus revealing the necessary focuses for policy development;
- Consideration of the past progress of indicator values, which would make the evaluation more future-oriented.

With the above-mentioned and other slight improvements, the presented GHG performance evaluation could be a useful tool in planning the implementation of policies to reach the Green Deal settings on European, as well as on a national level.

## ACKNOWLEDGEMENT

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# Spatial energy data acquisition for agricultural sector. Latvia case study

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*Abstract*—**The agricultural sector consumes significant amounts of energy and resources to produce food and other products. Different complex modeling methods have been used to forecast future development trends in agriculture. However, it is crucial to collect in-depth sectoral data to analyse the energy consumption by region and identify different types of energy used for different agricultural processes. The article presents the methodology for data acquisition in the particular sector for the Latvia case study. After processing the spatial data on different agricultural subsectors, it can be concluded that Zemgale region is the largest energy consumer in the Latvian economy. By subsector, crop production is the largest energy consumer. The most common energy sources are diesel, biogas, and electricity. Data can be further used for different energy policy models and energy consumption forecasting.**

*Keywords— agricultural sector analyses; energy consumption; data processing; energy efficiency.*

## I. Introduction

The agricultural sector plays a crucial role in society as a reliable source of nutrition, materials, and products and ensures employment. However, this sector also faces environmental challenges by reducing biodiversity, polluting the environment with nitrogen, phosphorus, and pesticides, and high freshwater consumption. Moreover, productivity should be increased due to population growth [1].

The agricultural sector is one of the most energy-intensive sectors, and agriculture (including forestry) accounts for 18.4% of total global GHG emissions [2]. It is the world's second-largest emitter of GHG emissions [3]. Energy is directly used in cultivation, animal husbandry, and product transportation, while indirect energy is used off-farm to produce and transport fertilizers, pesticides, and machines [4]. As the use of agricultural machinery and various technologies increases, so does the energy consumption of the agricultural sector, which of course, has an impact on the environment [5].

In Europe, agricultural sector trends of arable land for crop production vary from country to country due to the predominance of rapeseed and maize instead of wheat, rye, or potatoes [6]. In the European Union, 47% of the land is used for the agriculture sector, and 50% of the agricultural sector accounts for the agricultural crop sub-sector [4]. According to 2015 data, the agricultural sector in Europe produces 11% of GHG emissions [7]. 60% of all agricultural emissions come from livestock, most from dairy and beef cattle (80%), followed by pig farming (16%) and poultry (4%) [8].

The agricultural sector in Latvia is continuously developing. In 2019 there were 75.8 thousand farms with an average size of 38.3 ha, which is by 8.8 ha (30%) more than in 2010 [9]. As a result, the average usable land per farm has increased from 19.6 ha (in 2010) to 26.0 ha (in 2019).

According to 2017 data on land use in Latvia (see Figure 1), agricultural land accounts for 36% or 2.32 million ha. The area of agricultural land in Latvia increased by 153.9 thousand ha or 8.5%, reaching 1 959.4 thousand ha in 2019 [9]. The arable land occupies 67% of the total agricultural land, and in 2019 it increased by 1.8%. The most arable land is in the Kurzeme and Zemgale regions, occupying about 80% of agricultural land [9].
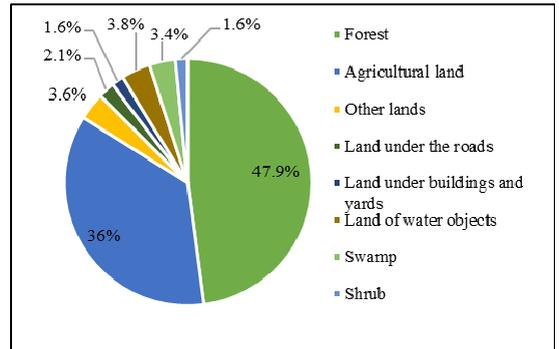


Fig. 1. Use of land in Latvia, 2017 [10]

In Latvia agricultural sector in 2017 consisted of crop production (43%), dairy farming (15%), pig and poultry farming (6%), and mixed crop and livestock production (15%) [11]. In the livestock sector in Latvia, pig farming, ensuring the largest share of meat production in the country, and beef production is gradually developing and can provide high-quality products.

Energy balance data about consumed energy in the agricultural sector show that total energy consumption has increased from 5062 TJ in 2008 to 8526 TJ in 2020 [12]. Energy consumption has increased for oil products, wood

biomass and electricity, while natural gas use has decreased (see Figure 2).
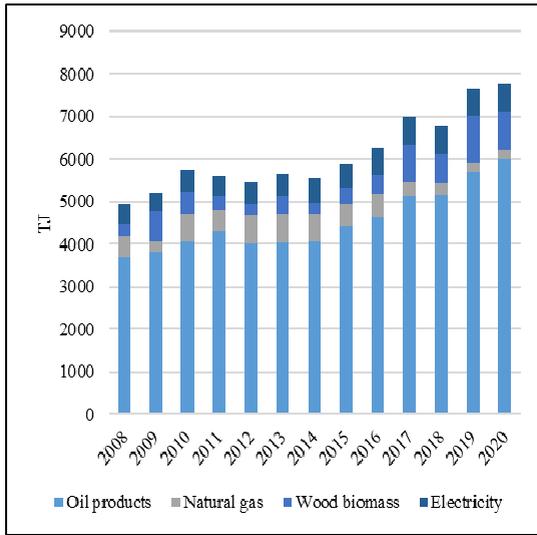


Fig.2. Consumed energy in the agricultural sector 2008 and 2020 [12]

Several studies have analyzed the agricultural sector and pollution. There is research on the environmental impacts of European agriculture on water, air, and soil quality, biodiversity, and climate change [13]. Researchers also model the economic costs of emissions from the agricultural sector and water pollution [14]. The agricultural sector and its efficiency are also addressed in studies related to agricultural resources efficiently because of the high environmental impact and the need to improve each agricultural strategy [15]. There are also studies analyzing the factors that influence agricultural energy intensity to improve efficiency [16]. A study on the agricultural sector in the European Union and changes in the energy used look at renewable energy in the agricultural sector [4]. Several studies highlight the challenges of energy consumption, pollution, efficiency, and renewable energy in the agricultural sector, but there is a need to broaden priorities further and address the future of climate change, new technologies, and changes in food systems [17]. Previous studies have shown that an assessment of the agricultural sector requires much data to clarify the current situation and to be able to make improvements in the agricultural sector to promote more efficient use of resources, a shift towards RES, and the implementation of energy efficiency policies.

The article aims to present a methodology for data acquisition in the agricultural sector by considering the spatial and sub-sectoral differences in energy consumption. The article presents an in-depth analysis of different energy consumers in the agricultural sector in Latvia. Through different data processing methods, authors have identified the energy consumption of different agricultural subsectors on a spatial basis, which has not been done previously.

## II. METHODOLOGY

The agricultural sector was divided into sub-categories according to the data from the official statistics of Latvia by farm size and type to determine the energy consumption [11]. According to the national energy balance, the energy consumption of the agricultural sector is presented together with the forestry sector [18].

The required data were used from public data registers of the State Environmental Service. The pollution permits were used to obtain more accurate data on the consumption of sub-sectors in various processes. Several indicators were identified through the information from the permits. The indicated farm's annual electricity consumption is divided for production processes, lighting, ventilation, heating, and other purposes. Also, data on the use of fuel were allocated for heating, electricity, and transport equipment.

Figure 3 shows agriculture sub-categories according to which farms with the necessary data to determine energy consumption were selected. The colored sectors and subsectors were included within the in-depth analyses as they use the most energy in the agricultural sector. According to the publicly available information of energy balance and type of farming, energy consumption in the agricultural sector is determined based on agricultural sub-sectors – crop agriculture, dairy farming, pig and poultry farming, and mixed crop and livestock production, as well as forestry sector [11], [18].

In total, 46 pollution permits were analyzed for indicator determination. From the available data of pollution permits, the energy consumption and agricultural production units (describing the number of animals or arable land in particular farms) for different subsectors were obtained. Further, the consumption of electricity or fuel was expressed per production unit. Therefore, it is assumed that the energy use at the national level for different processes is the same as presented in pollution permits of analyzed farmers.

Aggregated data obtained from the pollution permits in Table 1 shows the available information by the type of energy source and the process for which the particular energy source is used. Thus, the table can be used to estimate which processes are supplied with which resources. A wide variety of energy sources are used for heating and production processes, depending on farming. In addition, of course, electricity is used for various processes, such as lighting, cooling and freezing, ventilation, and other processes.
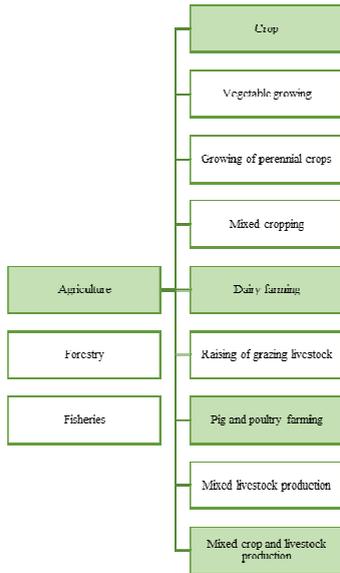
Fig. 3. Agricultural sub-categories [11]

Table I Calculated indicators

| Processes / Energy source | Electricity | Natural gas | Diesel fuel | Wood | Biogas | Liquefied gas | Other fuels - grain sieves | Other fuels |
|---|---|---|---|---|---|---|---|---|
| Production processes | ■ | ■ | ■ | | | | | ■ |
| Lighting | ■ | | | | | | | |
| Cooling and freezing | ■ | | | | | | | |
| Ventilation | ■ | | | | | | | |
| Heating | ■ | | | ■ | | | | ■ |
| Other purposes | ■ | | | | | | | |
| Feed production | ■ | | | | | | | |
| Transport in the territory | | | ■ | | | | | |
| Electricity generation | | | ■ | | ■ | | | |

2017 is the base year for assessment, and the results are expressed by regions - Pieriga, Vidzeme, Kurzeme, Zemgale, and Latgale, as spatial differences are taken into account.

The type and consumption of energy depend on the specific characteristics of the agricultural subsectors and used technologies. Figure 4 shows the example of a specific power consumption indicator representing the electricity consumption in pig farms. From the data on several pig farms, the average value for each process was determined, and the electricity consumption per pig was expressed. The energy consumption per production unit is calculated for all sub-sector.
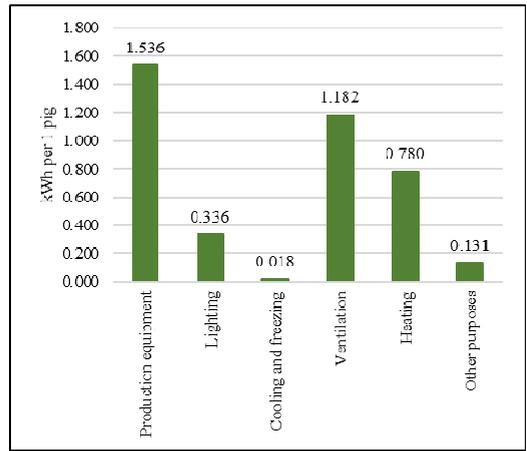


Fig.4. Electricity consumption for processes for 1 pig [19]

Each sub-sector has specific process characteristics that affect the energy sources used. For example, diesel is used for transport, manufacturing processes, electricity generation, and heating. Biogas is mainly used in cogeneration for heat and electricity generation. Wood and other fuels are used for heating, but electricity is mainly used for production processes and ventilation, heating, lighting, and cooling.

*A. Crop agricultural*

Crop energy consumption is expressed per 1 ha of field. The data for electricity consumption is expressed in MWh per ha. The primary fuels used in crop harvesting are natural gas, diesel, fuel, wood, and biogas. Energy is mainly used for production processes and heating. Figure 5 shows the date of the area for crop production (ha) in Latvia, which was 703 498 ha in 2017. For crop production, energy consumption is seasonal because of land preparation, sowing, tillage, harvesting, and post-harvesting from spring to autumn.
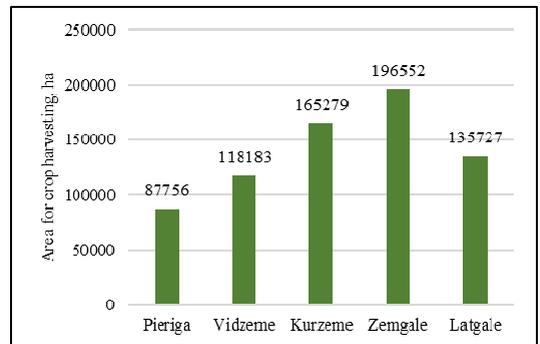


Fig. 5. Crop producing area in ha, 2017 [20]

*B. Dairy farming*

Dairy farming energy consumption is expressed as MWh per cow, and the data on specific consumption is obtained from previous studies on dairy farming in Latvia. Figure 6

shows the number of dairy cows in 2017. Dairy farming is widespread in Latgale and Vidzeme region.
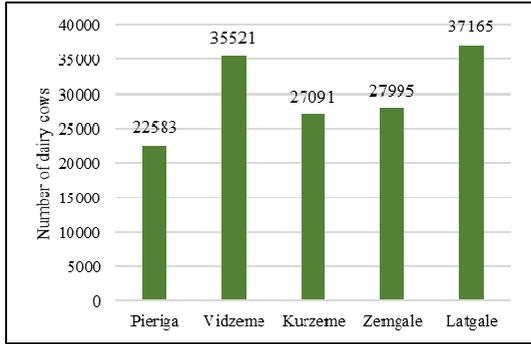


Fig. 6. Number of dairy cows in Latvia, 2017 [19]

Based on the literature review, electricity is consumed for milk cooling, milk harvesting (vacuum pumps), water heating, water pumping, lighting, and other processes [21]. According to the literature review, a dairy farm consumes 48.9 watts of electricity per 1 kg of milk. However, the most energy-intensive process results differ, as some researchers believe it is a milk cooling process, but others indicate that milk harvesting or water heating consumes the most electricity [21].

*C. Pig and poultry farming*

In Latvian, data about pig farming and poultry farming is defined as one sub-sector. As shown in Fig.7, pig farming is widespread in Zemgale and Kurzeme, but poultry farming is widespread in Zemgale and Pieriga.
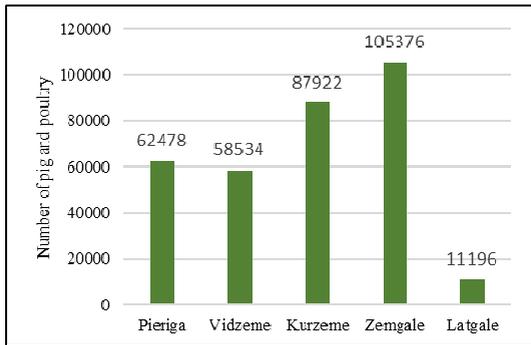


Fig. 7. Number of pigs and poultry in Latvija, 2017 [19]

*D. Mixed crop and livestock production*

Mixed crop and livestock production is a separate sub-sector. However, there are no more in-depth statistics regarding this subsector available. The majority of the mixed agriculture sub-sector in Latvia is pig farming with additional crop production, and the total number of farms varies from year to year. For example, in 2010, there were 10 814 farms, but in 2013 there was an increase to 12 257 farms. In 2016,

mixed farms decreased to only 10 319 mixed agriculture farms [11].

III. RESULTS

The results represented the energy consumption division in 2017. Figure 8 shows energy consumption by region in the crop production subsector. Zemgale (143 GWh) and Kurzeme (120 GWh) consume the most energy, with diesel (167 GWh) and biogas (95 GWh) as popular energy sources for crop production.
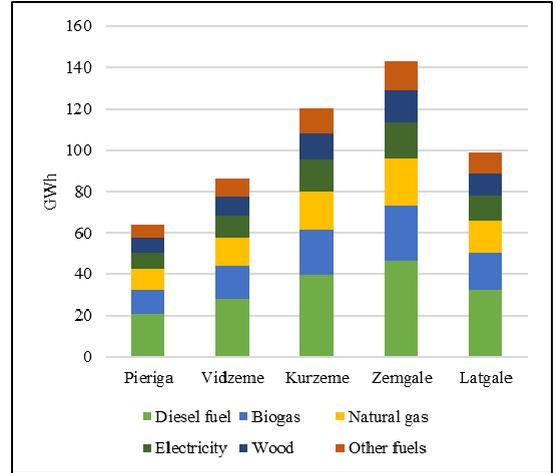


Fig.8. Crop sub-sector energy consumption

In the pig and poultry subsector, Zemgale (124 GWh) and Kurzeme (106 GWh) consume the most energy, as shown in Figure 9. The most commonly used energy sources are grain sieves (183 GWh) and biogas (140 GWh).
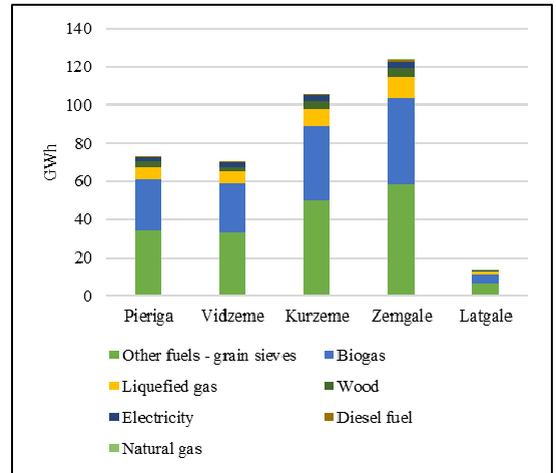


Fig.9. Pig and poultry farming sub-sector energy consumption

The energy consumption of the agricultural sector by region of Latvia is shown in Figure 10. Diesel, biogas and other fuels such as grain sieves, and electricity are the most consumed energy sources.
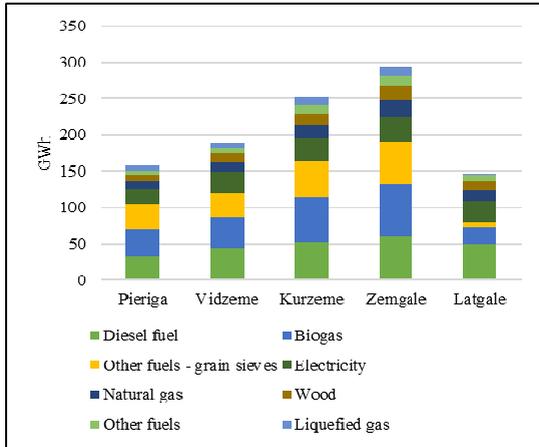


Fig. 10. Agricultural sector energy consumption in Latvia

Kurzeme and Zemgale have higher energy consumption in the agricultural sector, as crop and pig farming are popular agricultural sub-sectors in these regions. The calculated data on energy consumption by the agricultural subsector were compared and validated with the agricultural sector data from the 2017 Latvian Energy Balance showing the coincidence of total consumption.

## IV. CONCLUSION

The results conclude that energy consumption in the agricultural sector depends on the chosen region and the type of agricultural sub-sector. The spatial differences have not been considered in previous research, however, it shows crucial varieties. Zemgale region consumes 35% of the total energy used in the agricultural sector, and the most popular sub-sector is crop production. In Zemgale, 36% of the country's crops are produced, and 35% of all diesel fuel is consumed in agricultural processes. Kurzeme region consumes 26% of total energy, and, like Zemgale, the most popular agricultural sub-sector is crop production. The region produces 26% of all crop production.

The Latgale region consumes the least energy in the agricultural sector, accounting for only 11% of the country's total. Dairy farming is widespread in the region, with 25% of the country's dairy production. In Vidzeme, dairy farming is one of the most popular agricultural sub-sectors, accounting for 24% of the country's dairy production. Electricity consumption in Latgale and Vidzeme regions is higher than in other regions due to the large amount of electricity consumed in the dairy sector. The Pieriga region has average values in the agricultural subsector, but poultry farming is widespread in this region and accounts for 36% of the total subsector.

The obtained data can be further used in a more complex modeling tool, such as system dynamics models, which allows forecasting different development scenarios for the agricultural sector.

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# Quantitative and Qualitative Assessment of Healthcare Waste and Resource Potential Assessment

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*Abstract* **– Among other sectors prioritized in delivering the circular economy targets, such a major sector as health care should also be highlighted. According to World Bank data, current health expenditure is still rising, reaching globally 10.02 % in 2016 compared to 8.56 % in 2000. To ensure protection of public health, the management of health care waste should be based on the waste management hierarchy. Besides the preventive measures (waste minimization, green procurement, sustainable planning, environmental management systems), treatment methods should also be viewed in the context of the waste management hierarchy. To analyse the possibility to apply circular economy principles into health care waste management, evaluation of resource recovery alternatives as well as its multi-dimensional assessment was done. In the article quantitative and qualitative assessment was conducted through multicriteria decision analysis with a goal to do a quantitative and qualitative assessment of healthcare waste and resource potential assessment.**

*Keywords* **– circular economy; multicriteria decision analysis; resource recovery; valuable health care waste**

## 1. INTRODUCTION

Environmental pollution is causing health problems and even death, in 2015 pollution caused nine million premature deaths which is 16 % from all deaths globally [1]. Healthcare facilities help patients to solve health problems from pollution but at the same time the healthcare sector is one of the major emitters of environmental pollutants [1]. The population is aging and in 2050 people over the age of 60 will double from 901 million to almost 2.1 billion and the healthcare sector needs to deal with new healthcare needs and be more effective at it [2]. Policy-makers in the EU and at the national level have recognized the need to make health systems sustainable by making them more efficient, accessible and resilient [2].

Healthcare waste is divided into non-hazardous and hazardous waste and is strictly controlled with regulations which in case of EU Member states, this includes healthcare waste classification from Annex III of Directive 2008/98/EC and a List of Waste established by Commission Decision 2014/955/EU. According to the World Health Organization, 80–85 % of all healthcare waste is non-hazardous and 15–20 % is hazardous [3]. Healthcare waste is from hospitals, clinics, healthcare centres, dental centres, laboratories, research centres, mortuaries and autopsy centres, animal research and testing facilities, blood banks and collection services and nursing homes [4]. Non-hazardous waste is very similar to household waste which is possible to recycle and more than 50 % of the waste is paper, cardboard and

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plastic and the rest of the waste is food, metal, glass, textiles, and wood [5]. The hazardous healthcare waste consists of sharps (1 %), body parts (1 %), chemicals or pharmaceuticals (3 %) and radioactive and cytotoxic waste (less than 1 %) [6]. Healthcare waste is infectious, pathological, sharp, chemical, pharmaceutical, genotoxic and radioactive waste, and waste must be disinfected before disposal [4]. The World Health Organization has made recommendations to separate healthcare waste in different coloured trash bags and labels. To make waste management effective, it is also important to separate the waste in healthcare facilities into non-hazardous and hazardous waste.

During an outbreak of an infectious disease, the amount of healthcare waste increases rapidly and during the COVID-19 pandemic, the composition of healthcare waste is similar to that which would occur under normal conditions [7]. With the COVID-19 pandemic, the healthcare waste which is hazardous increased and mostly plastic waste from different types of personal protective equipment – face masks, disposable gloves, rubber boots and gowns, hand sanitizers and other medical equipment like syringes, test kits, plastic containers, bandages, tissues and others [8]. Effective waste management during the COVID-19 pandemic is essential as it will reduce the risk of spreading the virus through waste, so effective waste disinfection and management technologies, including recycling options are important [9].

Due to future growth of healthcare waste amounts, there is a need to assess and analyse the current issues in its management in order to properly assess and introduce measures it in a timely manner. In the research a literature review was conducted on healthcare waste management, as well as collection of data on healthcare waste compositions in Latvia and management of healthcare waste. After literature and data analysis, alternatives for application of recovered healthcare waste materials as resources were identified. Indicators for the valorisation of healthcare waste were also identified and the TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) methodology was used to assess healthcare waste treatment, taking into account the circular economy approach.

## 2. METHODS

### 2.1. Literature review

Incomplete management of healthcare waste can be a threat to the environment and the population. Impacts from the disinfection process of this waste can cause environmental pollution, as well as from the incomplete waste incineration process, hazardous substances for human health can be generated in the air and ash. There are several methods by which healthcare waste can be managed or disposed.

The main goal of healthcare waste technologies is to reduce potential hazards from the waste and there are thermal, chemical, irradiative and biological waste treatment technologies and mechanical treatment technologies that are used as the main treatment technologies [10]. Healthcare waste incineration is commonly used as a waste treatment technology, and this technology also affects the environment and population because incretion ash can be toxic which needs to disposal as hazardous waste [10]. Newer healthcare waste treatment technologies disinfect or sterilize healthcare waste thus leading to the treated waste being cleaner from a biological point of view than ordinary municipal waste and some treatment technologies make it possible to recycle the material or accelerate the natural decomposition of organic waste after treatment [10].

With thermal treatment technologies, pathogens are destroyed with heat and the temperature used depends on if the technology type is a low-heat (100 °C to 180 °C) or high heat (above

850 °C) technology [10]. Autoclaves and continuous steam technologies are low-heat technologies which operate in moist environments and use steam to disinfect the waste [10]. Microwave technologies are moist, low-heat thermal technologies, and frictional heat treatment technologies use moist heat and dry heat thermal processes and waste amounts reduce by 80 % and mass by 25–30 % [10]. Dry heat technologies use dry and hot air to operate and waste reduction can be in the range of 75–80 %, whereas incineration technology is a high heat technology and can reduce waste amount by 80–90 % and mass by 75 % [10].

Through the application of chemical treatment technologies, pathogens are destroyed with chemical disinfectants and the type of chemical disinfectant used depends on the technology's inactivation efficacy, and the waste amount reduction depends on the shredding, grinding or mixing technology used [10]. Popular chemical treatment technologies are chlorine-based chemical technology, glutaraldehyde/quarternary ammonium compound-based technology and lime slurry or calcium oxide technology, alkaline hydrolysis technology and ozone gas technology which has recently been developed [10].

Some irradiative technologies have shown results of destroying pathogens and inactivation efficacy depends on the dose absorbed by the mass of waste [10].

In biological technology enzymes can be used to speed up organic waste destruction which can contain pathogens, but biological technology is mostly used for waste from healthcare facility kitchens [10].

Mechanical technologies are used as an addition technology to shred, grind and mix waste and these technologies improve the efficacy of other applications in terms of heat transfer rate, vapour penetration or contact with chemical disinfectant and reduce waste amount and remove physical hazards, like sharps [10].

### 2.2. Data analysis

Healthcare waste is collected from different healthcare facilities and in Europe on average amounts to 3.10 kg healthcare waste per hospital bed, in the America it is 4.41 kg/per bed, in Asia it is 2.47 kg/per bed and in Africa it is 0.8 kg/per bed [11]. More waste for one bed is in countries with a high-income and with this diversity in healthcare there is not one best solution for the sector as a whole. Each healthcare facility has a specific type of treatment and this impacts the waste amount and type. According to World Health Organization data, 0.5 kg hazardous waste is produced in hospitals per bed in a day, for a clinic this amount is 0.07 kg hazardous waste per patient in a day and for a basic health unit it is 0.01 kg hazardous waste par patient in a day [12].

According to Eurostat data for 'Chemical and medical wastes' and 'Health care and biological wastes' in the period from the years 2004–2016 on average in Europe 0.15 tons of healthcare waste per capita and 0.09 tons of hazardous healthcare waste per capita were generated (Fig. 1). The most tons of healthcare waste per capita is recorded in Estonia at 1.11 tons healthcare waste and 1.01 tons of hazardous waste. Lithuanian also has a lot of healthcare waste per capita at 0.27 tons, but the country also has one of the lowest hazardous waste per capita at 0.02 tons. Finland with 0.26 tons and Belgium with 0.25 tons of healthcare waste per capita also have low levels of hazardous waste per capita – Finland 0.09 tons and Belgium 0.13 tons.
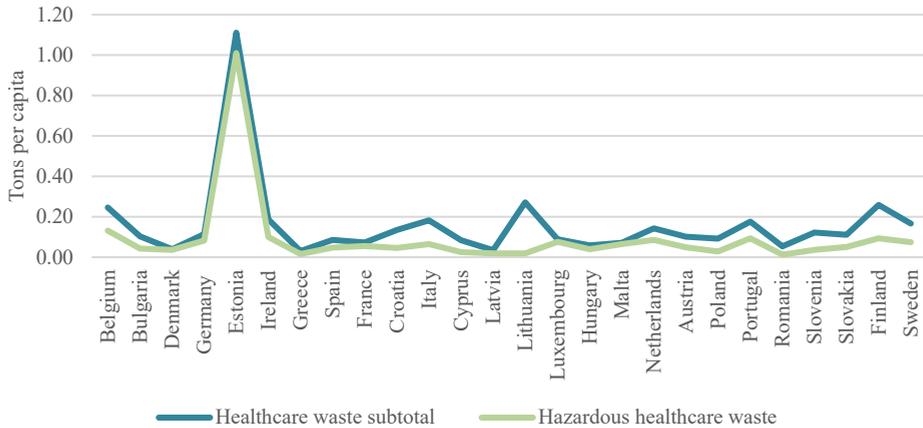
Fig. 1. Healthcare waste subtotal and hazardous healthcare waste tons per capita on average per 2004–2016 data, Eurostat data [13], [14].

Healthcare waste morphological analysis depends on the season, healthcare facility type and other factors and in this respect, healthcare waste heterogeneous [15]. Healthcare waste from disaster relief consists of plastic (43.2 %), biomass (26.3 %), synthetic fibre (15.3 %), rubber (6.6 %), liquid (6.6 %), inorganic salts (0.3 %) and metals (1.7 %) waste [16]. From children's hospitals healthcare waste consists of plastic (39.3 %), paper (11.15 %), textile (23.8 %), glass and sharps (22.7 %) and other (3.05 %) waste [17]. Common healthcare waste from a clinical pathology laboratory includes infectious waste (69.3 %) – sharps (8.6 %), blood collation tubes (37.4 %), other collectors (17.4 %) and other waste, such as toxic waste (8.6 %), infectious-and-toxic waste (13.7 %) and household types of waste (8.4 %) [18].

Based on literature, the main components of healthcare waste are plastic (39.3 – 50 %), textile (14–31 %), paper (11.2–25 %), glass (0.3–22.7 %), woodware (3.2–20 %), rubber (3.4–6.6 %), metal (0.3–5 %) and other (1.4–18.6 %) waste [15]. The main healthcare waste components are plastic, paper and textile waste and are used in sanitary consumables, like medicine bottles, packaging, bedding and toilet paper [15].

A morphological analysis of healthcare waste was performed to understand what material waste is more common. The composition of healthcare waste depends on the healthcare facility type and Fig. 2 contains data from eight healthcare facilities in Latvia. The data were obtained from the research conducted within the project, which are waste from laboratory, children's hospital, doctors' private practice and different types of hospitals. From all healthcare facilities most of the waste was textile (35 %) and different types of plastic (33 %). The waste also contained different types of mixed materials, like plastic with textile, metal with plastic and within the category 'others' all kinds of small waste fractions are included.
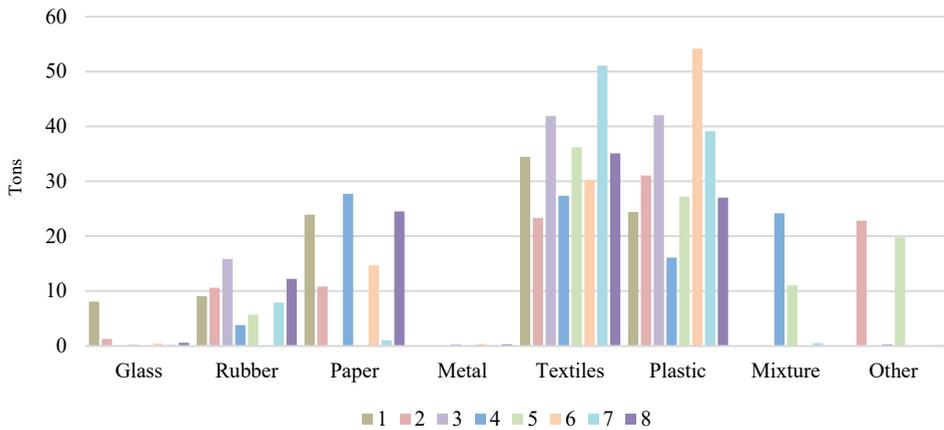
Fig. 2. Healthcare waste by waste material from different healthcare facilities, data were obtained from the research conducted within the project.

The amount of healthcare waste is increasing in Latvia as illustrated in Fig. 3 which shows data from two hazardous waste collection, transportation, management, and processing companies in Latvia. Together both companies in 2015 collected 1684 tons of healthcare waste and in 2019 the amount rose to 2173 tons of healthcare waste, which were classified under the 18 waste code. In five years, the amount of waste has increased by 489 tons.



Fig. 3. Total healthcare waste in Latvia [19].

On average each year, 1668 tons of hazardous waste are collected from waste class 180103 – wastes from natal care, diagnosis, treatment or prevention of disease in humans and waste collection and disposal of which is subject to special requirements in order to prevent infection; 74.5 tons of waste from class 180109 – medicine which is not cytotoxic; 35.3 tons of hazardous waste from waste class 180106 – chemicals consisting of or containing hazardous substances and 29.7 tons of hazardous waste from waste class 180202 – wastes from research, diagnosis, treatment or prevention of disease involving animals and waste collection and disposal of which is subject to special requirements in order to prevent infection.

### 2.3. Indicator analysis method

For healthcare waste treatment technology comparison seven waste treatment technologies were selected and as thermal technologies those included vacuum autoclaves, autoclaves with integrated shredding, batch wise microwaves, continuous microwave, frictional heat treatment and incineration technologies. The chemical treatment technology selected is sodium hypochlorite-based technology. Some types of healthcare waste need to be treated with higher temperatures because of its hazardous nature, but other healthcare waste, like infectious waste can be disinfected if a certain level of microbiological inactivation efficiency is achieved [3].

Autoclaves were originally used for medical instrument sterilization but in the last few decades healthcare waste treatment is possible with this technology [10]. The process temperature of the autoclave technology is 120–150 ºC and operates with a pressure of 2–5 bar [20]. Autoclaves can be used for a wide range of healthcare waste treatment but it is not suggested to use an autoclave for volatile and semi-volatile organic compounds, chemotherapy waste, mercury and other hazardous chemical waste, as well as radiological waste [10]. Low-heat waste treatment technologies, like autoclaves make less air pollution [12].

*Vacuum autoclaves* take less time to disinfect because they are more efficient at removing air and disinfecting waste [10]. The capacity for a vacuum autoclave is 5 to 3000 kg/hour and the technological advantages are its low impact to the environment and waste residues after treatment are non-hazardous and even  possible to recycle [12].

*Autoclaves with integrated shredding* include a hybrid autoclave which has improved heat transfer into waste, and has a high disinfection level at shorter time [10]. The capacity is 5 to 3000 kg/hour and the technological impact on the environment is low, has no hazardous residues but waste is unrecognizable after treatment and the waste amount is reduced [12].

Microwave technology typically use 2450±50 MHz and 915±25 MHz for disinfection [21]. Using this waste treatment technology it is possible to treat a wide range of healthcare waste, but volatile and semi-volatile organic compounds, chemotherapy waste, mercury and other hazardous chemical waste and radiological waste are not suggested for this waste treatment technology [10].  Microwave technology does not have a significant impact on the environment because wastewater is treated and there are minimal air emissions from this technology [12]. Microwave technology has complex influencing factors of disinfection and for healthcare waste and especially for hazardous healthcare waste this is an important indicator [9].

*Batch wise microwave* technology advantages are low environmental impact and after treatment waste is not hazardous and the technology capacity is 1 to 210 kg per hour [12].

*Continuous microwave* technology capacity is 100 to 800 kg per hour and after treatment the healthcare waste is unrecognizable and not hazardous after treatment, the amount of waste is reduced and  has low environmental impact [12].

*Frictional heat treatment* technology heats waste to 150 ºC and shreds waste into a powder and for waste disinfection a temperature range of 135 °C up to 151 °C is used [10]. With frictional heat technology it is possible to take care of infectious healthcare waste – glass, plastic, metal, liquids and pathological waste [10]. The capacity is 10 to 600 kg per hour and using frictional heat treatment technology there is low impact to the environment and after treatment the waste is not hazardous and is unrecognizable. Waste reduction is also an advantage of this technology [12].

*Sodium hypochlorite based technology* is alkaline hydrolysis or alkaline digestion process which in decontaminated aqueous solution turns anatomical parts [10]. This healthcare waste

treatment technology is used for pathological and biological waste treatment, but is not suggested for waste which contain aluminium, tin, zinc, magnesium, copper or galvanized iron as well as concentrated acids, flammable liquids and organ halogen compounds and nitromethane and similar nitro compounds [10]. Advantages of sodium hypochlorite based technology is amount reduction, unrecognizable and not hazardous after treatment and the technology capacity is 600 to 3000 kg per hour [12].

***Incineration*** with a dual chamber technology is known as starved-air incinerators, pyrolytic incinerators, two-stage incinerators or modular combustion units [10]. Incineration technology can treat a wide range of healthcare waste and is specially made for pathological waste, but it is not suggested for pressurized gas containers, large amounts of reactive chemical waste, radiographic wastes (silver, salts and photographic), as well as waste which contains mercury, cadmium or other heavy metals from broken thermometers, used batteries and sealed ampoules or vials that may burst, and radioactive waste [10]. Incineration capacity is 5 to 500 kg per hour and advantages include waste amount reduction and the waste is unrecognizable. Disadvantages of this technology include high impact on the environment due to the possibility of producing hazardous ash, air pollution and risk of burns [12].

To assess technology, indicators must reflect sustainability with environmental, technical and economic aspects [22]. Indicators are delineated as data from the technology and as evaluation from literature analysis.

Environmental aspects include energy consumption (kWh/kg) and water consumption (L/kg) data for each technology, and this represents how much energy and water is used to treat kg of healthcare waste. Other environmental aspects are criteria about water connection, quality, and wastewater, as well as environmental impact criteria and hazardous residues criteria.

In order to evaluate technical aspects, the criteria chosen include technology capacity which is represented by how wide the technology capacity range is and what type of healthcare waste can be treated with the technology because each technology provides information on what kind of waste can be treated. Other criteria include temperature for waste treatment process, the effectiveness of waste disinfection which for hazardous healthcare waste is a very important criterion. For the circular economy aspect, an important technical aspect is the criterion of whether the waste can be recycled after treatment with the technology.

Costs and maintenance criteria for the technology were selected for the economic aspect. In this research the focus is to look at the technical and environmental indicators for waste treatment technologies.

### 2.4. Multi-criteria decision-making analysis (MCDA)

It is important to use structured and sound arguments in the problem-solving and decision-making process, and thus the multi-criteria decision analysis (MCDA) improves the quality of decision-making [23]. MCDA has a lot of different methods and it is a tool for assessing related and contradictory criteria in order to evaluate alternatives and find the best solution [24].

One of the most popular MCDA methods is TOPSIS and it was presented by Hwang and Yoon in 1981 [25]. TOPSIS is recognized as one of the best MCDA methods that addresses the issue of ranking change that was observed after the application of the method, and one of the advantages of the TOPSIS method is the ability to quickly identify the best alternative [24]. TOPSIS idea is to approach the ideal solution for a problem and is commonly used in engineering to find a solution for multi-objective decision-making problems [26]. The TOPSIS framework starts with collecting input data, than calculations of normalized matrix and weighted standard matrix, the next step is distance from ideal and non-ideal solutions and

calculations of closeness between each alternative to ideal solution and the best alternative is with highest closeness [25].

## 3. RESULTS AND DISCUSSION

Experts evaluated criteria and gave them weights which are listed in Table 1 and for environmental criteria (C1–C5) weight is 0.4 which was divide to sub-criteria, for technical criteria (C5–C10) weigh is 0.4 which was also divided to sub-criteria and economic criteria (C11) is with 0.2 weight. Table 1 also provides information on each criterion ideal solution – minimal (MIN) or maximal (MAX) and it depends on each criterion qualitative or quantitative data.

TABLE 1. CRITERIA WEIGHTS AND IDEAL SOLUTION

|     | Criteria | Weight | Ideal value |
| --- | --- | --- | --- |
| C1 | Energy consumption | 0.10 | MIN |
| C2 | Water consumption | 0.10 | MIN |
| C3 | Water connection, quality, and wastewater | 0.02 | MIN |
| C4 | Environmental impact | 0.09 | MIN |
| C5 | Hazardous residues | 0.09 | MIN |
| C6 | Capacity interval | 0.08 | MIN |
| C7 | Infectivity removal efficiency | 0.09 | MIN |
| C8 | Temperature | 0.08 | MIN |
| C9 | Waste recycling after treatment | 0.12 | MIN |
| C10 | Types of waste can be treated | 0.03 | MAX |
| C11 | Costs and maintenance | 0.20 | MIN |

The alternatives for technologies included in the evaluation are – vacuum autoclave (A1), autoclave with integrated shredding (A2), batch wise microwave (A3), continuous microwave (A4), frictional heat treatment (A5), sodium hypochlorite-based technology (A6) and incineration (A7).

TABLE 2. NORMALIZED WEIGHTED DECISION MATRIX

|     | A1 | A2 | A3 | A4 | A5 | A6 | A7 |
| --- | --- | --- | --- | --- | --- | --- | --- |
| C1 | 0.0156 | 0.0039 | 0.0277 | 0.0237 | 0.0866 | 0.0232 | 0.0193 |
| C2 | 0.0890 | 0.0107 | 0.0045 | 0.0000 | 0.0327 | 0.0297 | 0.0000 |
| C3 | 0.0099 | 0.0099 | 0.0099 | 0.0033 | 0.0066 | 0.0066 | 0.0033 |
| C4 | 0.0285 | 0.0285 | 0.0285 | 0.0285 | 0.0285 | 0.0285 | 0.0569 |
| C5 | 0.0285 | 0.0285 | 0.0285 | 0.0285 | 0.0285 | 0.0285 | 0.0569 |
| C6 | 0.0149 | 0.0149 | 0.0446 | 0.0297 | 0.0297 | 0.0149 | 0.0446 |
| C7 | 0.0133 | 0.0265 | 0.0531 | 0.0531 | 0.0265 | 0.0265 | 0.0133 |
| C8 | 0.0081 | 0.0000 | 0.0064 | 0.0064 | 0.0096 | 0.0000 | 0.0734 |
| C9 | 0.0291 | 0.0000 | 0.0000 | 0.0582 | 0.0582 | 0.0582 | 0.0582 |
| C10 | 0.0134 | 0.0134 | 0.0089 | 0.0089 | 0.0134 | 0.0045 | 0.0134 |
| C11 | 0.0000 | 0.0894 | 0.0894 | 0.0894 | 0.0894 | 0.0894 | 0.0000 |

In Table 2 the normalized weighted decision matrix is presented and it shows that some alternatives did not have value, but the next step considers the ideal and non-ideal solution for each criterion alternative without values was not defended as ideal or non-ideal solution for criteria.

In Fig. 4 the results from MCDA method TOPSIS place the autoclave with integrated shredding waste treatment technology with a value 0.82 as the technology with the highest evaluation and the second best technology after criterion is chemical treatment technology – sodium hypochlorite based technology with 0.73 value.
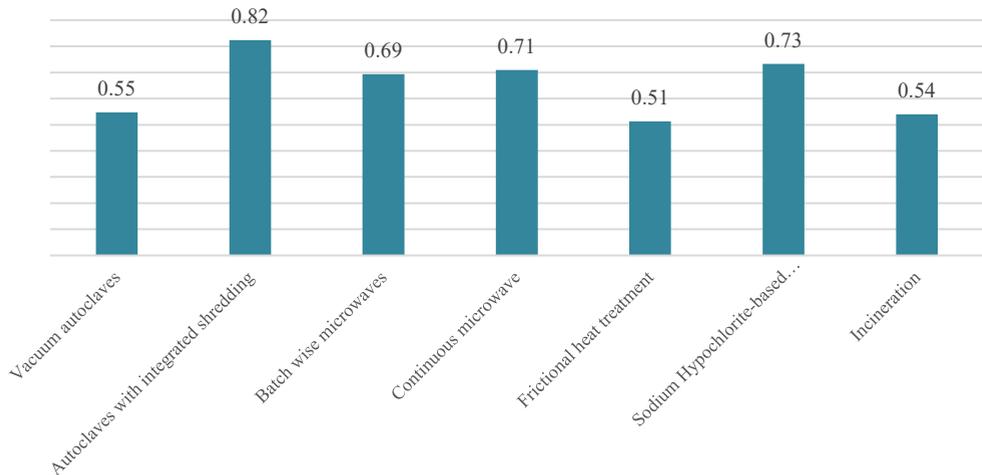


Fig. 4. TOPSIS results.

The vacuum autoclave technology was the only technology which after healthcare waste treatment could be possible to recycle waste and this indicator was one of the most important, but in other criteria the technology was not quite good and is not one of the top technologies in this case.

It is possible to recycle healthcare waste in material or energy. From plastic healthcare waste, like IV fluid bags, oxygen tubing and oxygen masks which do not contain body fluids or drugs it is possible to use as material for floor panelling or garden hose and other industrial products manufacturing [27], [28]. It is possible to recycle and use personal protective equipment for the production of different plastic product, like storage containers, outdoor decking, watering cans, outdoor flooring for sports fields and playgrounds [29]. Face masks are recycled and used as plastic and at the moment used as raw material for plastic visor production [30]. Needles and other sharps waste after shredding can be used in concrete as a small part in replacement of sand and compressive strength for cement is better [31]. Glass from healthcare waste can be recycled and used for nano glass production [32], ashes from healthcare waste can be used in cement production [33] and healthcare waste can be used to produce energy using gasification or pyrolysis process [34].

## 4. CONCLUSION

There are four main categories for healthcare waste treatments– thermal, chemical, irradiative and biological treatment technologies. Each technology has advantages and disadvantages, for example what type of waste can be treated, technology capacity, how

effective is waste disinfection or pathogen destruction, is there some specific requirement for the technology and is there environmental impact resulting from the technology.

In this research, after the selection of criteria for waste treatment in terms of environment, technical and economic aspects and after comparing technologies, the alternative for the best healthcare waste treatment technology is autoclave with integrated shredding technology. The evaluation can be improved and made more accurate in further research by using quantitate data for the comparison of healthcare waste treatment technologies.

## ACKNOWLEDGEMENT

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# The Versatility of the Bioeconomy. Sustainability Aspects of the Use of Bran

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*Abstract* – **As food consumption increases, so does the number of agricultural by-products. That is why it is necessary to find the best possible uses for them, operating by the principles of the bioeconomy. This work aims to gather information on the possibilities of using grain byproducts to develop new products and evaluate which bran products are the most suitable for commercialisation based on economic, environmental, social, and technical factors. Two methods were used in this work: literature review and multi-criteria decision analysis. As a result, 30 products were identified that could be made by using wheat bran, straw, husk, and dust. The products were divided into six groups – packaging materials, building materials, adsorbents, fuel, thermal insulation materials, and chemicals. In multi-criteria decision analysis, it was looked at seven bran products of which the best alternative for further commercialisation is mycelium-based biocomposite.**

*Keywords* – **Grain byproducts; multi-criteria decision analysis (MCDA); sustainable development; TOPSIS; value-added products; wheat**

## 1. INTRODUCTION

The bioeconomy is one of the main directions of economic development that will allow achieving the goals of the European Green Deal [1]. An essential aspect of the bioeconomy is gathering the existing knowledge and highlighting and evaluating new strategies and technological processes to choose the best directions for development, considering global, regional, and local specificities [2]. Global food consumption is projected to increase by 59 %–98 % by 2050 compared to 2005 [3]. All of this indicates that agricultural production and the number of byproducts generated will increase. Approximately 1.3 billion tons of food waste, including food byproducts, and yearly losses are generated worldwide. At the level of food production, 39 % of food waste and loss occurs [4]. The circular economy model promotes byproducts as a raw material for new products, thus creating new business models with more resource-efficient industrial management [5]. The circular economy aims to move away from a linear economy model and introduce an economy based on the 3Rs principle of reducing, reusing, and recycling [6]. Traditionally, grain byproducts are disposed of as waste or added to livestock feed [7]–[10]. It harms the environment, such as wheat bran disposal releases 259 $kgCO_2eq$ into the air [11]. Also, the possibility of producing value-added products such as single-cell oil is lost [12]. The use of agricultural residues in higher value-added products is in line with at least three of the seventeen UN Sustainable Development Goals (Goal 2;9;12) [13]. The concept of a cascade implies using biomass in a resource-

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efficient and closed-loop manner [14]. The idea has appeared in European Union (EU) policy planning since 2012 in documents such as the EU Forest Strategy, the EU Bioeconomy Strategy, and the EU Circular Economy Action Plan [15].

In Europe, the cultivated area under cereals in 2020 was 52.5 million hectares, and the yield was 286.5 million tons [16]. Globally, wheat is the most common type of cereal and one of the primary raw materials in the food industry. In 2017, the world produced 770 million tons of wheat, of which 150 million tons were grown in Europe [9]. In 2020, the wheat harvest in Europe was 126.7 million tons [16].

In 2020, the agricultural land in Latvia accounted for 36 % or 2.3 million hectares, of which 753.7 thousand hectares of the area was under cereals. Cereal production is one of the most important agricultural sectors in Latvia, as it does not only provides food for people and feeds the livestock sector. The grain yield in 2020 was 3.5 million tons, and the yield per hectare was 46.4 quintals. In 2020, 20 314 farms were engaged in growing cereals in Latvia. In recent years, summer and winter the growth of wheat was the highest, up to 66.2 % [17]

The cereal sector can be divided into three stages – 1) grain cultivation and harvesting, 2) grain primary and secondary processing, and 3) grain food retail and consumption [5].

Byproducts such as grain screenings, husk, bran, germ, dust, and straw are generated during cultivation, harvesting, and processing stages [10], [18], [19]. In grain cultivation, straws are produced, which can be used as a raw material in various industries, such as medicine and animal farming [20]. In the case of wheat, approximately 1.3 to 1.4 kg of wheat straw is produced per kilogram of grain obtained [21]. In primary processing, the grains are cleaned and dried. Grain screenings and dust are generated in this stage [19]. They account for about 0.9 % of the total weight [22], [23]. Dust, husk, bran, and germ are generated in secondary processing. Husk and bran are byproducts of flour milling, representing approximately 14.5–25 % by weight of the grain [8], [11], [24].

There have been several studies on what can be obtained from grain byproducts. Berthet *et al*. studied wheat straw as a source to obtain lignocellulosic fibres, which can be used as a filler in Poly(3-hydroxybutyrate-co-3-hydroxyvalerate) (PHBV). The material is further used as a film for fresh food packaging [25]. Wheat straw can be used as a source to get bio-polyol. It is a partial substitute for castor oil in biodegradable polyurethane foams, which can be used as a thermal insulation material in the agricultural sector [26]. Hernández-Martínez *et al*. described how to extract silicon from wheat husk ash, which can be used to produce solar cells [27]. Katileviciute *et al*. compiled several studies on using wheat bran to produce enzymes, proteins, organic acids, and other products [28]. The studied products can be classified into six groups: packaging materials, building materials, adsorbents, fuel, thermal insulation materials, and chemicals. The most studied grain byproducts are bran, straws, and husk. There are studies on their use as raw materials [29], [30], filler [9], [11], [31], binder [32], nutrients [5], [28], [33], and the source of various chemicals [34]–[36]. Most of the research looks at only one of the grain byproducts.

Looking at several articles on bioeconomy [37]–[40], we observed that the literature review is regularly used to gather information. It is used to collect data and data, which is further analysed using other methods, depending on the purpose of the work. In a review of the extraction and use of phenolic compounds from coffee byproducts, a literature review was conducted to identify and evaluate research on the studied topic [37]. Fiallos-Cárdenas *et al*. use the literature review method in their paper to compile quantitative studies on the use of banana lignocellulosic residues [38]. An overview of current scientific, technological, and commercial trends in using bio-waste in various industries conducted a literature review on the circular bioeconomy of agri-food and forest processing waste [39]. Corrado and Sala provided an overview of studies on food waste generation worldwide and in Europe. Ten

scientific articles were selected using a literature review, and the underlying quantification methodologies of these studies were further systematically analysed [40]. For the current research it is necessary to do a literature review to compile scientific articles that review products obtained from grain byproducts.

A multi-criteria decision analysis (MCDA) method can compare options and set priorities [41]. Lokesh *et al.* used a two-tier MCDA to identify promising biological value chains essential for EU bioeconomy planning. Twelve EU-based value chains, such as 'Starch to Bioplastic Food Packaging,' were selected for the study and evaluated against six criteria. As a result, the authors recommend using the research methodology in practice to make informed decisions about bio-based products that have the potential to replace fossil-based products [15]. Pieratti *et al.* conducted a study using MCDA to evaluate different forest management strategies at the local level. Six criteria based on the 4R principle of the circular bioeconomy were set, and five scenarios were analysed. The authors conclude that the main advantages of this method are that the results are easy to understand and compare. But before the results are used in practice, they should be analysed and checked [42].

Stephen *et al.* in his work he used a combination of MCDA and visualization technique to analyse the long-term and sustainable use of forest resources. The results obtained during the survey for obtaining criteria for MCDA were presented in the program for 3D visualization of various scenarios for the development of the task. This combination allowed the author to determine a number of optimal tools and measures to solve the problem and put forward ways to solve it.

Barney *et al.*, using MCDA, explored scenarios for decarbonizing the energy sector by converting it to renewable energy sources. The author included in the analysis the factors of three directions – economic, social and environmental, which made it possible to carry out the analysis as versatile as possible for the chosen task. The use of additional programs such as EnergyPlan, LCOE and TOPSIS deepened the result, making it closer to reality. Combining MCDA with various programs and methods allows you getting a result that can be applied in practice, regardless of the location of the object or territory under consideration.

The analysis of the literature on the optimal research methodology indicates that MCDA will show the required result for this work as well. Based on the conclusions about the method, this study will use MCDA to compare different products that can be made using wheat bran.

Several studies have been conducted on this topic, but primarily byproducts are considered separately. Review articles already summarise information on a specific byproduct and its use [28]. However, as far as we know, no summary of several grain residues has been made in one study. Therefore, this study aims to gather information from the scientific literature on the possibilities of using grain byproducts in developing new products and to assess which bran product is the most suitable for commercialisation based on economic, environmental, social, and technical factors.

## 2. METHODOLOGY

The methodology was selected based on the reviewed scientific articles in the bioeconomy field and their suitability for this research. Two methods have been chosen to identify and evaluate the products that can be made using grain byproducts – literature review and MCDA. The operation algorithm can be described by the following 5 steps, all of which are important and in order to get precise result, cannot be skipped:

1. Product identification. The step required to determine the main product, its needed properties and qualities;
2. Collection of information in the available literature and its analysis for a deeper study

of the selected product, its availability and diversity on the market;

3. Based on the analysis of the literature, the choice of criteria required for subsequent analysis. The right choice of criteria will allow you to comprehensively evaluate the product based on the required qualities. In case of technology, these criteria may be its readiness level, availability on the market and sustainability;
4. Conducting MCDA analysis based on selected criteria;
5. Product realization based on the results of the MCDA analysis (see Fig. 1).
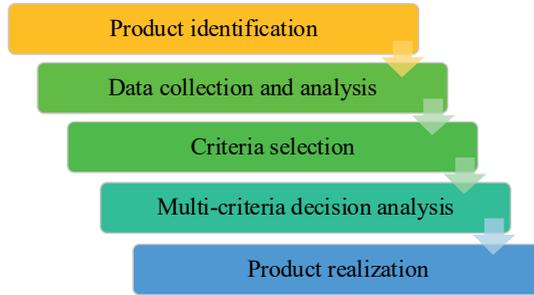


Fig 1. The stages of the research methodology.

The scientific databases ScienceDirect and the Web of Science were used in the literature review. Publications were searched using keywords. They were based on 'products from grain…' and in ellipsis place, different words were used: 'byproduct', 'germ', 'pulp', 'husk', 'chaff', 'bran', 'straw' and 'screenings'. Twenty-nine studies published between 2006 and 2021 were selected for the next phase, in which articles were grouped and analysed. The selected papers were in English and corresponded to the topic of this study.

The selected articles were grouped based on the byproduct used in the study and the final product. All final products were divided into the six groups shown in Table 1. The selected articles are about wheat byproducts because most articles on this topic research wheat residues. Wheat is also the most common type of cereal in Latvia and the world [2], [17].

TABLE 1. PRODUCT CLASSIFICATION INTO GROUPS

| Product group | Wheat byproducts | The final product |
|---|---|---|
| **Packaging materials** | Bran, straw, dust, and husk | Bio-based composite with polypropylene (PP) [11], [43], food film with antioxidant properties [24], bio-based food packaging [5], biocomposite – film for fresh food packaging [25], thermoplastic [8]. |
| **Building materials** | Straw, husk | Concrete [10], lightweight concrete [9], [31]. |
| **Adsorbents** | Bran, straw, and husk | Siliceous lignin microparticles as an adsorbent [35], adsorbent for Reactofix golden yellow 3 RFN dye [44], carbon microspheres [45], and absorbent for eliminating dyes and other toxic effluents from the textile industry [29]. |
| **Fuel** | Bran, straw | Fuel pellets [30], phenolic bio-oil and biochar [46], biofuel [28], [47]. |
| **Thermal insulation materials** | Bran, straw, and husk | Thermal insulation biocomposite [32], clay bricks [48], mycelium-based composite [33], polyurethane foam [26]. |
| **Chemicals** | Bran, straw, and husk | Silicon [27], hydrogen [7], organic acids – ferulic acid, lactic acid, itaconic acid and fumaric acid [28], [49], enzymes [28], protein [28], medicines and vitamins [28], cosmetics [28], single cell oil [12], antioxidant and antimicrobial extracts [50], xylanase [51], lignin [34], mesoporous biogenic silica nanoparticles [36]. |

MCDA method can be used to compare several options using different criteria. This method helps to process large amounts of information consistently [41]. In MCDA, the input data can be quantitative and qualitative [42]. The Technique of Order Preference Similarity to the Ideal Solution (TOPSIS) was used to compare different products and determine the optimal option. Obtained result of the TOPSIS method is the distance of alternatives to an ideal point. Alternative with the shortest distance to the ideal point is the best. Calculations this study performed analyses using formulas and calculation steps. Study calculations were made in *MS Excel*. MCDA three steps:

1. Input data Regardless of the chosen MCDA method, input data is an essential part of the analysis, as all calculations are based on them. It is necessary to set criteria and alternatives [52]. Alternatives in our study are products that can be obtained from grain byproducts, and the criteria are from four categories: environmental, economic, technical, and social. The selected six criteria are shown in Table 2.

2. Weight of criteria. Criteria need a weight that reflects their importance compared to other criteria. The Analytical Hierarchy Process method can be used at this stage. The weights obtained in this method can be further used in all MCDA methods [52]. In our case, the weight of the criteria was obtained using Sensitivity Analysis. Sensitivity analysis can be performed to investigate the effect of criterion weights on alternatives [53]. The resulting weights are used in the TOPSIS calculations to obtain the results of the Sensitivity Analysis. This was done for all criteria, and based on the results, the criterion weights were selected for the final TOPSIS analysis.

3. Calculations of the TOPSIS method. The TOPSIS method was used after defining input data and the criteria weights.

TABLE 2. CRITERIA FOR MULTI-CRITERIA ANALYSIS

| Criteria category | Criteria |
|---|---|
| **Environmental aspects** | Sustainability – compliance with the 12 UN Sustainability Goals (1–5)* |
| | Environmental impact – comparison of emissions from the production process for the new and existing product (1–5)* |
| **Economic aspects** | Product price comparison – the price difference between the product currently used and the new product (%) |
| | Market demand – global market size assessment (1–5)* |
| **Technical aspects** | Availability of technologies – assessment of the production of the new product, taking into account the level of technological readiness (TRL) (1–5)* |
| **Social aspects** | Social aspects – product job creation assessment (1–5)* |

* The criterion is evaluated in a 5-point system: 1 – does not meet the requirements; 5 – meets the requirements.

As a result, the best alternative can be determined by comparing the relative proximity to the ideal solution.

## 3. RESULTS

The literature review summarised 30 products shown in Table 1. The studied products were obtained from four wheat byproducts – bran, straw, husk, and dust. Of these byproducts, bran is the most widely used, while dust is used to produce only one product, bio-based packaging [54]. This study divided the products into six groups: packaging materials, building materials, adsorbents, fuels, thermal insulation materials and chemicals.

From the reviewed products, seven products were selected for MCDA. The analysis aims to find the product with the most significant potential for commercialisation, considering environmental, social, economic, and technical aspects. Of all product groups, fuels and building materials weren't considered further, as these products don't have a relatively high added value. This study found that wheat bran is the most widely used raw material, so their products were examined in MCDA. For bran, nine publications were reviewed, summarising information for thirteen products. When evaluating the data available for these products, the products shown in Table 4 were selected for MCDA.

Table 3 shows the input data for MCDA. Except for the product price comparison, all criteria were assessed on a five-point scale based on aggregated data and expert judgment. As the products are novel, they have not yet been studied extensively, and in many cases, data were taken from similar products.

The TRL of the product was evaluated for the availability of technology. TRL was assessed based on expert opinion. If the TRL was four or less, it was given a score of 1 to 2; if the TRL was 5 or 6, it was 3 points; and if the TRL was 7 or 8, the product received 4 points [55].

TABLE 3. INPUT DATA OF MCDA

| Criteria | Mycelium-based composite | Adsorbent | Bio-based PP composite | Bio-based film | Enzymes | Lactic acid | Single-cell oil |
|---|---|---|---|---|---|---|---|
| | **Alternatives** | | | | | | |
| **Availability of technologies** | 3 | 4 | 3 | 3 | 4 | 4 | 3 |
| **Sustainability** | 5 | 4 | 4 | 4 | 5 | 5 | 5 |
| **Product price comparison, %** | 92.5 | 92.6 | 14.2 | 0.01 | 50 | 32.6 | 37.9 |
| **Market demand** | 4 | 2 | 4 | 2 | 2 | 3 | 5 |
| **Environmental impact** | 4 | 5 | 3 | 2 | 3 | 4 | 5 |
| **Social aspects** | 5 | 4 | 5 | 5 | 3 | 3 | 4 |

The product's sustainability was assessed for compliance with the UN Sustainable Development Goals [13]. Using agricultural residues in higher value-added products aligns with at least three of the seventeen goals. If the product met all three goals, 5 points were given; if there were fewer goals, then correspondingly fewer points.

The possible prices of the products were compared with the products traditionally used and expressed as a percentage of the price difference. Using agricultural and industrial byproducts, the raw material cost of a mycelium-based biocomposite is 0.06–0.15 EUR kg$^{-1}$ [56]. There are no data on total production costs, but the authors believe that raw materials make up the majority. Such material was compared to polystyrene, which costs between 1.85–2.02 EUR kg$^{-1}$ [56]. The cost of commercial activated carbon is 5.85 EUR kg$^{-1}$, which is used as an adsorbent, while bioadsorbents cost is 0.05–0.43 EUR kg$^{-1}$ which is significantly cheaper [29]. Biocomposite with PP was compared to a study where coriander fibres were used instead of wheat bran. For PP granules, adding 40 % coriander fibres reduced the price from 1.27 EUR kg$^{-1}$ to 1.09 EUR kg$^{-1}$ [57]. Food film with antioxidant properties as compared to PLA, a natural material made from fermented vegetable starch. In 2016, PLA film cost 2 EUR kg$^{-1}$, while low-density polyethylene (LDPE), a fossil-based plastic, cost 1.25–1.45

EUR kg$^{-1}$ [58]. In our case, the product price would probably be lower because it would be obtained using low-cost residue. A rough price comparison for the production of enzymes showed that using wheat bran as a raw material would reduce the price by up to 50 % [28]. The price of lactic acid obtained from the brewery's spent grain is 0.76–1.11 EUR kg$^{-1}$, but lactic acid usually is 1.64 EUR kg$^{-1}$ [59]. This could be like our lactic acid price because the study also used byproducts as raw materials. If single cell oil was produced using glucose at zero cost, assuming waste or byproduct streams, it would cost 2.99 EUR kg$^{-1}$ at 10 000 tonnes per year. If the price of glucose is assumed to be 351.68 EUR t$^{-1}$, the cost of producing single-cell oil would be 4.82 EUR kg$^{-1}$ [60]. In this case, the data is also based on assumptions because, in reality, wheat bran has an economic value.

Market demand was measured by the size of the global product market. The global biocomposite market was 18.44 billion EUR in 2020 [61]. In 2020, the global adsorbent market was 3.43 billion EUR [62]. The global bioplastics market was estimated at 5.1 billion EUR in 2020 [63]. The value of the global enzyme market in 2019 was 7.6 billion EUR [64]. The market for organic acids in 2021 was 9.69 billion EUR [65]. In this study [12], the authors believe that single-cell oil could be added to non-biofuel markets such as producing higher-quality fatty acid-based oleochemicals. In 2020, the global market for oleochemicals was 27.62 billion EUR [66]. As the base years of the data differ, experts' opinions were also taken into account. Demand in the market was expressed in a five-point system comparing product market volumes.

Environmental impact was assessed on a five-point basis, considering emissions from the product during production compared to products currently in use. The higher the emission savings, the higher the rating of the product. Collected data were incomplete, so experts were also involved in this criterion. The mycelium-based composite was compared to MycoBamboo, a material with bamboo particles and mycelium. Production of such a sample emits 86 gCO$_2$eq per plate but 27 gCO$_2$eq per plate if renewable energy is used instead of natural gas. Each sample of MycoBamboo weighed approximately 33 g [67]. The material could be compared to extruded polystyrene foam with a global warming potential of 13.22 kgCO$_2$eq to 1.75 kg foam [68]. Using wheat bran fibre to produce biocomposite with PP can reduce emissions by 1470 kgCO$_2$eq t$^{-1}$ and create energy savings of 2130 MJ t$^{-1}$ compared to pure PP material [11]. The food film was compared to a PLA film with emissions of 0.27 kgCO$_2$eq (m$^2$)$^{-1}$. The weight of the film is 0.6 kg per 10 m$^2$ [69]. PLA was compared with LDPE film with emissions of 0.11 kgCO$_2$eq (m$^2$)$^{-1}$ and a weight of 0.5 kg per 10 m$^2$ [69]. The reviewed studies also consider emissions from the extraction of raw materials, which could be lower for the products in our study because the raw materials are agricultural byproducts.

From a social point of view, the experts assessed the amount of labour involved in the product's production process. If the production of the product is automated and doesn't require a lot of work, then it was given 1–3 points because, in that case, the factory will not create a relatively large number of jobs. But if the production process isn't fairly automated, then 4–5 points were given because the factory would create new jobs that would improve the social situation in the country.

Criteria weights were determined using Sensitivity Analysis. The sensitivity analysis showed that the sustainability aspect has the lowest sensitivity to changes in weight, which can also be determined by looking at the input data, as all alternatives scored 4 to 5 points. Therefore, this criterion was given the lowest weight (0.05). The technical and social aspects also had a small weight change compared to the other criteria, so they were given a weight of 0.15. The environmental impact and market demand became more sensitive to changes in weight when the unitary variation ratio ranged from 0.5 to 1.5, so the importance given to those criteria is 0.2. The product prices comparison reacted the most to the change in weight,

most likely because the input data differed more. After all, they were not expressed on a five-point scale. The sensitivity analysis results for this criterion are shown graphically in Fig. 2.
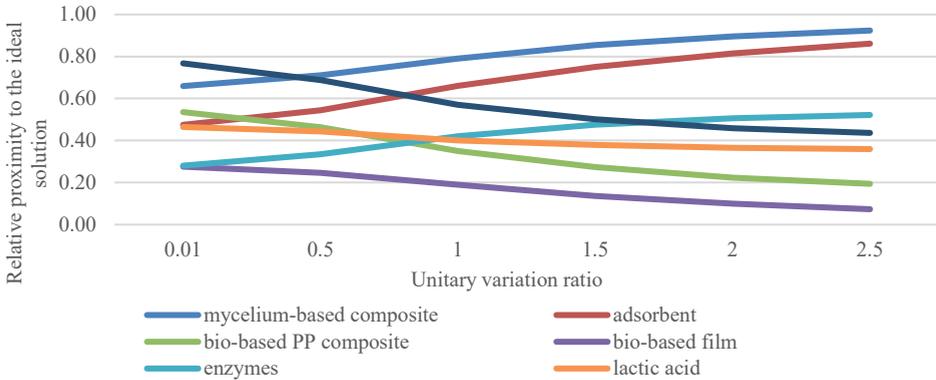


Fig. 2. Results of sensitivity analysis for product price comparison.
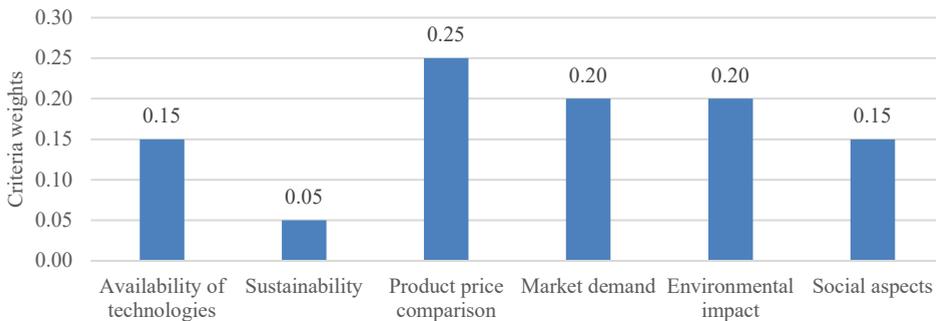
All criteria weights are shown in Fig. 3.



Fig. 3. Weight of criteria in TOPSIS.

TOPSIS calculations were made using the input data and the obtained criterion weights. Obtained results are shown graphically in Fig. 4. The results showed that the highest relative proximity to the ideal solution of the analysed products is for mycelium-based biocomposite material. This has been mainly due to the relatively high difference in product prices. Had this criterion not been considered, single cell oil would have gotten the highest result, which can also be assessed by looking at the input data. The adsorbent also has relatively good results, as its price and environmental impact are much lower than those currently used adsorbents. The worst result got the food film with antioxidant properties. This is because data for this product were used from PLA parameters, and PLA was compared with LDPE, which currently has lower production emissions and prices than bioplastics. Also, bioplastics have smaller market demand, which needs to be improved. However, the data was not taken specifically for our product. Product parameters are better because they are obtained from bran and not maise, with different extraction characteristics, such as water consumption and yield [69].
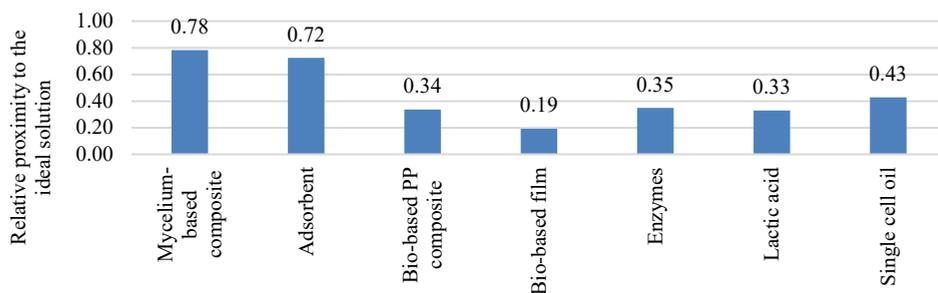
Fig. 4. Results from TOPSIS.

## 4.   CONCLUSIONS

Traditionally, grain byproducts are disposed of as waste or added to livestock feed. Therefore, several studies have been conducted to find better applications that provide higher added value. Byproducts such as grain screenings, husk, bran, germ, dust, and straw are generated during cereal production's cultivation, harvesting, and processing stages. This study gathered information on the potential use of grain byproducts in developing new products. It conducted MCDA to find the most suitable commercial product from wheat bran.

In the literature review, we identified 30 products that can be obtained using wheat bran, straw, husk, and dust. The studied products are classified into six groups – packaging materials, building materials, adsorbents, fuel, thermal insulation materials, and chemicals. Most products were obtained using bran, so seven bran products were selected for further analysis.

Six criteria from environmental, economic, technical, and social aspects were selected for MCDA. The analysis showed that the best alternative to move towards implementation is a mycelium-based biocomposite material (0.78). Its price (0.25) and environmental impact (0.20) are lower than the current thermal insulation materials. It is in demand on the market and would contribute to sustainable development.

As the input data for MCDA were based on many assumptions, it is necessary to perform an environmental and economic evaluation study for the mycelium-based composite material before it is commercialised. The study only compared bran products, so straw and husk pr products could be reached in future studies.

## ACKNOWLEDGMENT

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Research article

# Advantages and disadvantages of using more sustainable ingredients in fish feed

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ABSTRACT

As the population grows, demand for food increases. Fish is considered to be one of the most efficient sources of protein. But as demand increases, we need to think about the efficient and sustainable fish feed. There is a need to replace existing feed ingredients such as fishmeal and fish oil with more sustainable sources of protein and oil. In 1990, fish feed consisted mainly of fishmeal and fish oil, but today's fish feed is dominated by vegetable protein and vegetable oil. Comparing the advantages and disadvantages of the alternatives is concluded that previously used fish feed ingredients such as fishmeal and fish oil are not the most efficient, sustainable, and economically viable resources. The comparison shows why the composition of fish feed has shifted from 1990 to 2020 towards the use of plant resources in fish feed, as plant resources are more efficient, sustainable, and economically viable.

## 1. Introduction

Sustainability is essential in every sector to avoid resource depletion, achieve an ecological balance, and use resources efficiently. Society's interaction with the environment is deteriorating at an accelerating rate, where various global environmental, social, and economic problems are emerging [1]. Ensuring sustainability is a challenge to maintaining the ecological balance, where economic growth and environmental quality improvements are needed. People influence sustainability through their choices, as they contribute by choosing a more sustainable product or service.

As the population grows, from 7,16 billion in 2012 to 7,91 billion in 2021, an efficient food system that can feed the population in an environmentally and sustainably sustainable way is necessary [2]. In the food sector, people have access to a wide range of products and can choose more sustainable products, influence their food consumption and dispose of them efficiently instead of throwing them away. A valuable nutrition source with a relatively low environmental impact is blue food – aquatic animals, plants, or algae [3]. In 2019, the average person ate 710 kg of food, most of it was vegetables and fruit, but animal protein such as seafood, poultry, pork, and beef accounted for 9% of the total diet [4].

Fisheries and aquaculture production reaches an all-time high of 214 million tons in 2020 [5]. We are eating more aquatic food than ever before - around 20.2 kg per capita in 2020 and the consumed level is double than it was 50 years ago [5]. Forecast in the fish production sector shows that fish production will grow at an annual rate of 1.2% by 2030, with 90% of fish production going to food and 10% used to mainly produce fishmeal and fish oil by 2030 [6].

One of the main species produced in world aquaculture is Atlantic salmon, from 2380.2 thousand tons of live weight in 2015–2719.62 thousand tons of live weight in 2020 [5]. About 80% of the world's salmon harvest is farmed in large nets in protected waters such as fjords or bays, and the majority of farmed salmon comes from Norway, Chile, Scotland, and Canada [7]. Salmon farming is the most advanced form of large-scale intensive aquaculture and is effectively used to transform marine resources into high-quality food available all year round [8]. Farmed Atlantic salmon is a versatile and popular product that meets the needs of today's consumers [9]. Also, farmed seafood is an efficient source of protein [10].

Due to the increasing demand for animal protein, this will also lead to an increase in feed ingredients such as fishmeal and fish oil, which are available in limited quantities, and it is essential to develop feed that is sustainable and based on non-food resources [11]. The study aims to make a qualitative comparison between fishmeal and protein source alternatives and to compare fish oil with other oil alternatives used in fish feed production.

## 2. Methods

The Food and Agriculture Organization (FAO) has made a working paper on "Identification of indicators for evaluating the sustainability of

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animal diets" based on a survey where participated academics, industry, farmers' associations, government organizations, and non-governmental organizations (NGOs), and inter-governmental organizations [12]. Sustainable animal diets are based on the planet, people, and profit dimension and aspects such as resource efficiency, environmental protection, and social and economic benefits [12]. For the planet dimension, the most popular indicators are in Figure 1. Also, popular indicators are improving the sector's resilience to natural disasters, improving or at least not reducing biodiversity, and leaving a minimal carbon footprint [12].

Figure 2 shows the most popular indicators for the people dimension. Other indicators such as the social aspects of farming, not being culturally offensive to producers and consumers of animal products, and being part of corporate social policies were also quite popular in the survey [12].

Survey results on the profit dimension are in Figure 3 were, where the most famous indicator is the environmental and social costs of negative externalities such as environmental degradation, greenhouse gas emissions, and biodiversity loss [12].

Two critical components of sustainable fish feed are feed efficiency and feed ingredients, as feed can provide the best health and performance for fish [7]. Feed efficiency is an important indicator, as high-quality feed and effective fisheries management can reduce the amount of feed used and result in better fish growth from less feed consumed [13]. Feed ingredients have an impact on fish and the environment, as it is necessary to evaluate feed materials and whether or not an alternative is possible that would be more effective and have less impact on the environment.

Historically, fishmeal and fish oil were considered the two most essential ingredients in salmon feed due to their valuable nutrient composition [8]. Because the growth of aquaculture has led to a dependence on limited feed ingredients, particularly fishmeal and fish oil, alternatives are being explored and used as technically and economically feasible [8].

Figure 4 and 5 summarize the percentage changes in dietary ingredients for Norwegian salmon from 1990. Salmon diets have changed over the years, and marine ingredients are being replaced by alternatives to plant ingredients.

The use of marine proteins is declining and accounted for only 14.5% of feed in 2016 (Figure 4). However, plant protein increased to 40.3% in 2016, and 1990 salmon feed was not a feed ingredient at all. Carbohydrates are added as a binding agent in salmon feed and have been present in pretty similar proportions over the period 1990–2016, making up on average 10.3% of the feed. The micro-ingredients in the feed are slowly increasing and include mixtures of vitamins and minerals, phosphorus sources, astaxanthin, and crystalline amino acids [14].

According to Mowi (producer of Atlantic salmon), the composition of salmon feed has also changed. The 1990 feed was dominated by fishmeal (65%), and in the 2020 feed is dominated by vegetable raw materials (73%).

## 3. Results and discussion

Fish is a good source of protein and omega-three fatty acids, which also benefit human health, so fish food must be of good quality for fish
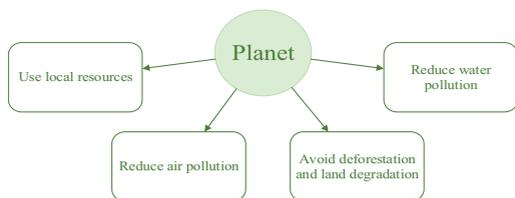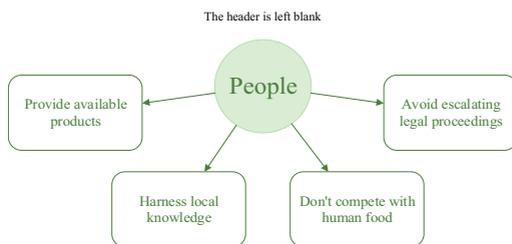


**Figure 2.** Elements of sustainable animal feed production were prioritised according to the sustainability dimension – people [12].
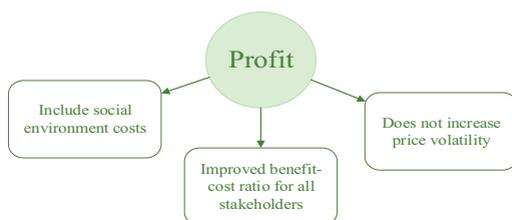


**Figure 3.** Elements of sustainable animal feed production were prioritised according to the sustainability dimension – profit [12].

and humans afterward (Table 1.). Protein is more important for fish in the early stages of growth and as they are growing, protein requirements decreases [15].

Feed ingredients not only have an impact on fish, but also on the environment, as it is necessary to evaluate feed materials, as well as whether or not an alternative is possible that would be more effective and have less impact on the environment. The fish feed alternative must be high quality and high nutritional value (omega-3 fatty acids, high protein content, adequate amino acids, digestibility, and taste), as well as insoluble carbohydrates, fiber and heavy metals need to be low because it affects the fish growth process and affects low feed conversion ratio, feed costs must be economically justified and feed production [20].

The use of insects in fish feed production is considered to be one of the most sustainable and economically viable alternatives [21]. Also, insect meal is rich in polyunsaturated fatty acid (PUFA) which is one of the healthy fats [22].

**Black Soldier Fly** is considered to be a more suitable fish meal alternative than plant-based alternatives, especially when considering specifically the gut health of fish [22].

The **mealworm** industry is evolving from a manual sector that is not very efficient to one that is becoming more efficient and profitable [23].

**Soybean** flour contains crude protein that makes the feed easily digestible, more sustainable than fishmeal, balanced amino acid content, and low price, but there is a possibility that biologically active compounds can affect fish health, growth, and reproductive development [24].

**Fishmeal** and fish oil are derived from wild fish, but catches are limited in a number of inseparable ways, so more sustainable solutions and alternatives are being sought [20].

To better compare the alternatives are summarized advantages and disadvantages of fish feed alternatives for protein sources in Table 2.

In Table 3 are comparison of alternatives according to their mineral values and in Table 4 are advantages and disadvantages.

**Algae oils** and fish oils are the primary natural sources of omega-3, but the advantage of algae oils over fish oils is their consistency, sensory properties, and ease of production [47]. The pigment obtained from microalgae improves the color of meat for salmonids and shrimps,
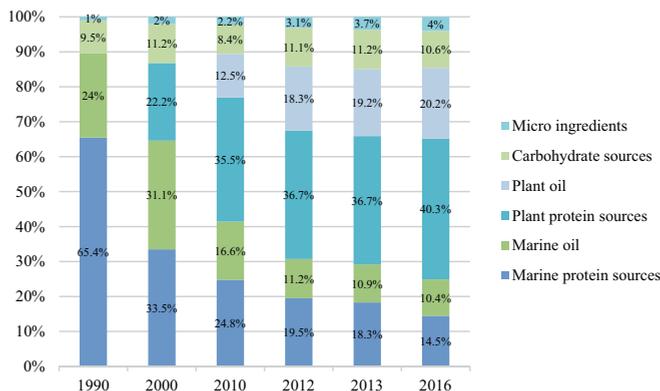


**Figure 1.** Elements of sustainable animal feed production were prioritised according to the sustainability dimension – planet [12].

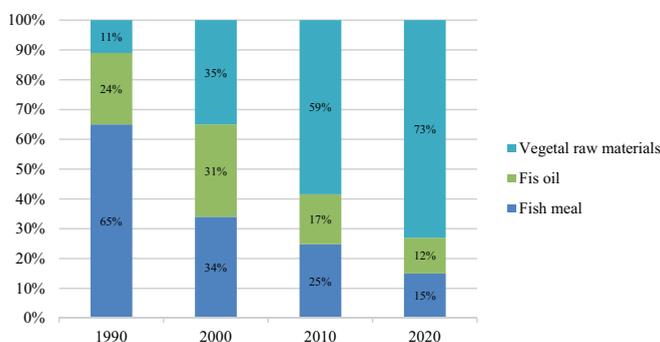**Figure 4.** Ingredients (% of feed) in Norwegian salmon feed [14].



**Figure 5.** Ingredients (% of feed) in Norwegian salmon feed from company Mowi [7].

increases the antioxidant content in meat, and improves the reproductive health of aquaculture [48].

As **plant oil** most commonly used are soybeans, linseed, rapeseed, sunflower, palm oil, and olive oil in fish feed [49]. As a good alternative, soybeans and rapeseed oil are considered salmon because they are rich in PUFAs (polyunsaturated fatty acids), especially linoleic acid and oleic acid, and do not contain n-3 PUFAs [49]. Replacing 50–60% of fish oil with plant oil results in fish growth processes as with 100% of fish oil [49].

**Fish oil** in traditional aquaculture has been widely used in fish feed, but now the supply of fish oil is dependent on fossil energy and increasing demand for fish [50]. As well as the production of fish oil, contributes to the loss of biodiversity and has an impact on the environment [50].

Table 5 compares the fatty acid values (g/100g) of algae oil, flaxseed oil (vegetable oil) and fish oil.

The nutritional value and quality of the feed are essential for fish feed and the physical properties of the feed, as physical properties are more important for aquatic animals than for terrestrial animals [19]. When choosing new feed ingredients, it is necessary to look at how this affects the technical properties of fish feed.

### 4. Conclusion

Population growth also leads to an increase in demand for food. This calls for more sustainable feed. In this case study, alternatives used in fish feed production were compared. The composition of fish feed has changed over the years, as in 1990, the main ingredients of fish feed were fishmeal and fish oil. Nowadays, fish feed ingredients have changed, and vegetable proteins and vegetable oils predominate.

Protein from Black Soldier Fly, mealworms, soybean and fishmeal were compared qualitatively and quantitatively as protein sources for fish feed production. One of the most important factors is sustainability. Black Soldier Fly and mealworms are sustainable alternatives as, for example, food leftovers can be used in the cultivation process and effectively converts low-quality organic matter into high-quality proteins and fats. Soybean and Fishmeal are not considered as sustainable alternatives. However, soybean has the benefit of price, which is a disadvantage for the other alternative. Also, Black Soldier Fly and mealworms alternatives is a good source of minerals and vitamins, but needs to be in balance in fish feed because unbalanced diet can cause negative aspect on fish growth.

Comparing the mineral values of protein alternatives, fishmeal is the best performer for zinc (mg/kg), calcium (mg/kg), phosphorus (mg/kg), sodium (mg/kg) and copper (mg/kg). Black Soldier Fly has high values for magnesium (mg/kg) and manganese (mg/kg) and the soybean alternative has better values for iron (mg/kg) and potassium (mg/kg). Minerals affect the health of the fish and subsequently the health of humans. For example, calcium affects bone health in fish and humans, iron affects fish biological reactions and in humans affects production of hemoglobin and potassium affects fish acid-base balance and

**Table 1.** Benefits for fish and humans [16, 17, 18, 19]

|  | Impact to fish | Impact to human |
|---|---|---|
| Vitamin A | – essential micronutrient <br> – an important role as an immunostimulant | – immune function <br> – growth <br> – vision |
| Vitamin D | – skeletogenesis <br> – ossification | – to prevent bone diseases <br> – immune function |
| Vitamin B12 |  | – impact for new cell development |
| Iron | – for biological reactions | – production of hemoglobin |
| Zinc | – for metalloenzymes | – immune function <br> – growth |
| Calcium | – for bone health | – for bone health <br> – in pregnancy |
| Selenium | – an essential trace element | – an essential trace element <br> – plays a role of an antioxidant <br> – stimulates the immune system |
| Omega-3 |  | – slows down the development of cardiovascular diseases |
| Iodine | – for thyroid hormones | – to maintain normal metabolism |
| Protein | – for energy | – essential amino acid <br> – necessary for cell |
| Potassium | – for acid–base balance <br> – for osmoregulation | – for the nervous system <br> – muscle function <br> – heart rate |

osmoregulation, but in humans affects the nervous system, muscle function and heart rate.

Algae oil, vegetable oil, and fish oil were compared as oil alternatives for fish feed. The benefits of algae oil are high productivity, improved health and - improve the appearance of aquatic species, as well as a high Omega-3 value. However, the disadvantages are cost and rigid cell wall which makes digestibility difficult. Vegetable oil also increases productivity, is a good alternative from an economic point of view and has a high Omega 6 value. However, it has the disadvantage of being low in Omega 3. Fish oil has the advantage of being rich in fatty acids and the disadvantage of not being as effective as vegetable oil.

Comparing the quantitative data on the fatty acid content of the oil alternatives shows how the qualitative comparison matches the quantitative one. Algae oil has the highest Omega 3 value of the alternatives and vegetable oil, which in this case is flaxseed oil has the lowest Omega 3 value. However, flaxseed oil has the highest Omega 6 value and fish oil the lowest Omega 6 value. Monounsaturated fatty acids (MUFA) are most abundant in flaxseed oil, which is slightly higher than fish oil. Polyunsaturated fatty acids (PUFA) are highest in flaxseed oil and only slightly lower in algae oil. Fatty acids in fish are influenced not only by species and environmental factors, but also by diet. These fatty acids are also important for humans, as fish are the main source of PUFAs.

The composition of fish feed has changed over the years. The nutrients provided by a fish's diet are strongly influenced by how the fish are fed. Therefore, fish are not only a source of protein but also of vitamins and nutrients, and the enrichment of fish feed needs to be further

**Table 2.** Advantages and disadvantages of fish feed alternatives – protein source.

|  | Advantages | Disadvantages | Ref. |
|---|---|---|---|
| Black Soldier Fly | - food waste (vegetable, fruit, factory waste and animal tissues) can be converted into high quality protein <br> - contains a high amount of protein <br> - good lipid source <br> - a well-balanced amount of amino acids <br> - good source of minerals and vitamins (iron, zinc, potassium, phosphorus, manganese, magnesium) <br> - palatability <br> - sustainability <br> - nutraceutical benefits <br> - a valuable source of protein and amino acid <br> - grow and multiplies rapidly <br> - no arable land is required <br> - effectively converts low-quality organic matter into high-quality proteins and fats | - price <br> - an unbalanced diet, too much of an insect meal can negatively affect growth <br> - the nutritional value of the feed and the effect on the fish vary depending on the species of insect | [21, 25, 26, 27] |
| Meal worm | - palatability <br> - sustainability <br> - nutraceutical benefits <br> - a valuable source of protein and amino acid <br> - grow and multiplies rapidly <br> - no arable land is required <br> - effectively converts low-quality organic matter into high-quality proteins and fats | - price <br> - an unbalanced diet, too much of an insect meal can negatively affect growth <br> - the nutritional value of the feed and the effect on the fish vary depending on the species of insect | [28, 29, 30] |
| Soybean | - high protein content <br> - improves fish growth <br> - price <br> - availability | - lectin and non-starch polysaccharides reduced feed intake <br> - low phosphorus content <br> - the presence of indigestible fibers <br> - lack of essential amino acids that affect the quality of fish <br> - low in methionine <br> - poor palatability <br> - no longer sustainable <br> - mycotoxin risk | [15, 20, 25, 27] |
| Fishmeal | - improves the growth of fish <br> - pleasant taste <br> - easily digests <br> - balanced nutrition - composition and concentration of proteins, minerals, essential fatty acids and essential amino acids <br> - low feed conversion factor, resulting in less feed waste <br> - increased immunity, which improves survival <br> - palatability | - no longer sustainable <br> - availability <br> - price | [20, 25] |

**Table 3.** Comparison of protein sources according to their mineral values [31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45]

|  | Black Soldier Fly | Meal worm | Soybean | Fishmeal |
|---|---|---|---|---|
| Iron (mg/kg) | 100–630 | 9.61–245 | 92,9–919 | 81–715 |
| Zinc (mg/kg) | 42–300 | 33.8–117.4 | 41,4–77,0 | 56–381 |
| Magnesium (mg/kg) | 2100–5610 | 620–2027 | 2550–4940 | 700–4000 |
| Calcium (mg/kg) | 5360–61,620 | 156–435 | 1600–4660 | 11,800–80,100 |
| Phosphorus (mg/kg) | 6800–13,220 | 2640–7061 | 5640–7660 | 1530–43,400 |
| Sodium (mg/kg) | 890–2500 | 225–3644 | 60–1090 | 3200–19,800 |
| Potassium (mg/kg) | 10,200–18,790 | 3350–9480 | 20,200–25,200 | 330–15,700 |
| Copper (mg/kg) | 7.5–34.25 | 8.3–20 | 9,0–18,7 | 3–108 |
| Manganese (mg/kg) | 190–730 | 3.2 | 29,7–70,8 | 3–37 |

**Table 4.** Advantages and disadvantages of fish feed alternatives – oil.

|  | Advantages | Disadvantages | Ref. |
|---|---|---|---|
| Algae oil | - higher productivity than terrestrial plants<br>- algae can be cultivated in the sea or in wastewater, so there is no need for land and freshwater use<br>- improves the health of aquatic species<br>- improve the appearance of aquatic species which is essential to buyers<br>- rich with omega-3 fatty acids | - high production cost<br>- microalgae have a rigid cell wall which makes digestibility difficult | [20, 27] |
| Plant oil | - increasing production<br>- high availability<br>- better economic value<br>- rich in omega 6 fatty acids | - poor in omega-3 fatty acids | [20, 49] |
| Fish oil | - contains polyunsaturated fatty acids, including docosahexaenoic acid (DHA) six times the unsaturated fatty acid | - not as effective as plant oil | [49, 50] |

**Table 5.** Fatty acid composition [51].

|  | Algae oil | Plant oil – Flaxseed oil | Fish oil |
|---|---|---|---|
| Omega 3 (g/100g) | 47.74 | 37.07 | 38.65 |
| Omega 6 (g/100g) | 7.88 | 20.26 | 3.22 |
| Omega-3/Omega-6 ratio | 6.06 | 1.83 | 12.02 |
| MUFA (g/100g) | 3.62 | 26.37 | 24.79 |
| PUFA (g/100g) | 55.62 | 57.33 | 41.78 |

MUFA - monounsaturated fatty acids.
PUFA - polyunsaturated fatty acid.

improved to produce a product with improved properties. In 1990, fishmeal and fish oil dominated, while in 2020, plant resources such as protein and oil dominated fish feed. These changes have come about as fishmeal and fish oil be more sustainable, efficient, and cost-effective alternatives. Alternatives also improve the composition of the feed and the appearance of the final product, which is an essential factor for the consumer.

## Declarations

### Author contribution statement

Beate Zlaugotne: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Jelena Pubule & Dagnija Blumberga: Conceived and designed the experiments; Wrote the paper.

### Funding statement

### Data availability statement

Data included in article/supp. material/referenced in article.

### Declaration of interests statement

The authors declare no conflict of interest.

### Additional information

No additional information is available for this paper.

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# Protein Alternatives for Use in Fish Feed – Life Cycle Assessment of Black Soldier Fly, Yellow Mealworm and Soybean Protein

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**Abstract – More production is needed as fish consumption increases. The increasing demand for fish also has implications for fish feed, the efficiency of its production and sustainability. Three protein alternatives – Black Soldier Fly, Yellow Mealworm, and Soybean – are compared to assess the sustainability of raw materials and their environmental impact. Each alternative has advantages and disadvantages. The advantages of Black Soldier fly and Yellow Mealworm are a valuable source of protein, sustainable growth (as the feed can be used in food waste) and no need for arable land. The disadvantages of Black Soldier fly and Yellow Mealworm are cost, unbalanced diets can adversely affect growth, and the nutritional impact on fish varies depending on the species of fly or mealworm. The advantages of soybeans are price, availability, and high protein content, while the disadvantages are the lack of essential amino acids, which affect the quality of the fish, and poor taste. An LCA study has been carried out on the proteins of black soldier fly, yellow mealworm and soybean. The most important impact categories from the PEFCR are climate change, particulate matter, acidification, land use, terrestrial eutrophication, and water use. The total single point value for the Black Soldier fly protein is 1.43E+01 µPt, the Yellow mealworm protein is 3.89E+02 µPt and the Soybean protein is 9.72E+01 µPt. The significant effect is due to the electricity consumption and the ingredients used in the feed. Sensitivity analysis was carried out for Black Soldier fly protein and Yellow Mealworm protein production where feed formulation was varied. In both sensitivity analyses, the lower environmental impact is from the new feed structure, which may be due to the use of food waste and wheat as feed ingredients in the new feed structure.**

**Keywords – Black soldier fly; fish feed; LCA; protein sustainability; soybean; yellow mealworm.**

## 1. INTRODUCTION

It is expected that, under the influence of demand, fish production will increase almost three times by 2050 [1]. The consumption of fish in the human diet has increased, because fish contains valuable nutrients, such as polyunsaturated fatty acids with functional effects [2]. As population continues to grow and is creating the need for more food, and at the same time, the food needs to be sustainable to minimize environmental impact [3]. To provide the necessary quantities of fish, resource consumption increases, including fish feed.

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One way to reduce environmental impact is to choose more sustainable fish feed. Fish feed must be rich in protein and energy to meet fish's nutritional requirements [4]. One option is to choose a more sustainable source of protein, which makes up 18–50 % of the total fish diet [5]. Protein is an expensive and limiting ingredient used in feed [1]. A common source of protein has been fishmeal, but this is considered a risky option because as the price increases, the catch decreases. [6]. Also, over the past two decades, it has been recognized that fish meal resources are limited, and other alternatives are being chosen as a source of protein for fish feed [4].

Alternatives to fish meals should be widely available, have good nutritional qualities, like a low carbohydrate and anti-nutritional factors, high protein content, adequate amino acid profile, high digestibility, and palatability, and, importantly, be a competitively priced alternative [7]. The nutritional requirements of fish vary from species to species, which should also be considered when assessing fish feed [8]. Options should also ensure positive effects on fish, such as feed conversion ratio, specific growth rate, final weight, and survival of different fish species [9].

Insect meal is considered a sustainable source of protein because it uses by-products, does not require agricultural land to grow insects, uses little water, and there is an opportunity to reduce greenhouse gas emissions if food waste is used as feed [10]. Black Soldier Fly larvae can also use food waste as food and then this food waste is converted into high-quality Black Soldier Fly protein [11]. Balanced amino acid profile similar to fish meal and better than it is for soybean protein [12]. Yellow Mealworm is a good alternative because of its high protein content, balanced amino acid profile, efficient feed conversion in cultivation and ability to live from organic by-products, low greenhouse gas emissions and water footprint, and reduced land use and possible mass production [13].

One of the alternatives to a fish meal is the use of plant proteins because it is more environmentally friendly and economically beneficial, and soybean protein is one of the most accessible and economically beneficial plant proteins with a high protein content, constant composition, and a good amino acid profile [14]. Fish feed with soybean meal is easily digestible because it contains crude protein [15]. The European Commission has developed a uniform environmental impact assessment Black Soldier Fly larvae can convert food waste into high-quality protein guidelines and obtain comparable economic characteristics for product categories – Product Environmental Footprint Category Rules (PEFCR) Feed for food-producing animals [16]. Ecological characteristics are expressed in 18 environmental impact categories and parameters. From PEFCR most relevant categories are climate change, particulate matter, acidification terrestrial and freshwater, land use, eutrophication terrestrial, and water scarcity.

The Life Cycle Assessment (LCA) is one of the tools that can be used for environmental impact assessment following the PEFCR guidelines. The LCA methodology evaluates environmental impacts throughout the life cycle of a product or service with a standardized approach. LCA is widely used in various sectors to evaluate products or services, raw materials, transport, and end-of-life scenarios. Also, sensitivity analysis can be performed for products or services by changing one or more parameters. The study used LCA, an observation is made on the protein source of fish meal, soybean meal and rapeseed meal used in trout fish feed, and it is concluded that fish meal has a more significant impact on the environment than the plant protein alternative [17]. The other LCA study compared partial algae and insect-based diets with a conventional fish meal and fish oil diet for salmon. It concluded that the alternative algae and insect-based diet had a more significant environmental impact than the fish meal and fish oil diet [18]. As well as in another study LCA evaluates protein extraction from mealworms fed on cereal or plant food waste, and by-

products and protein extraction from black soldier fly larvae fed on brewery by-products and plant waste, and the study concluded that using insects in the diet vegetables with low economic value may compete environmentally with existing protein sources in fish feed [19]. Studies have also been conducted on the effects of other fish feed ingredients, as pigment [20] and oil [21].

Aim of the research is to perform an environmental impact assessment using attributional LCA for three-protein alternatives and comparing insect and plant protein alternatives – Black Soldier Fly, Yellow Mealworm, and Soybean protein. Results will be expressed based on PEFCR categories, and sensitivity analysis will be performed for Black Soldier Fly and Yellow Mealworm protein alternatives using different insect diet composition.

## 2. METHODS

LCA is performed according to ISO 14040 Environmental management – Life cycle assessment – Principles and framework standard [22] and ISO 14044 Environmental management – Life cycle assessment – Requirements and guidelines [23]. Four main phases in LCA – definition of the goal and scope, inventory, impact assessment and interpretation of results. *SimaPro 9.4* software was used for assessment.

### 2.1. Goal and Scope

Goal is to assess an environmental impact assessment for Black Soldier Fly, Yellow Mealworm and Soybean protein.

Scope is procurement and transportation of raw materials and production processes can characterize the Functional Unit and PEFCR functional unit is 1 ton of animal feed. However, the functional unit used in this study is 1 kg of protein because it is consistent with the collected data flow.

### 2.2. System Boundary

To be able to compare different alternatives, it is defined that this LCA accounts for the life cycle of the product as "from the cradle to the gate", where the assessment is from resource extraction to the factory gate. System boundaries can be seen in Figs. 1–3 for protein alternatives. Black Solder fly and Yellow Mealworm protein production data are from a literature review, and Soybean protein production is from *Ecoinvent v.3.8* databases.
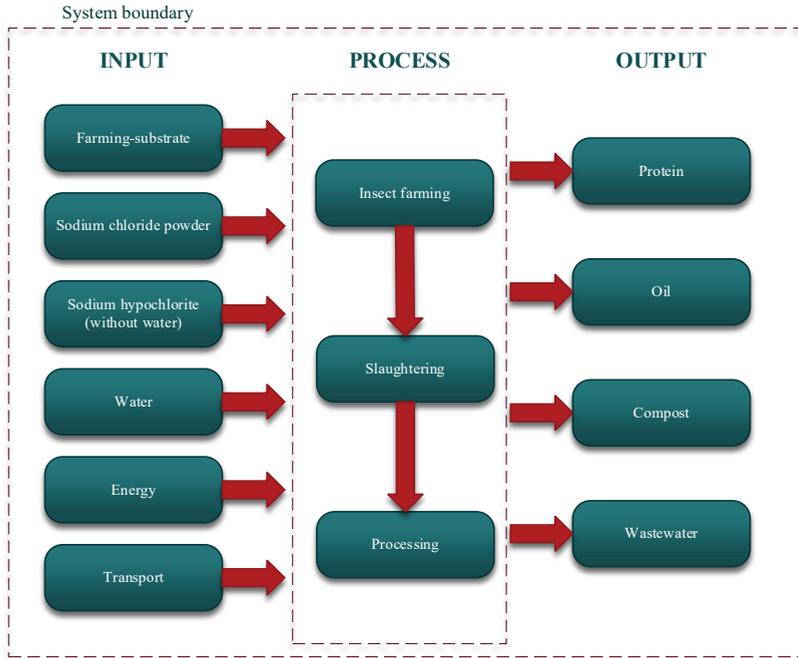
Fig. 1. System boundaries for the cradle-to-gate for protein alternative – Black Solder fly protein [8].
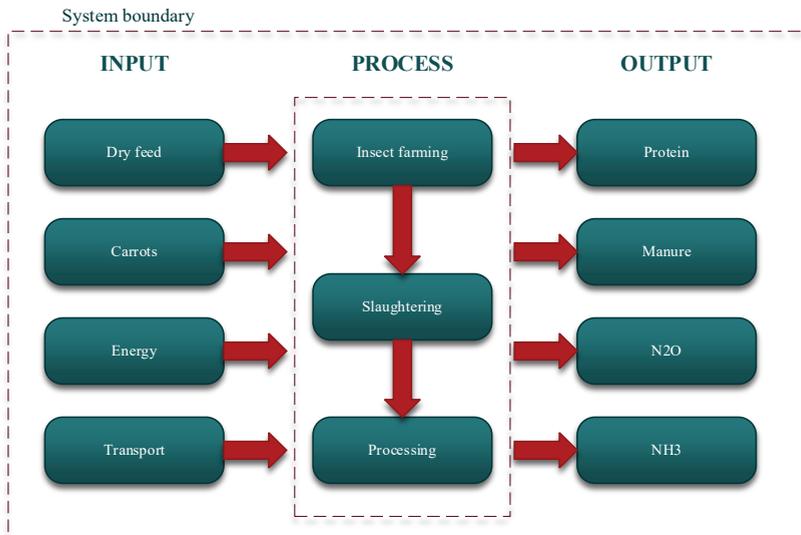


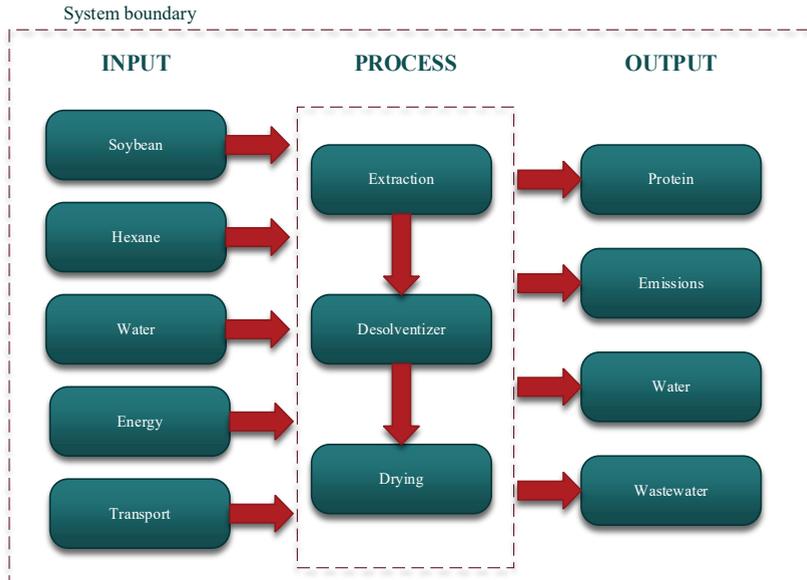Fig. 2. System boundaries for the cradle-to-gate for protein alternative – Yellow Mealworm protein [24].

Fig. 3. System boundaries for the cradle-to-gate for protein alternative – Soybean protein.

## 2.3. Life Cycle Stages

Production of feed ingredients, transport of feed ingredients to the feed mill, and feed production modules are product stages. The LCA inventory section has a complete list of raw materials to produce one functional unit for all products. For Black Solder fly protein and Yellow Mealworm protein, input data is from literature, but for soybean protein, input data is from the *Ecoinvent* database.

Although the data is from the literature review and the *Ecoinvent v3.8* database, assumptions have been made about the relevant background data. An assumption was made that the protein is produced in Norway, and the input data were modified to a Norwegian (electricity and water) or European (heat and transport) scale and raw materials as far as possible in Norway or Europe. But there are also input data that are global or worldwide. In this case, the excluded process is the packaging. Production equipment and technical lifespan have not been considered, because no data of this type is available.

## 2.4. Life Cycle Inventory Analysis

Table 1 to Table 3 are inventory data for protein alternatives to produce 1 kg of protein. Modeling according to inventory data, some of the input data in the model are created differently, as farming-substrate was modeled as compost and dry feed consisted of wheat bran, bread, brewer's yeast and lucerne. Allocation is only for the main product – protein because among the selected alternatives, the output data is not completely specified.

TABLE 1. LCI FOR BLACK SOLDER FLY PROTEIN [8]

| Description | Amount | Unit |
|---|---|---|
| **Input** | | |
| Farming-substrate | 6 | kg |
| Sodium chloride powder | 0.0017 | kg |
| Sodium hypochlorite (without water) | 0.0017 | kg |
| Water consumption | 6.3 | kg |
| Energy consumption | 3.367 | kWh |
| **Output** | | |
| Oil | 0.333 | kg |
| Field application as compost | 8.017 | kg |
| Wastewater discharge in the drainage system | 0.003 | $m^3$ |
| **Products** | | |
| Black Solder fly protein | 1 | kg |

TABLE 2. LCI FOR YELLOW MEALWORM PROTEIN [24]

| Description | Amount | Unit |
|---|---|---|
| **Input** | | kg |
| Dry feed | 3.61 | kg |
| Carrots | 2.78 | kg |
| Electricity consumption | 12.34 | MJ |
| **Output** | | |
| $N_2O$ (animal-related) | 25.50 | mg |
| $NH_3$ (animal-related) | < 1 | mg |
| Manure | 2.18 | kg |
| **Products** | | |
| Yellow Mealworm protein | 1 | kg |

TABLE 3. LCI FOR SOYBEAN PROTEIN [DATA FROM *ECOINVENT V3.8* DATABASE]

| Description | Amount | Unit |
|---|---|---|
| **Input** | | |
| Hexane | 0.00036 | kg |
| Soybean | 0.90759 | kg |
| Water | 0.46028 | kg |
| Electricity | 0.04181 | MJ |
| Heat | 0.54350 | MJ |
| **Output** | | |
| Hexane | 0.00036 | kg |
| Hydrogen chloride | 0.00005 | kg |
| Water | 0.00011 | $m^3$ |
| **Products** | | |
| Soybean protein | 1 | kg |

### 2.5. *Life Cycle Impact Assessment*

PEFCR Feed for food-producing animals describes impact assessment categories and using *SimaPro 9.4* software used method EF 3.0, which corresponds to PEFCR. The impact score is derived from 16 categories that are expressed in µPt value. Pt is the unit of the eco-indicator, and 1 Pt is representative of one thousand of the annual environmental loads of an average European citizen.

## 3. RESULTS

Results from LCA are expressed based on PEFCR impact assessment categories. In Fig. 4 are weighted results for impact categories based on PEFCR. The biggest impact occurs in the for all protein alternatives is climate change and for Yellow mealworm protein and Soybean protein is eutrophication freshwater and eutrophication marine, but for Black solder fly protein resource use minerals and metals and resource use fossils categories. In this case Black solder fly protein has the least impact on ozone depletion, eutrophication, and marine and land use categories. Based on this research, Yellow mealworm protein has minor effects on ozone depletion, human toxicity cancer and ionizing radiation. But ozone depletion, ionizing radiation and water use are categories which have a small effect on Soybean protein in this case.
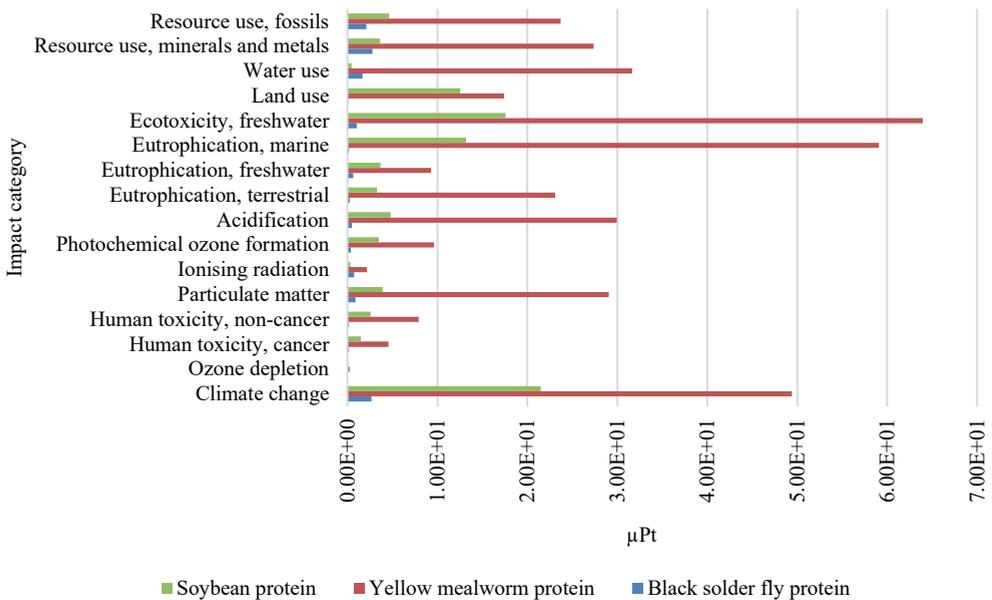


Fig. 4. Weighted protein results for impact categories.

Results from this study show that the least impact on the environment is from Black Solder fly, followed by Yellow Mealworm protein alternative. The LCA study comparing protein from two types of insect meal results show that based on climate change results in Black soldier fly has the lowest impact in comparison with Mealworm [19].

### 3.1. *Sensitivity Analysis*

   A sensitivity analysis is performed to find out how the impact on the environment changes if one of the components is replaced. After the sensitivity analysis, it can be concluded whether the selected variable component causes a large change in the impact of the product on the environment. A sensitivity analysis is performed for Black Solder fly protein and Yellow Mealworm protein alternative. In this sensitivity analysis, changes were made only to the feed composition in Fig. 5 and Fig. 6. Components were changed to see their overall effect on the final product – protein. It was chosen to compare feed for both insect alternatives because it is a factor that accounts for part of the value of the total environmental impact of the product. The existing feed composition is from a literature review, which was compared with insect feed used in production. In the composition of feed, input data such as compost, food loss from dairy and bakery, brewer's yeast and spent grains were modeled without influence, as they are generated or are as leftovers from other product production.
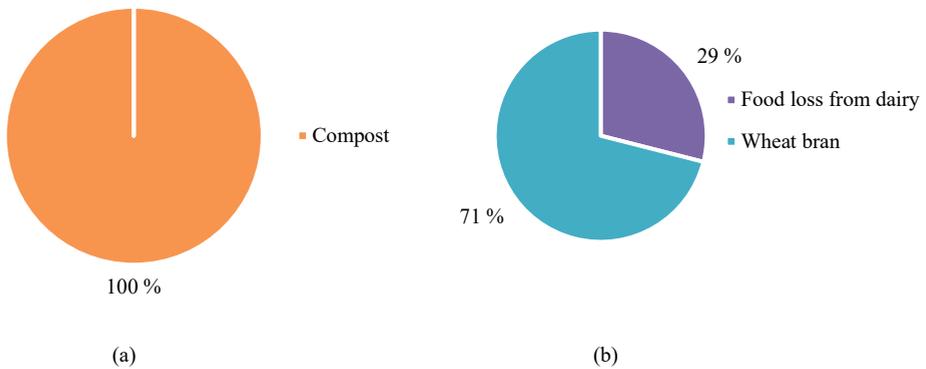
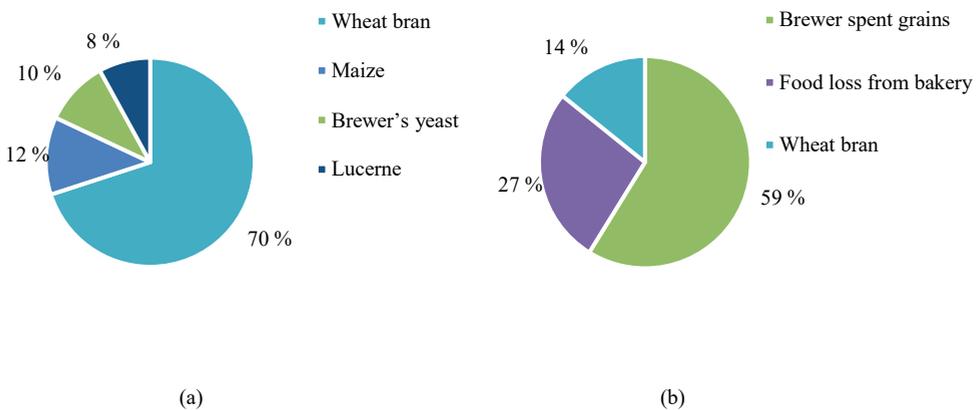Fig. 5. Black Solder fly feed component. a) Original feed component; b) New feed component.

Fig. 6. Yellow Mealworm feed component. a) Original feed component; b) New feed component.

Fig. 7 shows weighted results for impact categories. In this sensitivity analysis, the biggest impact is from ecotoxicity freshwater, eutrophication marine and climate change categories. The new feed structure will increase the Black Solder fly protein impact by 96 %.
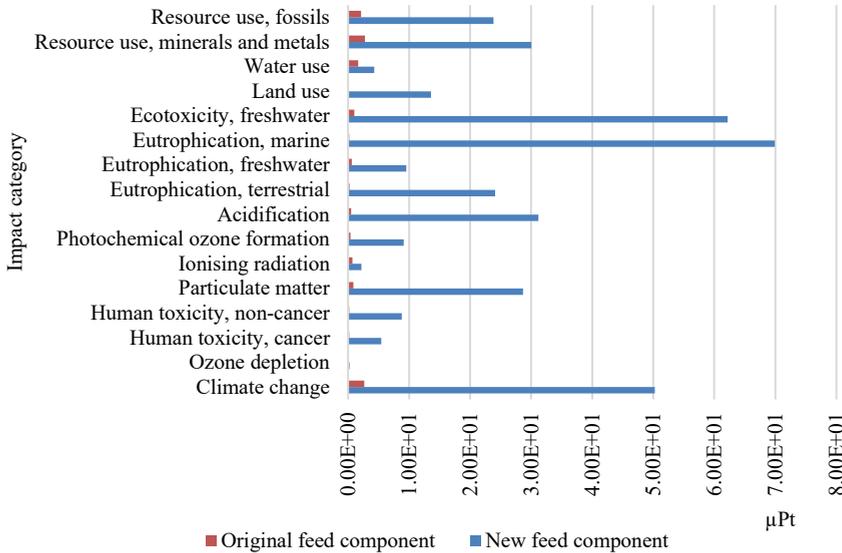


Fig. 7. Black Solder fly weighted protein results for impact categories for both feed structure.

Fig. 8 shows weighted results for impact categories. Ecotoxicity freshwater, eutrophication marine and climate change categories make a larger impact in this sensitivity analysis. The new feed structure increases the impact of total Yellow Mealworm protein by 40 %.
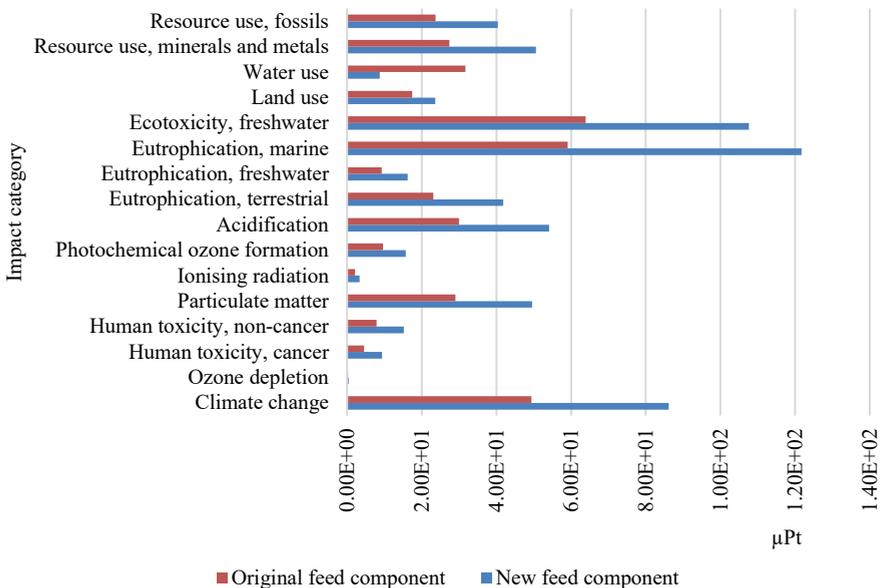


Fig. 8. Yellow Mealworm protein weighted results for impact categories for both feed structure.

## 4. CONCLUSION

An LCA study has been carried out for the Black Solder fly, Yellow Mealworm and Soybean protein. The LCA study used data from the literature and the *Ecoinvent* database. The document presents the results for the Functional Unit – 1 kg of protein. For a more accurate product comparison, the functional unit can be the protein concentration, but no data were found about protein concentration in the literature review. From PEFCR most relevant impact categories are Climate change, Particulate matter, Acidification, Land use, Eutrophication terrestrial and Water use. Of course, the (marine) biodiversity impact category can also be determined with additional methods, but the results of this LCA study are according to PEFCR.

Black Solder fly protein results for most relevant impact categories are Climate change 1.02E–01 kg $CO_2$eq, Particulate matter 5.87E–09 disease inc., Acidification 4.43E–04 mol $H^+$eq, Land use 1.21E+00 Pt, Eutrophication terrestrial 1.16E–03 mol Neq, Water use 2.26E–01 $m^3$ depriv. The total single score value for Black Solder fly protein is 1.43E+01 µPt, and the most significant impact is from electricity consumption. To reduce the impact on the environment, a greener electricity mix can be chosen or review the equipment used in production processes and their efficiency.

Results for Yellow Mealworm protein as most relevant impact categories are Climate change 1.70E+00 kg $CO_2$eq, Particulate matter 1.72E–07 disease inc., Acidification 2.40E–02 mol H+eq, Land use 1.61E+02 Pt, Eutrophication terrestrial 9.82E–02 mol Neq, Water use 3.81E+00 $m^3$ depriv. The total single score value for Yellow Mealworm protein is 3.89E+02 µPt, and the most significant impact is from mealworm feed ingredient – wheat. Reducing the impact on the environment might be necessary to replace the components in mealworm feed, as a sensitivity analysis can show that ratio changes in feed make a less environmental impact than the initially used ratio from literature.

Results for Soybean protein as most relevant impact categories are Climate change 8.26E–01 kg $CO_2$eq, Particulate matter 2.61E–08 disease inc., Acidification 4.33E–03 mol H+eq, Land use 1.29E+02 Pt, Eutrophication terrestrial 1.57E–02 mol Neq, Water use 6.01E–02 $m^3$ depriv. The total single score value for Soybean protein is 9.72E+01 µPt, and the most significant impact is from manure that used to grow soybeans. To reduce environmental impact, need to look at fertilizer alternatives and choose the one with the lowest impact. Also, improve and make a more sustainable soybean growing phase.

Sensitivity analysis was performed for Black Solder fly protein and Yellow Mealworm protein production, where feed composition was changed. The total single score for Black Solder fly protein original feed component is 1.43E+01 µPt, and for the new feed component 3.75E+02 µPt in this case, less environmental impact is from the original insect feed structure. The total single score for Yellow Mealworm protein original feed component is 3.47E+02 µPt, and for the new feed component 5.76E+02 µPt and less environmental impact is from the original insect feed structure. In both sensitivity analysis cases, the new feed structure uses food loss and wheat materials but has the largest impact to environment.

The results obtained in this study agree with the previously reviewed literature, as a source of protein is being sought to be used in fish feed with the least possible impact on the environment, and considering insects as an alternative, insect feed is very important. What can also be concluded after the sensitivity analysis carried out in the study, when choosing insect food, this alternative can have a greater impact.

Each alternative has advantages and disadvantages. The advantages for Black Solder fly and Yellow Mealworm are a valuable source of protein, sustainable growth (as feed can be used for food waste) and no need for arable land. Disadvantages for Black Solder fly and

Yellow Mealworm are price, an unbalanced diet can negatively affect growth, and nutritional value effect on the fish vary depending on fly or mealworm species. The advantages of soybeans are price, availability, and high protein content, but the disadvantages are a lack of essential amino acids that affect the quality of fish and poor palatability.

The study used LCA, an observation is made on the protein source of fish meal, soybean meal and rapeseed meal used in trout fish feed, and it is concluded that fish meal has a more significant impact on the environment than the plant protein alternative [17]. The other LCA study compared partial algae and insect-based diets with a conventional fish meal and fish oil diet for salmon. It concluded that the alternative algae and insect-based diet had a more significant environmental impact than the fish meal and fish oil diet [18]. As well as in another study LCA evaluates protein extraction from mealworms fed on cereal or plant food waste, and by-products and protein extraction from black soldier fly larvae fed on brewery by-products and plant waste, and the study concluded that using insects in the diet vegetables with low economic value may compete environmentally with existing protein sources in fish feed [19].

## ACKNOWLEDGEMENT

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# Life cycle assessment of fish feed for oil alternatives - environmental impact of microalgae, rapeseed and fish oil

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**Abstract.** Fish is an inexpensive source of high-quality protein as well as valuable micronutrients. Increasing the volume of fish and producing more fish feed is necessary to ensure the necessary consumption. One of the main components of fish feed is oil, the most crucial lipid source in fish feed. Fish oil is easily digestible and contains essential fatty acids, but replacing fish oil with alternative oil might make the fish feed more sustainable. Vegetable oils can replace fish oil due to reduced costs due to continued growth in production volumes, high availability and better economic value. Soy, linseed, rapeseed, sunflower, palm and olive oils are often used in fish feed. Also, microalgae oil is rich in essential fatty acids and a long-lasting alternative to fish oil. Important is not only the environmental impact of oil alternatives but also how these alternatives maintain or even improve the overall composition and quality of fish feed and products. An LCA assessment was performed to determine the environmental impact of microalgae, rapeseed oil, and fish oil. Where LCA system boundaries are "cradle to gate" and a functional unit of 1 kg of oil. LCA inventory is data from a literature review and SimaPro Ecoinvent database. The results obtained from LCA are based on PEFCR impact assessment categories. The LCA results show that the single score value for microalgae oil is 1.00E+00 mPt, for rapeseed oil 3.55E-01 mPt and fish oil 1.61E-01 mPt. It should be noted that the comparison presented reflects a generic comparison of alternatives, as the input data is derived from the literature analysis and the Ecoinvent v3.8 database.

**Key words:** fish feed; fish oil; LCA; microalgae oil; PEFCR; rapeseed oil.

## INTRODUCTION

Over 2015-2020, total annual world aquaculture production grew by 3.3% per year (FAO, 2022). Aquaculture is one of the fastest-growing food production sectors, which can provide high-quality protein for human consumption, and there is a growing global demand for aquaculture products, but its development is raising concerns about its environmental impact (Adegboye et al., 2020; Kong et al., 2020).

With the expansion of aquaculture, the industry's criticism of environmental, economic and social sustainability has increased, and by focusing more on environmental sustainability, attention is focused on the impact of production systems on the environment and its better management to promote sustainability (Cao et al., 2013).

To improve sustainability in the choice of feed ingredients, it would be necessary to avoid the use of unsustainable feed ingredients such as meals, oils and silages/hydrolysates derived from overexploited and/or unsustainably managed wild-caught marine fish, crustaceans, molluscs and aquatic species or from feed ingredient sources (Tacon et al., 2022).

Sustainable growth of aquaculture is possible by reducing dependence on fish oil for fish feed with fish oil alternatives which can provide the necessary fatty acids such as eicosapentaenoic acid (EPA) or docosahexaenoic acid (DHA) (Nasopoulou & Zabetakis, 2012; Cottrell et al., 2020; Zubair et al., 2021). The aquaculture sector uses plant-based raw materials to replace less sustainable raw materials in feed production (Zubair et al., 2021). However, replacing fish oil with a land plant alternative is more complex because land plants need to produce direct n-3 HUFA sources in sufficient quantities (Beal et al., 2018).

Vegetable oils often used in fish feed production are soybean, linseed, rapeseed, sunflower, palm and olive oils (Nasopoulou & Zabetakis, 2012). Rapeseed oil is a suitable lipid source for salmonids, freshwater and marine fish as it is rich in PUFA, especially linoleic acid (18:2 ω-6) and oleic acid (18:1 ω-9). Still, rapeseed oil does not contain n-3 PUFA (Nasopoulou & Zabetakis, 2012). Replacing fish oil with vegetable oil reduces costs, and vegetable oils have high availability and better economic value (Nasopoulou & Zabetakis, 2012).

Microalgae have a high lipid content, rich in essential long-chain polyunsaturated fatty acids (PUFAs), including omega-3 and omega-6 oils, and can replace fish oil in feed (Tacon et al., 2022). The advantages of microalgae oil include a fast growth rate, high antioxidant and colour content, and the availability of a wide range of species with a wide range of characteristics (Nagappan et al., 2021). Also, microalgae absorb $CO_2$ with $CO_2$ removal efficiency of 5% to 70% and thus produce $O_2$ during photosynthesis (Molino et al., 2019; Huang et al., 2021). Also, the cultivation of microalgae is beneficial for the prevention of global warming (Molino et al., 2020). However, the use of microalgae as lipids are limited by high production costs (Carvalho et al., 2022).

Fish oil is obtained from pelagic fish and is used in high-energy fish feed (Carvalho et al., 2022). To produce 1 kg of fish oil, there are needed 12.2 kg of fish (Naseem et al., 2021). Traditional aquaculture fish oil is popular and widely used, but it impacts the environment and reduces biological diversity (Carvalho et al., 2022).

At the suggestion of the European Commission, category rules for products were developed to have a uniform methodology for evaluating ecological parameters. Product Environmental Footprint Category Rules (PEFCR) Feed for food-producing animals aims to assess the ecological characteristics of compound feed in a coherent manner (European Commission, 2021). PEFCR defines more relevant impact categories - climate change, particulate matter, acidification terrestrial and freshwater, land use, eutrophication terrestrial, and water scarcity. However, in total, 18 Environmental Footprint impact categories are defined to be used to calculate the Product Environmental Footprint (PEF) profile.

Life Cycle Assessment (LCA) is used for PEF profile calculation based on PEFCR. LCA is an ISO-standardized methodology for environmental impact assessment from raw material acquisition to production, use and end-of-life treatment. Using the LCA method, different types of comparison can be made - comparison of product or raw material alternatives, the impact of energy or raw material alternatives of the effects of

the product. The LCA study compared the environmental impact of two feed scenarios, one with a standard diet of fishmeal and oil and the other with vegetable protein and oil used in Atlantic salmon and rainbow trout farming. It concluded that the environmental burden is reduced by using plant alternatives (Boissy et al., 2011). A study on the LCA of Greater amberjack feed compared fish oil and a vegetable oil blend consisting of linseed oil, sunflower oil, and palm oil and concluded that replacing fish oil with vegetable oils would reduce wild fish use and greenhouse gas emissions. Still, there may be trade-offs, such as greater eutrophication to improve environmental sustainability in aquafeed production (Bordignon et al., 2023). LCA compares the environmental impact of fish oil production when different energy sources are compared and concludes that optimising production processes improves product quality and reduces environmental impact due to reduced energy consumption (Hilmarsdóttir et al., 2022).

Important aspects of the sustainability of fish feed are the availability of ingredients, their production method and transportation. This study compares oil alternatives used in fish feed production. According to the PEFCR methodology, fish oil, microalgae oil and rapeseed oil are compared to find out which of the alternatives has the least impact on the environment. The study also carried out a sensitivity analysis of the microalgae oil alternative with changes in the form of electricity.

## MATERIALS AND METHODS

LCA consists of four stages - the goal and scope (defines the boundaries to be studied), inventory (accounting of relevant input/output data), impact assessment (evaluation based on assessment method), interpretation (conclusions and recommendations from the results) (International Organization for Standardization, 2006).

### Goal and scope
The scope of the study includes the evaluation of oil alternatives used in fish feed production. The oil alternatives are microalgae oil, rapeseed oil and fish oil.

Functional Unit from PEFCR is 1 tonne of animal feed as fed. In this study function unit is 1 kg of oil because it corresponds to the collected data stream.
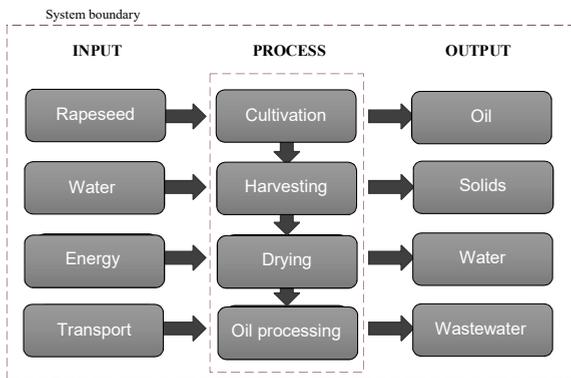
### System boundaries
This LCA is 'cradle to gate' and system boundaries diagrams can be seen in Fig. 1 to Fig. 3 are for oil alternatives. Microalgae oil production data is from a literature review. Microalgae are obtained through a dark fermentation process, solid-liquid separation (Lu et al., 2021). Rapeseed oil and Fish oil production is from Ecoinvent v.3.8 database.

### Life cycle stages
The product stage for all protein alternatives is divided into 'Production of feed ingredients', 'Transport of feed ingredients to the feed mill', and 'Feed production' modules. The components with the most significant impacts referring to the interpretation of results will be explained in this report as the relative effect of energy and raw materials in the life cycle stages.
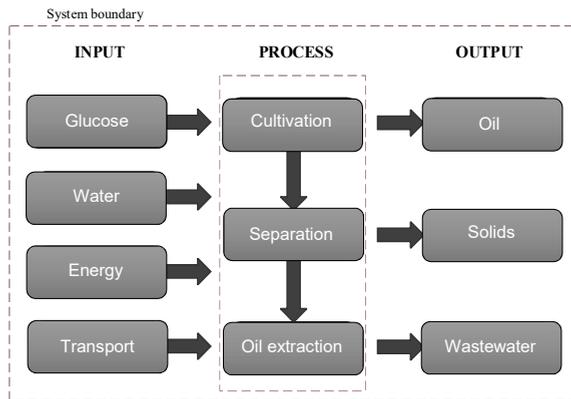
**Figure 1.** System boundaries for the cradle to gate for oil alternative – Microalgae oil (Lu et al., 2021).



**Figure 2.** System boundaries for the cradle-to-gate for oil alternative – Rapeseed oil.
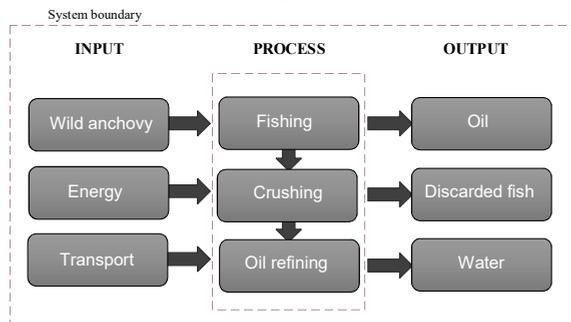


**Figure 3.** System boundaries for the cradle-to-gate for oil alternative – Fish oil.

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### Assumptions about relevant background data

Although the data are from the literature review and Ecoinvent v3.8 database, it is necessary to conduct an environmental impact assessment of the oil alternatives produced in the US. As much as possible used data in the LCA model is modified to the US. Inputs such as electricity and water are modelled for the US, but another type of energy is modelled based on global values. As much as possible, raw materials are for the US; if not, then use global or rest of the world data. Transport was also modelled for the US.

### List of excluded processes

The necessary data have been collected from the literature and the Ecoinvent v3.8 database, and are few specific input data, and in this LCA model, the excluded process is the packaging.

### Life Cycle Inventory Data

Table 1 to Table 3 shows inventory data for oil alternatives. Assumptions for Microalgae oil inventory are Sodium Glutamate is Sodium Nitrate, but corn syrup was less than 5% and was not included in the module.

**Table 1.** LCI for Microalgae oil (Lu et al., 2021)

| Description | Amount | Unit |
|---|---|---|
| Input | | |
| Glucose | 3.2922 | kg |
| Yeast | 0.3687 | kg |
| Sodium Nitrate | 0.3687 | kg |
| Potassium | 0.0401 | kg |
| Ammonium Sulfate | 0.0184 | kg |
| Magnesium | 0.0121 | kg |
| Iron | 0.0001 | kg |
| Enzymes | 0.0651 | kg |
| Tap water | 4.4026 | l |
| Electricity | 3.0188 | kWh |
| Output | | |
| Water Evaporation | 1.465 | l |
| Algae Liquid | 18.436 | kg |
| Algae Flow | 10.886 | kg |
| Algae Waste Dry | 0.880 | kg |
| Water | 2.190 | kg |
| Products | | |
| Microalgae oil | 1 | kg |

### Life Cycle Impact Assessment

The PEFCR Feed makes the impact assessment calculations for food-producing animals, where the necessary parameters are defined to characterise the environmental impact indicators.

**Table 2.** LCI for Rapeseed oil

| Description | Amount | Unit |
|---|---|---|
| Input | | kg |
| Rape seed | 1.895 | kg |
| Hexane | 0.0004 | kg |
| Electricity | 0.111 | kWh |
| Heat | 0.227 | MJ |
| Output | | |
| Emissions | 1.736 | kg |
| Wastewater | 0.00000087 | m³ |
| Products | | |
| Rapeseed oil | 1 | kg |

**Table 3.** LCI for Fish oil

| Description | Amount | Unit |
|---|---|---|
| Input | | |
| Fish residues | 6.309 | kg |
| Cyclohexane | 0.002 | kg |
| Electricity | 0.087 | kWh |
| Heat | 12.069 | MJ |
| Output | | |
| Emissions | 0.602 | kg |
| Products | | |
| Fish oil | 1 | kg |

The method used in SimaPro 9.4 software is EF 3.0, which incorporates the PEFCR as an impact assessment method. The impact categories are in the result section (Table 5).

# RESULTS AND DISCUSSION

The Life cycle impact assessment calculations are made in full accordance with the Product environmental footprint category rules (PEFCR) Feed for food-producing animals, where the necessary parameters are defined to characterise the environmental impact indicators. This section presents the environmental performance results for all oil alternatives considering all input material flows.

Weighted results for all oil alternatives expressed in µPt value. Pt is the unit of the eco-indicator, and 1 Pt is representative of one thousand of the annual environmental load of an average European citizen.

In Fig. 4 are weighted results for impact categories, and in Table 4. Life cycle impact assessment results.
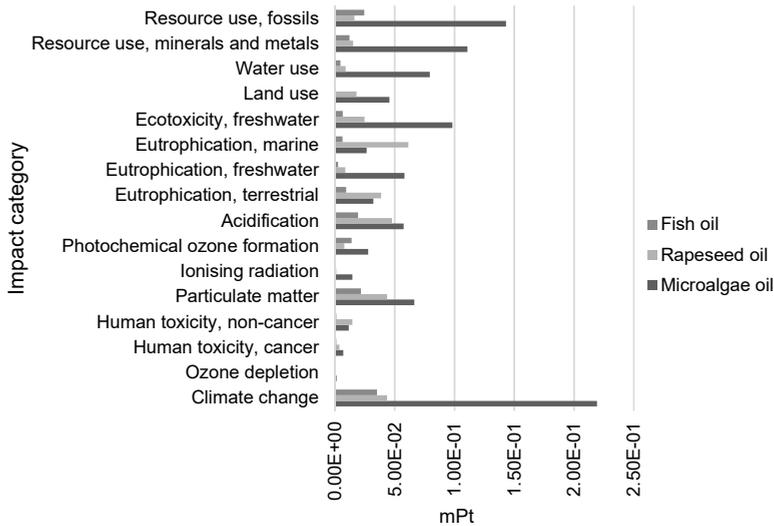


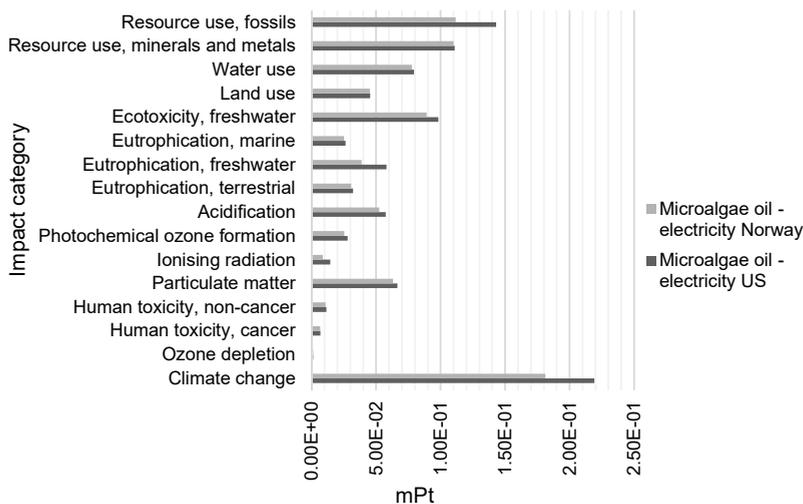**Figure 4.** Oils weighted results for impact categories.

In this study, where FU 1 kg of oil according to PEFCR impact categories, fish oil has the least impact, followed by rapeseed oil and then microalgae oil. In a study with FU 1 ton of DHA, comparing the production of fish oil and algae oil expressed per 1 ton of DHA, the LCA results obtained by the ReCiPe 2016 method concluded that the algae alternative caused less ecosystem damage than the fish alternative, also in the sensitivity analysis (Bartek et al., 2021). In a study where EPA and DHA production from microalgae and fish biomass was compared according to CML 2001 methodology with LCA, where FU is 1 kg of EPA+DHA, it was concluded that microalgae oil alternative could replace fish oil (Bartek et al., 2021).

**Table 4.** Life cycle impact assessment results for oils

| Impact category | Unit | Microalgae oil | Rapeseed oil | Fish oil |
|---|---|---|---|---|
| Climate change | kg $CO_2$ $_{eq}$ | 8.43E+00 | 1.68E+00 | 1.36E+00 |
| Climate change - Biogenic | kg $CO_2$ $_{eq}$ | 3.52E-01 | 1.22E-03 | 1.14E-03 |
| Climate change - Land use and LU change | kg $CO_2$ $_{eq}$ | 1.90E-01 | 2.16E-03 | 2.06E-03 |
| Ozone depletion | kg CFC11 $_{eq}$ | 1.12E-06 | 1.93E-07 | 2.10E-07 |
| Human toxicity, cancer | CTUh | 5.56E-09 | 3.08E-09 | 8.98E-10 |
| Human toxicity, non-cancer | CTUh | 1.45E-07 | 1.83E-07 | 1.40E-08 |
| Particulate matter | disease inc. | 4.42E-07 | 2.91E-07 | 1.45E-07 |
| Ionising radiation | kBq $U^{235}$ $_{eq}$ | 1.23E+00 | 9.52E-02 | 6.27E-02 |
| Photochemical ozone formation | kg NMVOC $_{eq}$ | 2.37E-02 | 6.67E-03 | 1.19E-02 |
| Acidification | mol H+ $_{eq}$ | 5.16E-02 | 4.28E-02 | 1.75E-02 |
| Eutrophication, terrestrial | mol N $_{eq}$ | 1.54E-01 | 1.84E-01 | 4.45E-02 |
| Eutrophication, freshwater | kg P $_{eq}$ | 3.34E-03 | 5.11E-04 | 1.62E-04 |
| Eutrophication, marine | kg N $_{eq}$ | 1.75E-02 | 4.07E-02 | 4.16E-03 |
| Ecotoxicity, freshwater | CTUe | 2.19E+02 | 5.50E+01 | 1.46E+01 |
| Land use | Pt | 4.71E+02 | 1.87E+02 | 4.05E+00 |
| Water use | $m^3$ depriv. | 1.07E+01 | 1.22E+00 | 6.21E-01 |
| Resource use, minerals and metals | kg Sb $_{eq}$ | 9.35E-05 | 1.29E-05 | 1.03E-05 |
| Resource use, fossils | MJ | 1.12E+02 | 1.28E+01 | 1.93E+01 |

**Sensitivity analysis**

A sensitivity analysis is performed for the Microalgae oil alternative. In this sensitivity analysis, changes were made only to the electricity used - microalgae oil production used the US electricity and compared to production using Norwegian electricity. In Fig. 5 are the weighted results.



**Figure 5.** Microalgae oils sensitivity analysis weighted results for impact categories.

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Table 5 shows results for Microalgae oil production in impact score per environmental category

**Table 5.** Characterisation results for Microalgae oil

| Impact category | Unit | Electricity the US | Electricity Norway |
|---|---|---|---|
| Climate change | kg $CO_2$ eq | 8.43E+00 | 6.97E+00 |
| Climate change - Biogenic | kg $CO_2$ eq | 3.52E-01 | 3.52E-01 |
| Climate change - Land use and LU change | kg $CO_2$ eq | 1.90E-01 | 1.90E-01 |
| Ozone depletion | kg CFC11 eq | 1.12E-06 | 1.04E-06 |
| Human toxicity, cancer | CTUh | 5.56E-09 | 5.27E-09 |
| Human toxicity, non-cancer | CTUh | 1.45E-07 | 1.37E-07 |
| Particulate matter | disease inc. | 4.42E-07 | 4.19E-07 |
| Ionising radiation | kBq $U^{235}$ eq | 1.23E+00 | 7.28E-01 |
| Photochemical ozone formation | kg NMVOC eq | 2.37E-02 | 2.16E-02 |
| Acidification | mol H+ eq | 5.16E-02 | 4.70E-02 |
| Eutrophication, terrestrial | mol N eq | 1.54E-01 | 1.47E-01 |
| Eutrophication, freshwater | kg P eq | 3.34E-03 | 2.23E-03 |
| Eutrophication, marine | kg N eq | 1.75E-02 | 1.66E-02 |
| Ecotoxicity, freshwater | CTUe | 2.19E+02 | 1.99E+02 |
| Land use | Pt | 4.71E+02 | 4.67E+02 |
| Water use | $m^3$ depriv. | 1.07E+01 | 1.05E+01 |
| Resource use, minerals and metals | kg Sb eq | 9.35E-05 | 9.29E-05 |
| Resource use, fossils | MJ | 1.12E+02 | 8.74E+01 |

## CONCLUSIONS

An LCA study has been carried out for microalgae oil, rapeseed oil and fish oil. The document presents the results for the Functional Unit – 1 kg of oil. From PEFCR most relevant impact categories are Climate change, Particulate matter, Acidification, Land use, Eutrophication terrestrial and Water use.

Results for Microalgae oil for most relevant impact categories are Climate change - 8.43E+00 kg $CO_2$ eq, Particulate matter - 4.42E-07 disease inc., Acidification - 5.16E-02 mol H+ eq, Land use - 4.71E+02 Pt, Eutrophication terrestrial - 1.54E-01 mol N eq, Water use - 1.07E+01 $m^3$ depriv.

Results for Rapeseed oil as most relevant impact categories are Climate change - 1.68E+00 kg $CO_2$ eq, Particulate matter - 2.91E-07 disease inc., Acidification - 4.28E-02 mol H+ eq, Land use - 1.87E+02 Pt, Eutrophication terrestrial - 1.84E-01 mol N eq, Water use - 1.22E+00 $m^3$ depriv.

Results for Fish oil as most relevant impact categories are Climate change - 1.36E+00 kg $CO_2$ eq, Particulate matter - 1.45E-07 disease inc., Acidification - 1.75E-02 mol H+ eq, Land use - 4.05E+00 Pt, Eutrophication terrestrial - 4.45E-02 mol N eq, Water use - 6.21E-01 $m^3$ depriv.

Sensitivity analysis was for Microalga oil alternatives - in one case, for production, it was used electricity in the US and in another case was used electracy in Norway. If production happens in Norway, the impact from used electricity is less impacting the environment than when production is in the US with the US electricity.

The total single score value for Microalga oil is 1.00E+00 mPt; the largest impact is from glucoses and electricity consumption. Impact can be reduced by using a greener electricity mix and more sustainable glucoses.

The total single score value for Rapeseed oil protein is 3.55E-01 mPt, and largest impact is from rape seed, and it is because of intensive or extensive cultivation processes. To reduce the impact can choose organically grown rape seed.

Total single score value for Fish oil is 1.61E-01 mPt and largest impact is from using fresh landed anchovy. To make a less impact it is possible to use more fish residues as main input for fish oil production.

Comparing the results of this study with other studies, it is concluded that the comparison of the impact on the environment is made according to different methodologies, but in the reviewed studies, the alternative of microalgae oil has a lower impact on the environment than the alternative of fish oil.

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# Life Cycle Impact Assessment of Microalgae and Synthetic Astaxanthin Pigments

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*Abstract* – **The marketability of fish depends on the visual appearance of the fish, so the feed ingredient pigment contributes to the nutritional value and visual appearance of the product. The benefits of a natural pigment derived from microalgae are the ecological benefits, as the culture can fix carbon and release oxygen. The economic aspect is a benefit of synthetic pigments. The Life Cycle Assessment (LCA) method was used to determine the environmental impact of natural and synthetic pigments. The results obtained from the LCA are expressed according to the impact categories defined by the Product Environmental Footprint Category Rules (PEFCR). A sensitivity analysis was also carried out comparing the environmental impacts of electricity generated with hydropower or using a field mix from Norway for the natural pigment. The total single score value for natural pigment is 1.17E+01 mPt and the largest impact is from sodium nitrate and electricity. The sensitivity analysis results for electricity from the country mix is 1.82E+01 mPt. The total single score value for synthetic pigment is 8.24E−01 mPt, with the largest impact from methanol. Synthetic pigments have a lower environmental impact than natural pigments, but a sensitivity analysis shows that the environmental impact can be reduced by choosing an alternative to electricity. It should be noted that the comparison presented represents a general comparison of alternatives, as the input data is derived from a literature review.**

*Keywords* – **Astaxanthin; fish feed; LCA; microalgae pigment; synthetic pigment; sustainability.**

## 1. INTRODUCTION

Global food production and consumption dynamics have evolved rapidly in recent decades, including fish consumption worldwide [1]. The rapid development of the industry has a positive impact on socio-economic indicators, but the impact of the industry on the environment and sustainability is causing concern for the industry [2]. Feed is one of the key elements in the aquaculture industry to achieve sustainability [3]. Sustainability is a balance between environmental, economic and social development [4]. Problems with the environment have slowly and steadily developed from previous generations and the time has come when society must live more sustainably to preserve and rejuvenate the environment [5].

Fish cannot synthesize the pigment by themselves, so it is absorbed from the diet [6]. Pigments give fish an attractive colour and astaxanthin is a red pigment which increases salmon marketability due to the appearance of the fish [7]–[9]. Also, astaxanthin pigment has high antioxidant activity and is an important dietary component for adequate growth and

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reproduction [7]–[9]. Under stressful conditions, astaxanthin production can be increased, as plants containing the pigment help improve stress response processes in animals [10].

Most pigments on the market are chemically synthesised pigments [11]. Synthetic astaxanthin has a lower price and a more complex production than natural astaxanthin in terms of production and cost [12]. Other advantages of synthetic astaxanthin are low antioxidant activity and high availability of synthetic astaxanthin, but the disadvantage is the use of hazardous chemical reagents, hence high environmental impact and not sustainable and renewable [13].

Microalgae are considered a potential source of valuable nutrients such as pigments, proteins, carbohydrates and lipid molecules [14]. Astaxanthin pigment can be obtained from a variety of microalgae species, but most of the astaxanthin pigment is obtained from the microalgae *Chlorella zofingiensis* or *Haematococcus pluvialis*, while *Chlorella sorokiniana*, *Tetraselmis* sp. and *Scenedesmus* sp. are minor producers of astaxanthin pigment [12]. The use of microalgae in aquaculture brings economic benefits and also creates ecological benefits, as microalgae culture can capture carbon and release oxygen, thus large-scale pigment production from microalgae can be considered a greenhouse mitigation process [15]. Other advantages of natural pigments include low environmental impact, sustainability and renewability, but disadvantages include the expensive biorefining process and production, the short lifetime of the bio-product and the low availability of natural astaxanthin, as well as the space and time-consuming cultivation of *H. pluvialis* [13].

The Product Environmental Footprint Categorization Regulations (PEFCR) are designed to allow the comparison of products from the same industry. The PEFCR of feed production has 18 categories that describe the impact on the environment, which is determined using a Life Cycle Assessment (LCA). The LCA carried out an environmental impact assessment of three different photobioreactor technologies used to produce astaxanthin from *Haematococcus pluvialis*, with energy consumption as the most influential factor, although the technologies have different technical solutions and productivity [16]. Another LCA is an environmental impact assessment, which compares extraction methods to extract astaxanthin from *Haematococcus pluvialis* microalgae, and the more sustainable method is the one with a higher yield, lower cost, fast turnaround time and medium environmental impact [17].

The study aims to carry out an environmental impact assessment and to compare a natural pigment and a synthetic pigment. LCA was used and environmental impacts were determined according to the impact categories defined by PEFCR. The study also includes an analysis of the sensitivity of the natural pigment when the type of electricity is changed and how this affects the environmental impact.

## 2. METHODS

LCA consist of goal and scope, inventory, impact assessment and interpretation results in interpretation, which are carried out by ISO 14040 [18] and ISO 14044 [19]. The used software is *SimaPro 9.4*.

### 2.1. Goal and scope

The scope of the study includes the evaluation of pigment that can be used in fish feed. The astaxanthin pigment alternatives are natural pigments from microalgae culture Haematococcus *Pluvialis* and synthetic pigments. Functional Unit in this LCA study is 1 kg of pigment.

*2.2.* System boundary

In this case, LCA is "cradle to gate" and used data from the literature review. In Fig. 1.is system boundaries for boundaries for natural pigment and data is from literature review [20]. In Fig. 2 is system boundaries for synthetic pigment and data is from literature review [21].
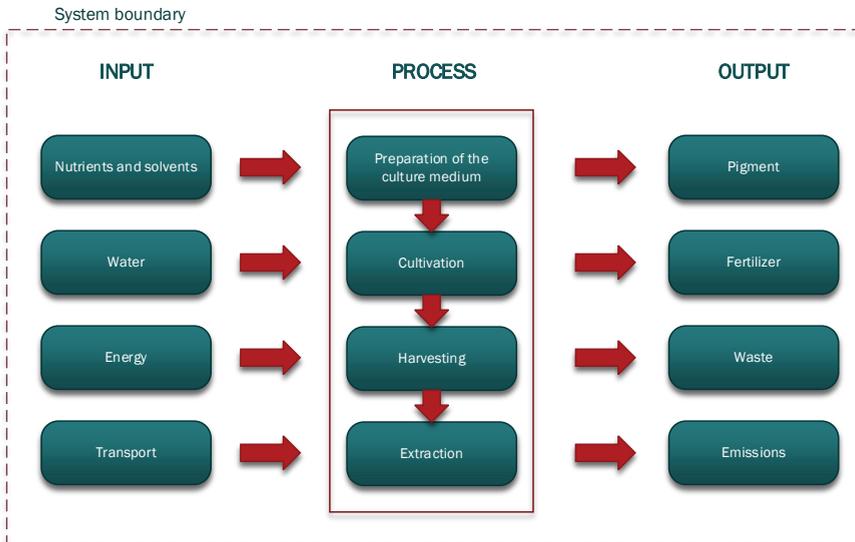


Fig. 1. System boundaries for the cradle-to-gate for microalgae pigment [20].
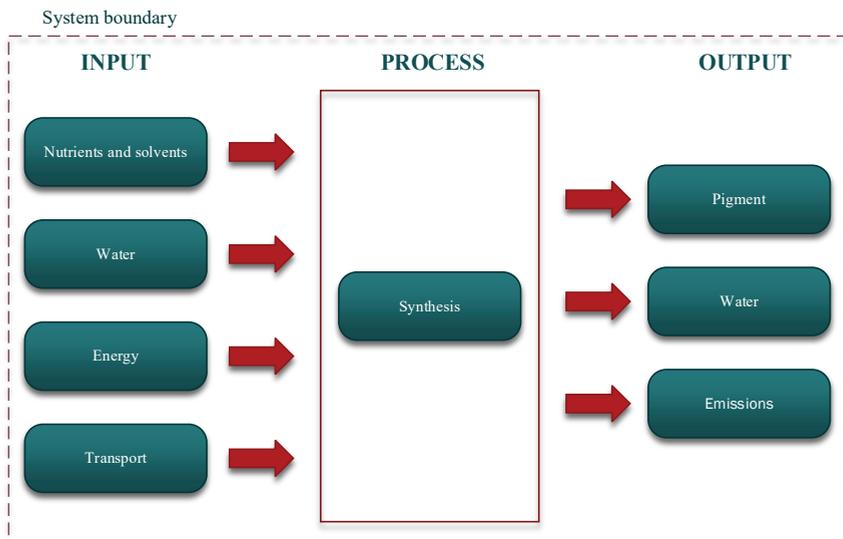


Fig. 2. System boundaries for synthetic pigment [21].

## 2.3. Life cycle stages

Life cycle stages consist of – the production of feed ingredients, transport of feed ingredients to the feed mill and feed production phases. The life cycle inventory energy and material inputs and outputs are quantified from literature analysis and available data in the *Ecoinvent v3.8* database.

The used data is from a literature review, but the assumption was made, that pigment is produced in Norway. Data in *SimaPro* were modelled to Norway or Europe and used energy – electricity is from hydropower, but as input data is used hydropower from France. As excluded processes, in this case, were packaging process because in literature review data about packaging were not found.

## 2.4. Life Cycle Inventory Data

Table 1 and Table 2 are inventory data for pigment alternatives from the literature. Mostly chemicals are used for Preparation of the culture medium phase. Data is collected for all production phases and in model is used market input values – transport is already taken into account and is recommended to be used in cases where specific data is not known. The input and output data are from the literature, so it is possible that the authors of the literature did not provide a complete accounting of the data.

TABLE 1. LCI FOR NATURAL PIGMENT [20]

| Description | Amount | Unit |
|---|---|---|
| **Input** | | |
| $NaNO_3$ | 5.581 | kg |
| $CaCl_2$ | 0.364 | kg |
| $MgSO_4$ | 1.684 | kg |
| NaCl | 0.149 | kg |
| $C_6H8O_7$ | 0.036 | kg |
| $Na_2CO_3$ | 0.597 | kg |
| $H_3BO_3$ | 0.017 | kg |
| $ZnSO_4$ | 0.001 | kg |
| FeCl3 | 0.004 | kg |
| $MnCl_2$ | 0.012 | kg |
| Biomass | 0.021 | kg |
| River/rain water | 0.983 | $m^3$ |
| Air (excluding $CO_2$) | 543.4 | t |
| $CO_2$ | 0.325 | t |
| Co-solvent (fish/vegetable oil) | 5.838 | kg |
| Electricity | 2477.95 | kWh |
| **Output** | | |
| Nitrogen-rich fertiliser | 0.539 | kg |
| Phosphorous-rich fertiliser | 0.353 | kg |
| Air (excluding $CO_2$) | 543.4 | t |
| $CO_2$ | 0.3 | t |
| $NaNO_3$ | 0.111 | kg |
| $CaCl_2$ | 0.005 | kg |
| $MgSO_4$ | 0.024 | kg |
| NaCl | 0.002 | kg |
| $C_6H8O_7$ | 0.0005 | kg |

|  |  |  |
|---|---|---|
| $Na_2CO_3$ | 0.008 | kg |
| $H_3BO_3$ | 0.0003 | kg |
| $ZnSO_4$ | 0.00001 | kg |
| FeCl3 | 0.00005 | kg |
| $MnCl_2$ | 0.0002 | kg |
| **Products** | | |
| Microalgae pigment | 1 | kg |

TABLE 2. LCI FOR SYNTHETIC PIGMENT [21]

| Description | Amount | Unit |
|---|---|---|
| **Input** | | |
| Phosphonium salt | 2.83 | kg |
| Aldehyde | 0.35 | kg |
| Methanol | 7.91 | kg |
| Solution of sodium methoxide | 0.39 | kg |
| Water | 10 | kg |
| Electricity | 43.36 | kWh |
| **Products** | | |
| Syntenic pigment | 1 | kg |

## 2.5. Life Cycle Impact Assessment

In *SimaPro 9.4* software used EF 3.0 method, which makes impact assessment according to PEFCR assessment categories.

## 3. RESULTS

LCA results for microalgae and synthetic pigment from characterization are shown in Table 3, it depicts impact score per environmental category.

TABLE 3. CHARACTERIZATION RESULTS

| Impact category | Unit | Microalgae pigment | Synthetic pigment |
|---|---|---|---|
| Climate change | kg $CO_2$ eq | 3.35E+02 | 7.19E+00 |
| Climate change – Biogenic | kg $CO_2$ eq | 6.30E−02 | 9.94E−03 |
| Climate change – Land use and LU change | kg $CO_2$ eq | 4.00E−02 | 4.30E−03 |
| Ozone depletion | kg $CFC_{11}$ eq | 5.48E−06 | 2.10E−06 |
| Human toxicity, cancer | CTUh | 4.96E−08 | 3.45E−09 |
| Human toxicity, non-cancer | CTUh | 5.37E−07 | 5.90E−08 |
| Particulate matter | disease inc. | 3.22E−06 | 1.90E−07 |
| Ionising radiation | kBq $U_{-235}$ eq | 3.11E+00 | 2.48E−01 |
| Photochemical ozone formation | kg NMVOC eq | 1.78E−01 | 2.43E−02 |
| Acidification | mol H+ eq | 2.41E−01 | 3.01E−02 |
| Eutrophication, terrestrial | mol N eq | 6.47E−01 | 6.27E−02 |

| | | | |
|---|---|---|---|
| Eutrophication, freshwater | kg P eq | 1.02E−02 | 1.00E−03 |
| Eutrophication, marine | kg N eq | 7.07E−02 | 5.90E−03 |
| Ecotoxicity, freshwater | CTUe | 5.10E+02 | 1.38E+02 |
| Land use | Pt | 8.86E+02 | 3.07E+01 |
| Water use | m³ depriv. | 2.39E+01 | 2.71E+00 |
| Resource use, minerals and metals | kg Sb eq | 3.23E−04 | 3.70E−05 |
| Resource use, fossils | MJ | 4.23E+02 | 2.84E+02 |

Fig. 3 shows weighted results for microalgae and syntenic pigment, expressed in mPt value. Pt is the unit of the eco-indicator, and 1 Pt is representative of one thousand of the annual environmental loads of an average European citizen.

Fig. 3 also shows weighted results for natural pigment production in impact category. For microalgae pigment very large impact is to climate change impact category, but for synthetic pigment the largest impact is to resource use fossils impact category.
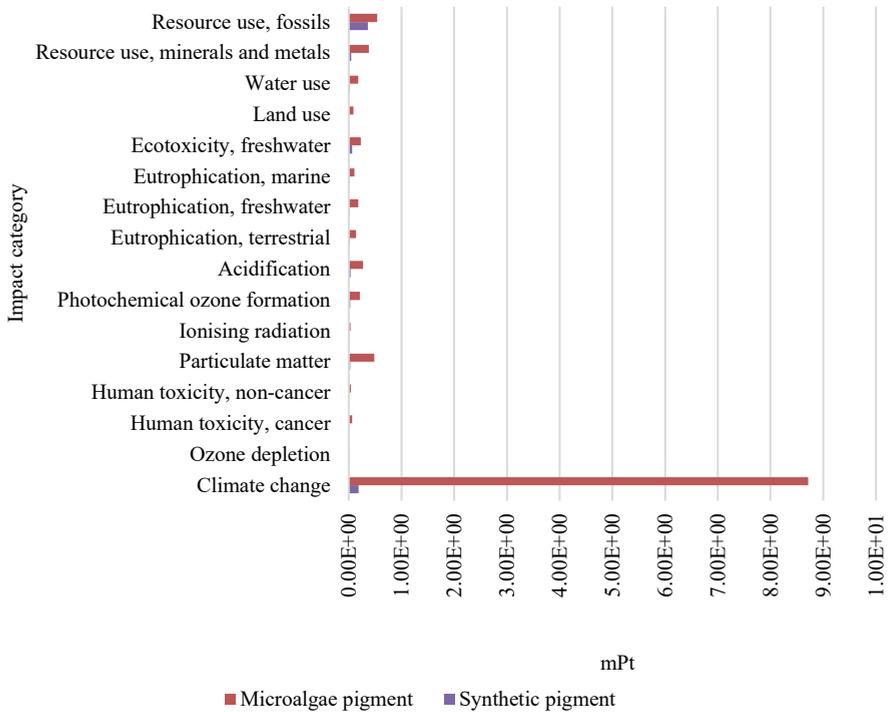


Fig. 3. Weighted results of microalgae and synthetic pigment for impact categories.

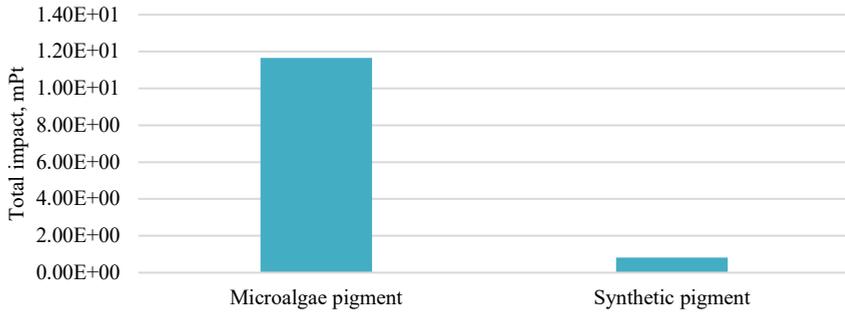The total impact value for microalgae and synthetic pigment is presented in Fig. 4.

Fig. 4. Total impact for microalgae and synthetic pigment.

Fig. 5 and Fig. 6 illustrate contribution networks to identify environmental hotspots for pigment alternatives. Largest impact comes from sodium nitrate and electricity for microalgae pigment and for synthetic pigment largest impact is from methanol.
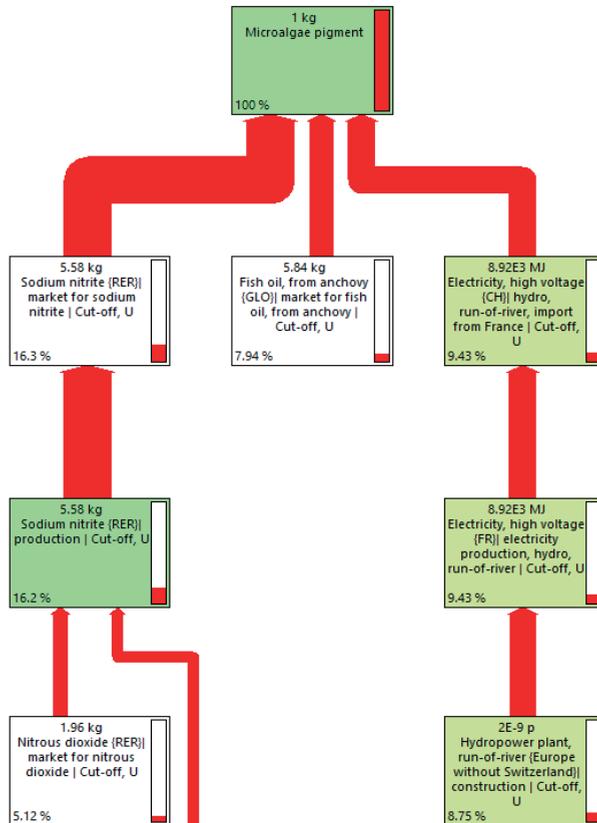


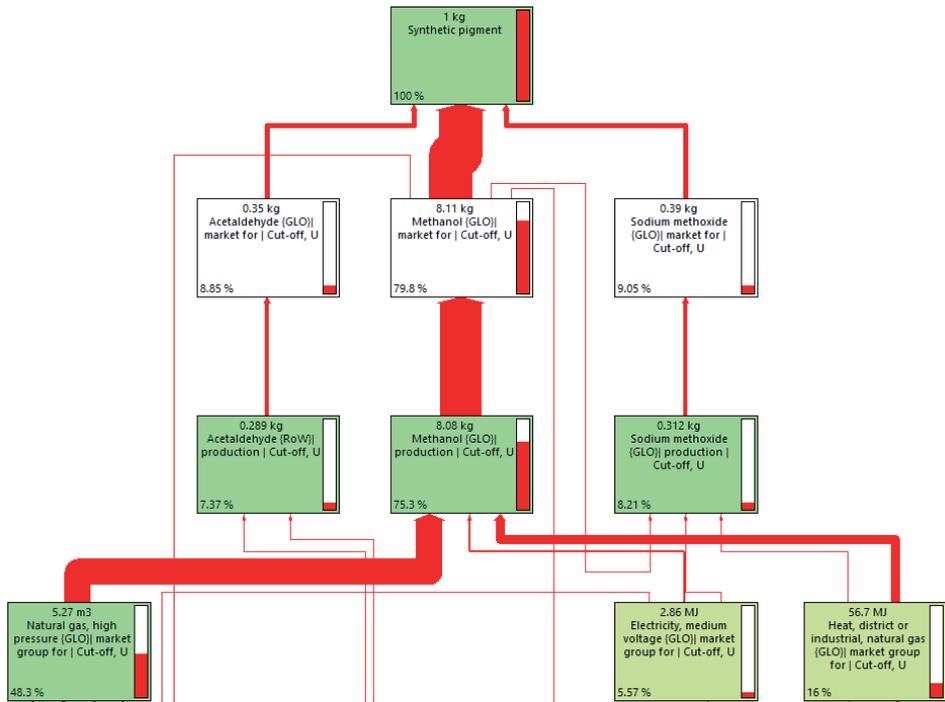Fig. 5. Tree diagram for microalgae pigment.

Fig. 6. Tree diagram for synthetic pigment.

## 3.1. Sensitivity analysis

A sensitivity analysis is performed for microalgae pigment. In this sensitivity analysis, changes were made only to electricity because it is second largest impact contributor. In original, electricity was produced by hydropower, but in sensitivity analysis, it will be compeered by a country mix from Norway.

Fig. 7 depicts weighted results for microalgae pigment production in impact category. There is quite a difference in sensitivity analysis results. The largest difference in results is to impact category resource use minerals and metals and the impact category of climate change. Total impact result is 1.17E+01 mPt for microalgae pigment using hydropower electricity, but for microalgae pigment using country mix electricity is 1.82E+01 mPt.
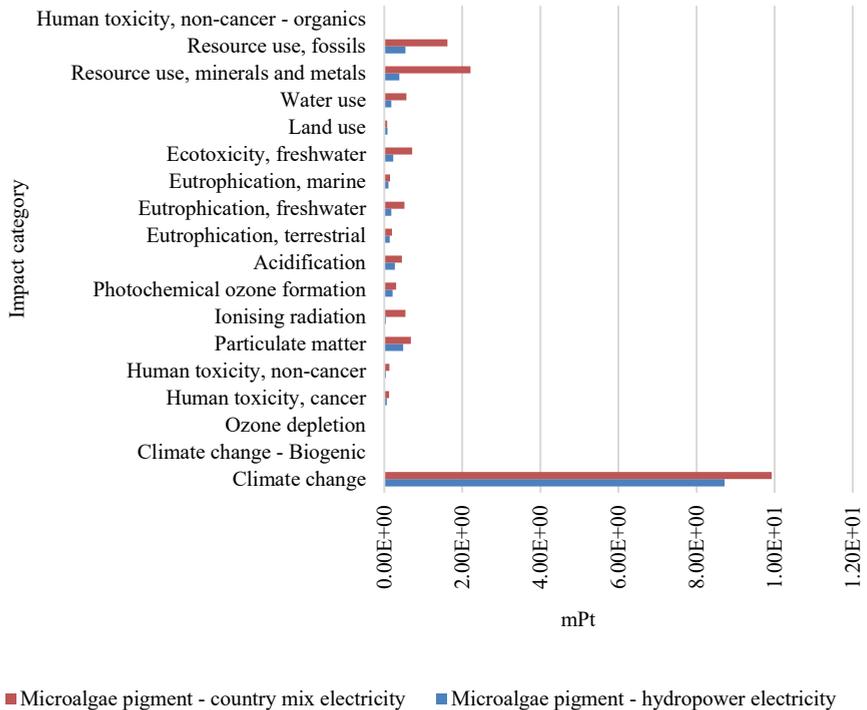
Fig. 7. Natural pigment weighted results for impact categories for hydropower electricity and country mix electricity.

## 4. CONCLUSION

An LCA study has been carried out for natural and synthetic pigments. The LCA study used data from the literature review. The document presents the results for the Functional Unit – 1 kg of pigment. From PEFCR most relevant impact categories are Climate change, Particulate matter, Acidification, Land use, Eutrophication terrestrial and Water use. Of course, the (marine) biodiversity impact category can also be determined with additional methods, but the results of this LCA study are according to PEFCR.

The total single score value for Microalgae pigment is 1.17E+01 mPt, and the most significant impact is from sodium nitrate. The sensitivity analysis results for electricity from the country mix is 1.82E+01 mPt. The total single score value for synthetic pigment is 8.24E−01 mPt. The most significant impact is from methanol.

There are many differences between microalgae and synthetic pigments. Synthetic pigment is more economical than microalgae pigment, but microalgae pigment is sustainable and renewable, whereas synthetic pigment is not [22]. Microalgae pigment is more environmentally friendly because it uses natural resources, but the production of synthetic pigment uses different types of chemicals [22]. However, pigments will continue to be used because the product's visual appearance attracts buyers. Microalgae pigment production continues to develop, which means that the use of microalgae pigment could increase and thus become more economically viable as the problem of efficient production is solved.

## ACKNOWLEDGEMENT

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*Article*

# Carbon Neutrality in Municipalities: Balancing Individual and District Heating Renewable Energy Solutions

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**Abstract:** Carbon neutrality in municipalities can be achieved by combining individual heating and district heating solutions involving the use of renewable energy sources. Each approach has advantages and disadvantages, but the best solution depends on the specific circumstances of each municipality. As an environmentally friendly and efficient energy use, a decentralised heat supply contributes to achieving energy conservation and emissions reduction goals. Decentralised energy use, such as solar collectors with thermal energy storage or biomass as a resource, reduces dependence on centralised heat generation and transmission. The appropriate infrastructure for connection to district heating networks has not yet been built. On the other hand, it is easier to make investments to construct proper infrastructure in the case of large-scale centralised heat supplies. Moreover, a centralised heat supply with renewable energy sources can provide more inhabitants with renewable heat energy. Within the framework of the study, the possibilities of using renewable energy sources in one of the municipalities of Latvia—the Carnikava parish of Ādaži Municipality—are analysed. The study examines two scenario complexes including individual heating solutions in buildings or district heating solutions with a centralised approach. The study evaluates several alternatives to increase the share of RES (solar collectors, biomass, heat pumps, etc.) in the centralised heat supply. To evaluate individual RES solutions in various municipal buildings, this study evaluates alternatives with different technical solutions that increase the use of RES in heat supply.

**Keywords:** carbon neutrality; municipalities; individual heating; district heating; renewable energy

## 1. Introduction

### 1.1. Nature of the Study

The progress of the European Union (EU) towards increasing the share of renewable energy sources (RES) in the energy sector is dynamic. From 2014 until May 2022, four regulatory legislative measures were announced, setting out the target for the share of RES in the energy sector to be achieved by 2030. Initially, the target was only 27%, but given the recent developments in the world and the Russian Federation's aggression against Ukraine, it soared to 45% [1]. Given that the Republic of Latvia (RoL) is an EU Member State, participation in the achievement of this target is its responsibility. According to Latvia's National Energy and Climate Plan 2021–2030 [2,3], it plans to increase the share of RES to be used in energy production by 2030 from 40% to 50%. One way of achieving this objective is to modernise different municipalities' district heating (DH) systems.

Before modernisation, an in-depth study is carried out with a structured analysis of each case and a description of the existing situation. It is standard practice worldwide to develop a Sustainable Energy Action and Climate Plan (SECAP) in a city/municipality context [4]. Municipalities have competence in achieving the energy transition objectives locally, including

increasing the RES share in the energy mix [5,6]. Various aspects must be considered, which can accelerate and ease the energy transition process or make it more difficult.

The main strength of the local government in such matters is its influence [7]. Influence can be seen through local regulatory legislative measures, investments, taxes, and fees [8]. The main area for improvement is related to the search for attracting, splitting, and relating the bureaucracy of funding sources. There are examples where the rational use of local government influence resulted in high-value results for achieving the energy transition objectives. Municipal green energy initiatives have contributed significantly to energy diversification and have influenced energy policy in countries such as Denmark (Denmark has consistently reduced both primary and final energy consumption since 2010, and Denmark [9] installed significant amount of large-scale solar heating plants [10] and set the national target for a building sector solely supplied by RES in 2035 [11]), Germany (Germany has a long history of seasonal thermal energy storage development [10] and a number of policies to reduce greenhouse gas (GHG) emissions [12]), and Britain, United Kingdom (UK) (the UK has set itself on a transition to carbon neutrality in both its economy and society, through the imposition of a goal, under the 2008 Climate Change Act, of reducing GHG emissions by 80% by 2050 [9]). In the meantime, such examples apply to DH and do not relate to initiatives and actions in local or individual heating (IH) [10]. In some municipalities, the share of IH may be higher than DH, which means that the influence should be directed to supporting IH in the transition to RES. It is necessary to balance DH and IH support to move optimally towards carbon neutrality [11–13]; however, most studies are based on a theoretical approach while manuscripts with case studies rarely occur.

Despite a narrow range of similar analyses, the study described in this article brings new scientific contributions. First, a developed methodology offers access to the analysis of the various DH and IH alternatives using three different parameter categories: technical, economic, and environmental. This approach makes it possible to identify an economically viable alternative and a more sustainable and environmentally friendly one. The methodology's structure can be reproduced in other similar studies and adapted for specific purposes. Secondly, the methodology developed was examined in a case study (see Section 2.1). The study's calculations are based on the real system, not on the model. Thirdly, alternative variations consist of a variety of RES technology combinations. Each alternative is scientifically justified.

### 1.2. Comparison of DH and IH

Various factors determine the difference between DH and IH [12–14]. By nature, DH and the IH differ in the level of centralisation. For example, local boilers may be installed in each private property or apartment, which in some ways ensures tariff independence and allows for a more intensive change in their consumption [15–18]. DH provides continuous heating through heating networks from heat generators (e.g., boilers, cogeneration plants, etc.) which are located away from the consumer [19–21]. Two further factors are related to infrastructure nuances—distribution costs (including building/renewal and periodical management of the heating networks) and heat losses in heating networks [11,16]. The distribution costs are closely linked to the shares of DH and IH in each municipality. This share can be characterised by linear heat density [16]. A higher share of DH means a higher linear heat density value. Accordingly, the higher linear heat density value means heating distribution costs for consumers [11]. Heat losses in heating networks only exist in the case of DH and affect the need for a higher-power boiler. This is certainly reflected in costs [17]. The reduction in heat loss in networks can be achieved by transitioning to a fourth-generation DH [18,19]. In this respect, the fourth generation means reducing the temperature regime in the heating networks (low-temperature network) by considering the specific thermal energy consumption of each connected building, which impacts the heat loss and fuel consumption reduction [6,18]. There are examples of good practices where the transition to the fourth-generation DH positively impacted the development of municipal infrastructure [6]. Since 2013, the German company BTB GmbH Berlin has

implemented a project aimed at a low-temperature network with two-way connections and network substations. A new residential area called "Life in Camp" was created, including 1200 apartments in single-family homes, row houses, and multi-apartment houses—sixty-two buildings with low heat demand, five buildings with low energy consumption, and three buildings with additional energy. The main characteristic is developing a low-temperature district heating network (60/40 °C) using a return stream from a conventional heat grid (110/55 °C). This is probably due to a low thermal energy consumption of less than 15 W/m$^2$ [20].

Under Project LowTEMP: Low-Temperature District Heating for the Baltic Sea Region, fourth-generation DH was tested and implemented from 2017 to 2020 in the village of Gulbene municipality, Latvia. The project renovated a boiler house (replacing a 1 MW wood boiler with a modern high-efficiency container-type 200 kW pellet boiler) and heating networks. The heating system was rescheduled to minimise the length of the heating networks and thus reduce heat losses. The renovated buildings were switched to low-temperature DH, reducing heat supply temperature and reducing total heat losses. Heat transmission losses decreased from 40% to 5% due to heat reconstruction and reduced heat carrier temperature [21].

Within the framework of the study, the possibilities of using renewable energy sources in one of the municipalities of Latvia—the Carnikava parish of Ādaži Municipality—are analysed.

The objective of the research is to understand exactly how, in certain municipal buildings of residents (residential buildings with multiple apartments) that have a centralized heat supply using fossil fuels (natural gas) and in municipal buildings using individual natural gas boilers, a partial or complete conversion to RES heat supply solutions is possible. In the concrete municipality, the issue of how to transfer the residential and municipal buildings sector from natural gas to RES is important for the municipality's progress in meeting the goals of the Latvian National Energy and Climate Plan and the European Green Deal in the buildings sector.

This study examines two scenario complexes including IH individual heating solutions in buildings or DH solutions with a centralised approach. The study evaluates several alternatives to increase the share of RES (e.g., solar collectors, biomass, heat pumps, etc.) in the centralised heat supply. The study was carried out based on real data on the thermal energy consumption of Carnikava's buildings and scientific data sources in order to make assumptions.

In order to evaluate the most sustainable RES heat supply solutions (technology combinations) that could replace the natural gas solutions used in DH and IH in Carnikava village, the CSI was created.

## 2. Methodology

### 2.1. Case Study

Carnikava is a village and the centre of the Carnikava parish of Ādaži Municipality in Latvia. The geographical limits of the study were defined (see Appendix B). The area includes twenty-eight residential buildings, six municipal buildings, and five commercial buildings.

### 2.1.1. DH System

The Carnikava DH system consists of six interconnected boiler houses and heating networks. The total length of the heating networks is 2837 m, of which 1156 m is industrially insulated. All boiler houses have Viessmann natural gas boilers with different capacities, from 520 kW to 1500 kW (as shown in Appendix B). The main data on DH in Carnikava are shown in Table 1. Losses in heating networks range from 15% to 17%. The loss value indicates that the heat transmission infrastructure is inferior. The main reason is the preparation of hot water outside the heating season. As summer consumption is meagre, the percentage of heat losses is very high in the summer months.

| Parameter | Unit | 2019 | 2020 | 2021 |
|---|---|---|---|---|
| Natural gas consumption | 1000 m$^3$ | 1076.01 | 1024.16 | 1185.29 |
| Share of RES | % | 0% | 0% | 0% |
| Fuel input energy | MWh per year | 10,274.8 | 9756.4 | 11,247.9 |
| Thermal energy produced | MWh per year | 9308.8 | 8764.0 | 10,085.4 |
| Electricity produced | MWh per year | 0 | 0 | 0 |
| Production losses | MWh per year | 965.9 | 992.4 | 1162.5 |
| Efficiency of production | % | 90.6% | 89.8% | 89.7% |
| Thermal energy transferred to users | MWh per year | 7792.0 | 7263.4 | 8617.9 |
| Losses in heating networks | MWh per year | 1516.9 | 1500.6 | 1467.6 |
| Losses in heating networks | % | 16.3% | 17.1% | 14.6% |

#### 2.1.2. Municipality Buildings

According to 2019 data, the municipality has more than 9500 inhabitants and in the case of this study 6 municipal buildings were analysed. Therefore, municipal buildings are very diverse in terms of their functionality and building characteristics, and they are not connected to the DH system. Table 2 contains a summary of the technical parameters of municipal buildings. Each parameter is obtained using the information provided by the municipality, data on electricity, heat energy, as well as calculations based on real and scientific assumptions. Scientific assumptions for making calculations are summarized in Appendix A.

**Table 2.** Technical Parameters of Municipal Buildings in Carnikava Village.

| Parameter | Unit | Elementary School | Preschool | Cultural Centre | Music and Art School | Leisure Centre | Office Building |
|---|---|---|---|---|---|---|---|
| Technical condition | - | Renovated | - | - | - | - | Built-in 2020 |
| Heating area | m$^2$ | 7398 | 2643 | 769 | 258 | 150 | 2343 |
| Roof area | m$^2$ | 2301 | 2622 | 460 | 212 | 192 | 2970 |
| Heat consumption | MWh per year | 318 | 486 | 97 | 36 | 16 | 215 |
| Electricity consumption | MWh per year | 237 | 124 | 21 | 5 | 4 | 60 |
| Max heat load | kW | 110 | 130 | 35 | 12 | 10 | 57 |
| Fuel type | - | Natural gas | Natural gas | Natural gas | Natural gas | Natural gas | Natural gas |

Figure 1 shows the average monthly heat and electricity consumption from 2019 to 2021. The largest energy consumers are the elementary school, preschool, and office building. The largest heat energy consumption is in the heating season, especially in winter. During the summer, the heat energy consumption is for preparing hot water. From September to April, electricity consumption is higher in the preschool and elementary school, but in other buildings the difference in electricity consumption between winter and summer is up to 1 MWh per month.

Analysing the specific energy consumption of municipal buildings, the buildings with the highest specific energy consumption are preschool, music and art school, and culture centre buildings (see Figure 2). The preschool and music and art school have the highest specific heat energy consumption, but the elementary school has the lowest. The preschool and primary school have the highest specific electricity consumption, while the music and art school has the lowest specific electricity consumption. On average, the specific electricity consumption is four times lower than the specific heat energy consumption. However, the most similar specific electricity and heat energy consumption is for the elementary school, but the biggest difference in the specific electricity and heat energy consumption is for the music and art school.
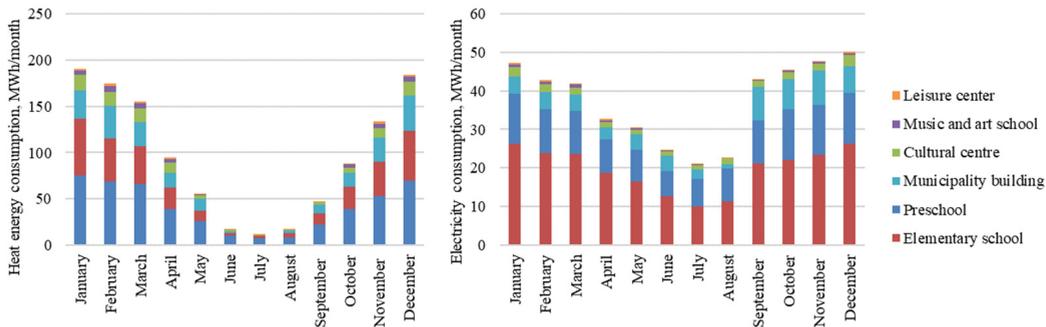
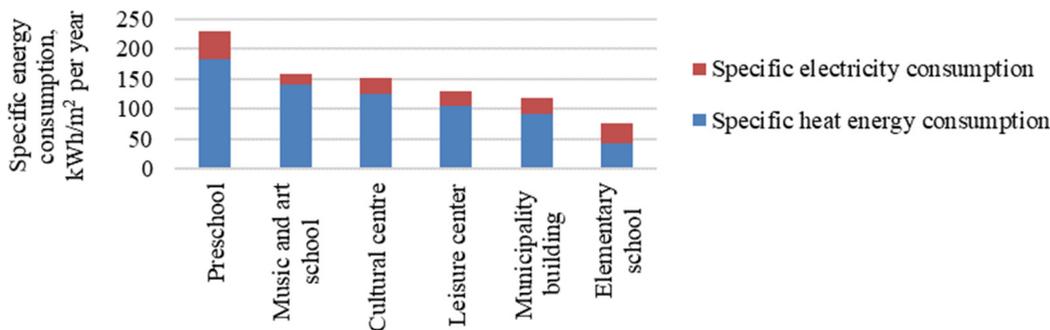**Figure 1.** Average heat and electricity consumption (2019–2021), MWh/month (2019–2021) in Carnikava Village.



**Figure 2.** Specific energy (electricity and heat) consumption in municipal buildings in Carnikava village.

### 2.2. Development Scenarios

The existing solutions in Carnikava's district heating are natural gas—six local boiler houses and natural gas boiler houses in municipal buildings. To compare the sustainability of DH solutions and individual IH solutions, by comparing the values of different factors, the case of Carnikava is used and six DH alternatives are compared with -four IH scenarios for municipality buildings. In the case of district heating, different scenarios are evaluated by combining existing and connecting new consumers. Based on research in the scientific literature, alternative RES solutions have been selected and identified, which can be used in DH residential buildings and IH municipal buildings. The selection of technology combinations was carried out in such a way that solutions with biomass, e.g., wood chips and pellets; air heat pump solutions, which are considered economically easier to implement; as well as additional sources for covering the summer load, including solar energy solutions, i.e., solar collectors for heat supply and electricity supply/for operating the heat pump and solar panels, were included (Table 3).

**Table 3.** Scenarios for district heating and municipal buildings.

| Scenarios | | District Heating | Municipal Buildings |
|---|---|---|---|
| | | **With New Consumers** | |
| 1. | Wood chip boiler with flue gas condenser | 1 boiler house with flue gas condenser | - |
| 2. | Wood chip boiler and PV panels + heat pump solution | + | - |
| 3. | Wood chip boiler and solar collectors with storage | + | - |
| 4. | Natural gas boiler and solar collectors with storage | | + |
| 5. | Pellet boiler | 2 boilers | + |
| 6. | Pellet boiler and PV panels + heat pump solution | + | - |
| 7. | Pellet boiler and solar collectors with storage | - | + |
| 8. | Heat pump solution + PV panels | | + |

### 2.2.1. District Heating System

Six possible alternatives were defined for increasing the share of RES in DH. Alternatives can be introduced at the same time as the implementation of IH development scenarios. They mainly involve the combination of separate systems and heat networks.

Different RES alternatives for consumer scenarios were evaluated for the scenario of existing consumers and the scenario of connecting new consumers. Two cases of DH development were evaluated—the five boiler houses on the left side of the railroad and the DH system contained in them were combined into a whole, and two DH were combined according to their distance from each other. Since the DH in Carnikava is also used for hot water production, which means that there is also a summer load, the scenarios of installing heat pumps and solar collectors were also evaluated when comparing the alternatives. For the created large gas boiler plant, the scenario of installing a wood chip boiler was evaluated, while in the case of the two smaller created plants, the installation of pellet boilers was evaluated as a basic alternative. The heat pump and solar collector scenarios are each supplemented by the fuel boiler used for each system—wood chips for the large system and pellets for the two smaller systems. The six alternatives for DH are listed in Table 4.

*Woodchip boiler*. In the scenario that envisages combining the five existing DH plants of Carnikava into one and connecting the municipal buildings, the construction of a woodchip boiler house was evaluated.

*Pellet boiler*. The construction of pellet boiler houses was evaluated in the scenario that proposes to combine Carnikava's five existing DH systems into two separate systems and connect municipal buildings to them. By creating two separate systems, the consumer load is slightly too low for using a wood chip boiler.

*Woodchip boiler + solar collectors with storage*. Considering that the number of consumers in Carnikava is small and distributed over a large area, the scenario where solar collectors with storage are installed to cover the summer load will be studied. They should be placed closer to the consumers. A woodchip boiler will be used to cover the heating load in the case of a combined CSA system.

*Pellet boiler + solar collectors with storage*. Considering that the number of consumers in Carnikava is small and spread over a large area, it is planned to study the scenario where PV panels are installed in combination with an air source heat pump to cover the summer load. They will be placed closer to the consumers. In the case of two separate CSA systems, pellet boilers will be used to cover the heating load.

**Table 4.** Alternative DH in multi-apartment buildings—the current situation with new consumers.

| | |
|---|---|
| 1. | Wood chip boiler with flue gas condenser |
| 2. | Wood chip boiler and PV panels + heat pump solution |
| 3. | Wood chip boiler and solar collectors with storage |
| 4. | Pellet boiler |
| 5. | Pellet boiler and PV panels + heat pump solution |
| 6. | Pellet boiler and solar collectors with storage |

2.2.2. Individual Heating Solutions

Four possible alternatives were defined for increasing the share of RES in IH in municipality buildings, replacing natural gas boilers Alternatives can be introduced at the same time as the implementation of DH development scenarios. The alternatives for IH solutions are as follows in Table 5.

**Table 5.** Alternatives for individual heating solutions in municipality buildings.

| | |
|---|---|
| 1. | Pellet boiler |
| 2. | Heat pump solution + PV panels |
| 3. | Solar collectors with thermal energy storage and natural gas boiler |
| 4. | Solar collectors with thermal energy storage and pellet boiler |

*Pellet boilers*. One of the alternatives is to replace natural gas boilers with a pellet boiler that provides heating and hot water: solar panels and a heat pump. The building has a summer heat load, so one alternative is ***solar panels***, which would generate electricity for the ***heat pump*** during the summer months. ***Solar collectors***. Assuming the roof of the building is suitable for installing solar panels, solar panels can be considered another heat energy alternative. Thus, the necessary summer heat load can be met with solar collectors.

One of the alternatives is to replace the natural gas boilers with a pellet boiler that provides heating and hot water. The provision of thermal energy with solar panels and a heat pump was analyzed as another technological solution since the heat pump does not require a large area, and the building has a large roof area that can be effectively used for solar panels. The electricity consumption of the heat pump can be covered in the summer months by using electricity from solar collectors. Therefore, this alternative evaluates the installation of both an air source heat pump and a solar power plant. In these scenarios, solar panels are considered to meet the summer load and the existing natural gas system or its replacement with a pellet boiler to meet the remaining heat load. Solar collectors could meet the summer load of the building's hot water consumption, provided the building's roof is suitable for solar collector installation. The installation of solar collectors is not considered for buildings that have low summer hot water consumption or are heavily shaded. In addition to the solar collectors, a suitable buffer tank should be integrated to cover 2–3 days of consumption.

*2.3. Decision-Making Analyses*

Sustainability assessment requires an integrated approach and a structure with several interconnected steps. The methodology of this study is based on three main pillars:

- The identification of the internal and external context that influences the sustainability of the heat supply system

- The calculation of the composite sustainability index
- The analysis of the results and the decision-making process.

Identifying the internal and external context includes a literature review of current practises in the sustainability assessment of energy supply technologies to identify key sustainability issues and develop a research methodology. The core element of the sustainability assessment is the construction of the composite sustainability index.

Composite indices are commonly used amongst scientists when choosing the most appropriate methodology to evaluate sustainable development. The method combines various aggregate values that are used to determine indicators of the topic being studied. Composite index is commonly used in research projects for policymakers to simplify the problem and highlight significant findings. A composite index allows for easy comparisons to assess the sustainability performance of regions, sectors, and other factors.

The main chronological steps that are applied when developing a composite sustainability index are illustrated in Figure 3 below.
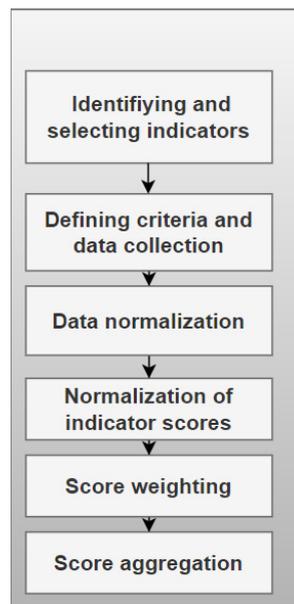


**Figure 3.** Construction of CSI [16,22].

In this study, the composite sustainability index is calculated for six district heating scenarios and four different technical solutions for decentralised (individual) heat supply. The indicator considers only the consumption of primary resources, shown as fuel consumption/total energy production in MWh in each of the scenarios. The share of solar collectors and PV panels are not considered in the calculation of efficiency; however, solar collectors and PV panels are included in the investment calculations.

The methodology of composite sustainability and the selected indicators were chosen following the study in [15].

### 2.3.1. Identification of Criteria

The second step is to identify and select appropriate criteria that are significant determiners of the study's dependent variable. When identifying key indicators, it is crucial to consider data availability for the indicators (see Table 6).

**Table 6.** Indicators for the construction of CSI for DH and IH technologies.

| No | Indicator | Units | Indicator Description | Impact |
|---|---|---|---|---|
| I1 | Consumption of fuel energy | MWh/MWh | The indicator considers only the consumption of used fuel energy and electricity from grid. Fuel consumption/total energy production in MWh in each of the scenarios.The share of solar collectors and PV panels are not included in the efficiency calculation. Electricity consumption from grid at scenarios with heat pumps also taken into account. | - |
| I2 | Specific NOx emissions | g/MWh | Gram per amount of energy produced in each of the scenarios. | - |
| I3 | Specific PM emissions | g/MWh | Indicates how much PM is produced from each MWh. | - |
| I4 | Costs of $CO_2$ reduction | EUR/t | Depending on the type of energy resource, the amount of $CO_2$ emissions produced varies. Emission factor of 0.202 ($CO_2$), $tCO_2$/MWh. The total investment is divided per ton of $CO_2$. Describes how much to invest in each system. | - |
| I5 | Investments | EUR/MWh | The investment required for the amount of energy produced | - |
| I6 | Internal rate of return | % | Internal rate of return (IRR) or economic rate of return (ERR) characterizes the interest rate at which investments in a given project are effective. If the IRR is greater than the discount rate, then the project is economically beneficial to society. The higher the value, the more efficient the project. | + |
| I7 | Production costs | EUR MWh | Production costs include alternative fuel, electricity, service, and administrative costs. | - |
| I8 | Opportunities for diversification of utilised energy resources (technology is not limited only to one type of energy resource supply | count | The energy resources are numerically evaluated as to how much it is possible to use the energy resource in each of the scenarios, taking into account the production of electricity and thermal energy. Electricity and solar PV. How many energy sources are included in the solution. The number of energy resources in each of the scenarios describes the diversification of utilised resources. | + |

Indicators such as fuel enerrgy consumption (i1), specific NOx emissions (i2), specific PM emissions (i3), $CO_2$ reduction costs (i4), investments (i5), IRR (i6) (example of net cash flow for technologies in Table 7), production costs (i7), and opportunities for diversification of energy resources used (i8) were used to evaluate and compare the district heating and individual heating scenarios.

**Table 7.** Net cash flow EUR/year (for 15 years) for DH wood chip boiler with flue gas condenser technologies.

| | 1. | 2. | 3. | 4. | 5. | 6. | 7. | 8. | 9. | 10. | 11. | 12. | 13. | 14. | 15. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| EUR/year | −1,022,215 | 318,937 | 331,662 | 344,770 | 358,270 | 372,176 | 386,499 | 401,251 | 416,446 | 432,097 | 44,828 | 464,822 | 48,194 | 499,539 | 517,683 |

All scenarios are calculated based on the same input data (e.g., thermal energy consumption, thermal energy tariff, etc.) and assumptions (technology efficiency, technology investment and operating costs, etc.). The assumptions were made based on the scientific literature, technology catalogue manuals, findings of energy industry representatives, and other sources. At the same time, the selected parameter values reflect the current situation and are partially subject to uncertainties related to the authors' vision and the energy sector's rapidly changing situation (see parameters in Appendix A). The most appropriate solution was selected based on the above indicators, including the internal rate of return (IRR) and $CO_2$ savings per amount of money invested. As an additional parameter, the amount of investment required is given, which describes the amount of money originally intended for implementing the project.

Calculations for each indicator.

**I1 Consumption of fuel energy (Equation (1)):**

$$\text{Consumption of fuel energy}\left(\frac{\text{MWh}}{\text{MWh}}\right) =$$
$$\frac{\text{fuel consumption} \times \text{fuel's lowest heat of combustion}, \frac{\text{MWh}}{\text{m}^3}}{\text{total energy production}, \text{MWh/year}} \tag{1}$$

Example calculations for DH wood chip boiler with flue gas condenser:

$$\text{Consumption of fuel energy}\left(\frac{\text{MWh}}{\text{MWh}}\right) =$$
$$\frac{\text{wood chip consumption} \times \text{wood chip lowest heat of combustion}, \frac{\text{MWh}}{\text{m}^3}}{\text{annual amount of energy produced}, \text{MWh/year}}$$

where
Wood chip consumption—10,876 ber/m.
Wood chip lowest heat of combustion—0.7 MWh.ber/m$^3$.
Annual amount of energy produced—7689 MWh.

$$\text{Cosumption of DH wood chip boiler}\left(\frac{\text{MWh}}{\text{MWh}}\right) = \frac{10,876 \times 0.7}{7689} = 0.99$$

All greenhouse gas emissions result from the combustion and fugitive release of fuels. The emission factor is a relative measure and can be used to estimate emissions from various sources of air pollution. An emission factor is a representative value that relates the amount of a pollutant released into the atmosphere to an activity associated with the release of that pollutant. It is expressed as the mass of the pollutant divided by the unit mass, volume, distance, or duration of the activity that releases the pollutant (e.g., kilograms of particles emitted per megagram). Residential wood combustion is the primary emission source for some pollutants. PM and $NO_x$ emissions per MWh generated vary depending on whether the boiler is small or large. PM and $NO_x$ emission factors once for different technologies and different resources. All $NO_x$ and PM emission factors for each technology are based on the AARHUS UNIVERSITY department of Environmental Science emission factors (for fuel input) database [23].

**I2 Specific $NO_x$ emissions (Equation (2)):**

$$\text{Specific NOx emissions} = \text{Consumption of fuel energy}\left(\frac{\text{MWh}}{\text{MWh}}\right) \times \text{NOx emission factor} \tag{2}$$

Example calculations for DH wood chip boiler with flue gas condenser:

$$\text{Specific NOx emissions of DH wood chip boiler} =$$
$$\text{Consumption of DH wood chip boiler}\left(\frac{\text{MWh}}{\text{MWh}}\right) \times \text{NOx emission factor for DH wood chip boiler}$$

where
Consumption of DH wood chip—0.99 MWh/MWh.
NOx emission factor for DH wood chip boiler—324 g/MWh (data based on AARHUS University Department of Environmental Science emission factors [24] (group 010203—district heating plants, wood and similar combustion plants <50 MW (boilers)).

$$\text{Specific NOx emissions of DH wood chip boiler} =$$
$$\text{Consumption of DH wood chip boiler}\left(\frac{\text{MWh}}{\text{MWh}}\right) \times \text{NOx emission factor for DH wood chip boiler}$$
$$\text{Specific NOx emissions of DH wood chip boiler}\left(\frac{\text{g}}{\text{MWh}}\right) = 0.99 \times 324 = 321$$

**I3 Specific PM emissions (Equation (3)):**

$$\text{Specific PM emissions}\left(\frac{\text{g}}{\text{MWh}}\right) = \text{Consumption of fuel energy}\left(\frac{\text{MWh}}{\text{MWh}}\right) \times \text{PM emission factor} \qquad (3)$$

Example calculations for DH wood chip boiler with flue gas condenser:

Specific PM emissions of DH wood chip boiler = Consumption of wood chip (MWh/MWh) $\times$ PM emission factor for DH wood chip boiler.

$$\text{Specific PM emissions of DH wood chip boiler}\left(\frac{\text{g}}{\text{MWh}}\right) = 0.99 \times = 35.6$$

where

Consumption of DH wood chip—0.99 MWh/MWh.

PM emission factor for DH wood chip boiler—emission factor for $PM_{2.5}$ is 36/MWh. (Data based on AARHUS UNIVERSITY Department of Environmental Science emission factors [24]. Group 010203—district heating plants, wood, and similar combustion plants <50 MW (boilers)).

**I4 Costs of $CO_2$ reduction**

By switching from fossil fuels to RES, a reduction in $CO_2$ emissions is achieved. Reducing $CO_2$ emissions is one of the priorities at the national and municipal levels, as the consequences of climate change affect everyone.

(1)　The reduction in $CO_2$ emissions depends on the amount of fossil energy replaced and the type of fossil energy (see Equation (4)).

$$\Delta_{CO_2} = \frac{Q(\text{annual amount of heat energy produced})}{\text{boiler efficiency}, \%} \times f_{CO_2} \qquad (4)$$

where

$\Delta_{CO_2}$—reduction in $CO_2$ emissions, tons.

Q—the annual amount of heat energy produced, MWh.

$f_{CO_2}$—$CO_2$ emission factor, $kgCO_2/kWh$.

(2)　Costs of $CO_2$ reduction (Equation (5)):

$$\text{Costs of } CO_2 \text{ reduction (EUR/tons)} = \frac{\text{Total investments, EUR/year}}{CO_2 \text{ reduction, tons}} \qquad (5)$$

Example calculations:

1.　The reduction in $CO_2$ emissions for DH wood chip boiler with flue gas condenser:

$\Delta_{CO_2}$—reduction in $CO_2$ emissions, tons;

Q—7689 MWh;

Boiler efficiency—90%;

$f_{CO_2}$—$CO_2$ emission factor, $kgCO_2/kWh$—0.202.

$$\Delta_{CO_2} = \frac{7689}{90\%} \times 0.202 = 1725.8$$

2.　Cost of $CO_2$ reduction for DH wood chip boiler with flue gas condenser:

$$\text{DH wood chip boiler } Costs\ of\ CO_2 \text{ reduction (EUR/tons)} = \frac{1,022,215}{1726} = 592$$

**I5 Investments—investments per unit of energy produced, EUR/MWh (see Equation (6)):**

$$\text{Investments per unit of energy produced, } \tfrac{\text{EUR}}{\text{MWh}} = \frac{\text{Investments per unit of energy produced, thousand.EUR/MWh}}{1000} \qquad (6)$$

$$\text{Investments per unit of energy produced,} \frac{\text{EUR}}{\text{MWh}} = \frac{132.9}{1000} = 0.13$$

**I6 Internal rate of return (IRR), % (Equation (7))**

$$\text{IRR, \%} = \text{IRR (net cash flow for 15 years)} \tag{7}$$

Internal rate of return, % for DH wood chip boiler:

$$\text{IRR, \% DH wood chip boiler with condesator} = \text{IRR(project net cash flow for 15 years)} = 34.4$$

**I7 Production costs**

Production costs, EUR/MWh (Equation (8)).

$$\text{Productions costs,} \frac{\text{EUR}}{\text{MWh}} = \frac{\text{production costs, EUR/year}}{Q(\text{annual amount of energy produced,} \frac{\text{MWh}}{\text{year}})} \tag{8}$$

where production costs, EUR—458,312. Q—the annual amount of heat energy produced, MWh/year—7689.

$$\text{Productions costs,} \frac{\text{EUR}}{\text{MWh}} = \frac{458,312}{7689} = 59.6$$

**Calculated data for CSI construction**

Table 8 shows the calculated data for constructing the composite sustainability index for each alternative. Values equal to 0 are denoted as 0.00001 because setting the input value to 0 in the complex index is not permissible.

**Table 8.** Calculations for district heating and individual heating comparison (based on scientific assumptions and Appendix A).

| | DH Wood Chip Boiler with Flue Gas Condenser | DH Wood Chip Boiler and PV Panels + Heat Pump Solution | DH Wood Chip Boiler Additionally, Solar Collectors with Thermal Energy Storage | DH Pellet Boiler | DH Pellet Boiler and PV Panels + Heat Pump Solution | DH Pellet Boiler and Solar Collectors with Thermal Energy Storage | IH Pellet Boiler | IH Heat Pump Solution + PV Panels | IH Solar Collectors with Thermal Energy Storage Natural Gas Boiler | IH Solar Collectors with Thermal Energy Storage Pellet Boiler |
|---|---|---|---|---|---|---|---|---|---|---|
| I1 MWh/MWh | 0.99 | 0.82 | 0.82 | 1.18 | 0.95 | 0.97 | 1.11 | 0.36 | 0.93 | 1.04 |
| I2 g/MWh | 321 | 228 | 238 | 343 | 242 | 254 | 351 | 0.000001 | 41 | 187 |
| I3 g/MWh | 36 | 28 | 29 | 42 | 30 | 31 | 206 | 0.000001 | 0.00001 | 110 |
| I4 EUR/t $CO_2$ | 592 | 832.8 | 1385.7 | 380.8 | 684.5 | 1145.8 | 587.9 | 19.4 | 5410.8 | 957.6 |
| I5 EUR.thousand./MWh | 0.13 | 0.19 | 0.31 | 0.09 | 0.15 | 0.26 | 94.62 | 284.48 | 126.53 | 193.43 |
| I6 % | 34.45 | 25.74 | 9.40 | 7.75 | 7.29 | −11.57 | 0.01 | 0.4 | −0.1 | 0.03 |
| I7 EUR/MWh | 59.6 | 52.7 | 54.2 | 106.5 | 94.5 | 97.9 | 86.9 | 291.1 | 110.6 | 95.2 |
| I8 Count of resources | 2 | 3 | 3 | 2 | 3 | 3 | 2 | 3 | 3 | 3 |

### 2.3.2. Data Normalization

When creating a complex composite sustainability index, the data must first be normalized for mutual comparison of measures and indicators. To compare and compile indicators, the data must first be normalized. To standardise the indicators, the min–max method was used in sustainability studies for normalization. The min–max normalization method was used for normalisation, which is also used in environmental decision making and policy analysis. This method presents the results on a scale of [0;1]. The indicators selected for the study were normalized using Equation (9).

$$I_{N,ij}^{+} = \frac{I_{act,ji}^{+} - I_{min,ji}^{+}}{I_{max,ji}^{+} - I_{min,ji}^{+}} \tag{9}$$

where

$I^+_{N,ij}$    Normalized indicator;

$I^+_{act,i}$    The actual value of indicator;

$I^-_{min,i}$    Minimum value of an indicator;

$I^+_{max,i}$    Maximum value of an indicator;

$i$       Specific indicator [16,24,25].

### 2.3.3. Weighting of Indicators

To determine the weight of each indicator, it is possible to use expert interviews to determine the importance of the indicators or assign the same weight to each indicator so that the total weight of the indicators is one. An equal weighting technique was used in this study. Since eight indicators have been chosen, which describe the economic profitability and environmental dimension of RES technologies, the weight of each indicator is 0.13.

The composite sustainability index is calculated as the total sum of all indicators, according to Equation (10).

### 2.3.4. Aggregation of Indicators into CSI

The sum of all indicators results in the final CSI, which can be used for further comparisons.

$$I_{CSI} = \Sigma^n_j \, W_j \times I_i \qquad (10)$$

where

$I_{CSI}$    is a composite sustainability index;

$W_j$    the impact weight of indicators of equal importance (calculated in %) [23,25]

$I_i$    the normalized value of an indicator.

## 3. Results and Discussion

The selected indicators make it possible to assess the economic potential of the selected DH and IH alternatives, characterized by the costs of implementing the relevant technologies instead of the existing natural gas boilers, the technical possibilities for diversifying resources, as well as the impact of technological solutions on the environment.

**Economic dimension indicators**. The calculations show that out of the six alternatives offered in the centralized heat supply and four alternative solutions in the individual heat supply, the highest fuel energy consumption is for the alternatives DH pellet boiler and IH pellet boiler. The highest investment in the energy produced is calculated for the alternative IH heat pump solution + PV panels. Among the technological solutions, the lowest IRR, replacing the existing natural gas boiler by introducing one of the RES technologies, was evaluated for the DH alternatives pellet boiler and solar collectors with storage, but the highest for the DH alternative wood chip boiler with flue gas condenser. The highest costs of $CO_2$ production are calculated for IH solar collectors with storage and natural gas boiler. The IH heat pump solution + PV panels are rated as the highest-production-cost alternatives.

For the **environmental dimension indicators,** among the alternatives, the highest NOx and PM emissions were assessed for the IH wood pellet boiler.

From the calculated indicators, it was not unequivocally determined which of the proposed alternatives will be the most sustainable solution, which should be introduced in the municipality as the first, and whether they will be DH or IH technological heat supply solutions, which would allow the existing heat supply solution—natural gas boilers—to be partially or wholly abandoned. In order to determine the sustainability of these solutions based on the calculated indicators for each of the alternatives, the CSI was created.

*Assessment of Alternatives in DH and IH*

The composite index results (see Figure 4) show the highest score for three DH alternatives—DH wood chip boiler and PV panels + heat pump solution (0.79); DH wood chip boiler and solar collectors with storage (0.73); and DH pellet boiler and PV panels

+ heat pump solution (0.69). All three solutions rated above combine either wood chip boilers or wood pellet boilers in combination with heat pumps and/or solar panels or solar collectors. Two higher rated DH alternative solutions include air-type heat pumps, and two include PV panels. All three alternatives have lower production costs and investments needed compared to the other alternatives, and it is also possible to diversify energy sources.

The fourth highest rated alternative was the IH heat pump solution + PV panel (0.66). This technological solution does not require fuel energy consumption, emissions are formed only from the electricity required to operate the pump, and it also has the lowest $CO_2$ reduction costs of the alternatives.

Four lower rated alternatives were three alternative solutions for individual heat supply for municipal buildings and one DH alternative solution—IH solar collectors with storage and natural gas boiler (0.59); IH solar collectors with storage and pellet boiler (0.54); DH pellet boiler (0.49); and IH pellet boiler (0.34).

IH alternatives with solar collectors with storage and natural gas boilers are undervalued due to economic indicators such as IRR and investments/produced energy. Therefore, the lowest indicator for the alternative of solar collectors with a natural gas boiler is the IRR, which determines that installing such a combination of technologies for a specific municipal building is not profitable. Similarly, IH solar collectors with storage and pellet boilers in the case of an alternative. The low score for individual heat supply with solar collectors can be explained by the fact that a specific urban building was evaluated and not a set of several buildings in this case. Therefore, in the case of solar collectors, a larger investment is required for one building, and the maximum roof area of the urban building for installing solar collectors must also be considered.
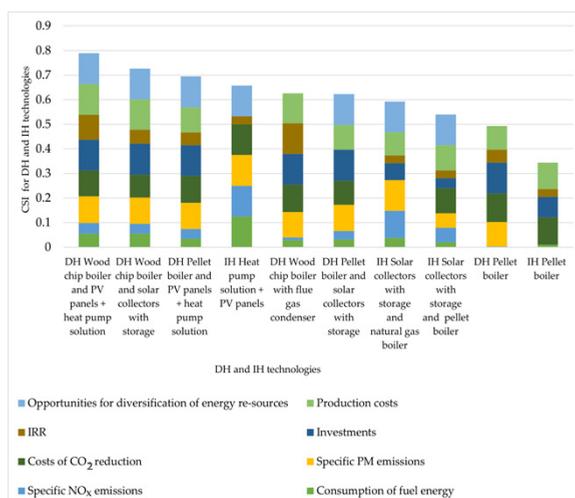


**Figure 4.** CSI for IH and DH technologies.

The DH pellet boiler alternative is rated with the second lowest rating in CSI. Such indicators as fuel energy consumption and $NO_x$ emissions influence the low rating of the alternative. The lowest alternative in the sustainability index is the installation of an IH pellet boiler instead of existing natural gas boilers, which is determined by such indicators as fuel energy consumption, emissions, and IRR, which characterize the fact that such a project will not be economically feasible to implement.

The following are the limitations of the study: The low score is influenced by the fact that a solution with solar collectors was only considered for a single municipal building, but solutions for other technologies were considered for multiple buildings, adding up

the volume produced and the total investment by types of alternatives. Solar collectors are one of the highest investments in terms of technology, and the maximum roof area of each building influences the possible number of collectors. In addition, this scenario includes the installation of a pellet boiler. Therefore, compared to the other alternatives, it is not economical for the specific urban building to implement this solution, which is also reinforced by the low IRR indicator.

In future studies, it would be necessary to use expert surveys to add indicators characterizing the social dimension to the economic environmental indicators for the most complete analysis.

## 4. Conclusions

This research aims to understand how it is possible to switch to renewable energy technologies in multi-apartment buildings and municipal buildings in Carnikava, where natural gas is used as fuel. Furthermore, it asks which economic or environmental indicators affect the potential and sustainability of RES technologies. This study was conducted based on real data on the thermal energy consumption of Carnikava's buildings and scientific data sources to make assumptions.

The two main technological solutions compared to existing natural gas combustion systems were wood chip and pellet boilers. Solar collectors and heat pumps were evaluated as additional alternative scenarios to complement the wood chip and pellet boilers. The scenario with solar collectors included the installation of a wood chip or pellet boiler to meet the heating load, supplemented by solar collectors with storage to meet the summer hot water load. The scenario with heat pumps also provided for installing a wood chip or pellet boiler to cover the heating load, supplemented by installing heat pumps to cover the summer hot water load. Since electricity is needed to operate the heat pump, installing heat pumps and solar panels to generate electricity was considered. Air-to-water-type heat pumps were chosen for the analysis of alternatives.

The composite index results show the highest score for three DH alternatives—DH woodchip boiler and PV panels + heat pump solution (0.79); DH woodchip boiler and solar panels with storage (0.73); and DH pellet boiler and PV panels + heat pump solution (0.69). Only the fourth highest rated alternative was for the IH alternative heat pump solution + PV panel (0.66).

The lowest rated alternatives were IH solar collectors with storage and natural gas boiler (0.59) and IH solar collectors with storage and pellet boiler (0.54). The low ratings of the solar collector solutions can be explained by the fact that the possibilities of installing solar collectors were analyzed for a municipal building, where the implementation of such a project is too expensive, and that the low rating is mainly influenced by factors such as the IRR and the total investment concerning the total amount of energy generated.

The DH pellet boiler (0.49) and IH pellet boiler (0.34) boiler alternatives are rated the second lowest and lowest in CSI. Indicators such as fuel energy consumption and NOx emissions influence the low rating of the alternatives. The lowest alternative in the sustainability index is the installation of an IH pellet boiler instead of the existing natural gas boilers. This is determined by indicators such as fuel energy consumption, emissions, and IRR, which characterize the fact that such a project is not economically feasible. It can be concluded that the significant impact on the sustainability rating in CSI comes from IRR and investments per unit of energy produced. If the alternative is not economically feasible to implement and the invested investments do not pay off, this determines that the alternative will have a lower rating in the long-term evaluation. Alternatives that include wood pellet boiler solutions are most affected by indicators such as fuel energy consumption and NOx emissions.

It can be concluded that DH solutions in the case of Carnikava are more sustainable, which is determined by economic indicators such as IRR and investments, economic and technical indicators such as fuel energy consumption, and environmental indicators such as NOx emissions. The analysis and creation of a CSI based on real data and assumptions based on the scientific literature serves as an effective method that can be used in the decision-

making process to simultaneously evaluate the economic and environmental dimensions and decide on the most sustainable solutions, so that municipalities can decide to increase RES in centralized and individual heat supply.

## Nomenclature

| | |
|---|---|
| Individual heating | IH |
| District heating | DH |
| Composite sustainability index | CSI |
| Renewable energy sources | RES |
| Particulate matter emissions | PM emissions |

## Appendix A

**Table A1.** Parameters and values used in the study.

| Parameter | Value | Unit |
|---|---|---|
| Technology creators | | |
| Natural gas boiler efficiency | 90 | % |
| Chip boiler efficiency | 87 | % |
| Pellet boiler efficiency | 85 | % |
| Diesel boiler efficiency | 90 | % |
| Solar panel area | 1.92 | m$^2$ |
| Power of one solar panel | 405 | W |
| Nominal efficiency of solar panels | 0.211 | |
| Loss factor of solar panels | 0.95 | |
| Nominal efficiency of the solar collector | 78.8 | % |
| Maximum efficiency of the solar collector | 0.89 | % |
| The average temperature of the solution circulating in the solar collector at the given hour | 70 | °C |
| Absorption area of the solar collector | 1.78 | m$^2$ |
| Solar panel area | 2.05 | m$^2$ |
| Technology costs | | |
| Pellet boiler | $526.803.94 \times x^{(-0.299)}$ | EUR/kW |
| Pellet boiler with hydraulic system | $104.0117.4 \times x^{(-0.349)}$ | EUR/kW |
| - Part of the boiler and equipment costs | 40 | % |
| - Part of construction and design costs | 45 | % |
| - Part of the cost of the heating unit and thermal insulation | 6 | % |
| - Part of other costs | 9 | % |
| Chipped boiler house | $-4081.6 \times x^3 + 74,447.43 \times x^2 - 452,854.13 \times x + 1,151,845.31$ | EUR/kW |

**Table A1.** *Cont.*

| | Parameter | Value | Unit |
|---|---|---|---|
| - | Part of the boiler and equipment costs | 33 | % |
| - | Part of construction and design costs | 45 | % |
| - | Part of the cost of the heating unit and thermal insulation | 6 | % |
| - | Part of other costs | 16 | % |
| | Flue gas condenser | 100 | EUR/kW |
| | Heat pump (technology + installation) | 266.36 | EUR/kW |
| | Solar panels (technology + installation) | $y = 5883.3086467157x - 0.3743667246$ [1] | EUR/kW |
| | Solar collectors (high-power projects) | 155.4 | EUR/m$^2$ |
| | Solar collectors (low-power projects) | 275.3 | EUR/m$^2$ |
| | Thermal energy storage (large-capacity projects) | 113.8 | EUR/m$^3$ |
| | Thermal energy storage (low-capacity projects) | 735 | EUR/m$^3$ |
| | The heating unit of the building | 50 | EUR/kW |
| | CSS pipeline (metal pipe) | $=1.3756 \times x + 150.89$ [2] | EUR/m |
| | Fuel indicators | | |
| | The lowest heat of combustion of natural gas | 9.5 | MWh/1000 m$^3$ |
| | The lowest heat of combustion of wood chips | 0.7 | MWh/t |
| | The lowest heat of combustion of pellets | 5 | MWh/t |
| | The lowest heat of combustion of diesel fuel | 9.91 | Mwh/m$^3$ |
| | Cost of energy resources | | |
| | The price of natural gas | 90.00 | EUR/MWh |
| | Chip price | 32.00 | EUR/MWh |
| | The price of pellets | 64.00 | EUR/MWh |
| | Electricity tariff | 300.00 | EUR/MWh |
| | Electricity price for electricity transferred to the network (within the Net settlement system) | 250.00 | EUR/MWh |
| | Electricity received from the network (within the Net settlement system) | 50.00 | EUR/MWh |
| | The price of diesel fuel | 93.24 | EUR/MWh |
| | Heat energy production indicators | | |
| | Service costs | | |
| | Natural gas | 12.500 | EUR/MW gadā [3] |
| | A splinter | 20.000 | EUR/MW gadā |
| | Granules | 17.500 | EUR/MW gadā |
| | Diesel fuel | 12.500 | EUR/MW gadā |
| | Administrative costs and salaries | | |
| | Natural gas | 15.000 | EUR/MW gadā |
| | A splinter | 25.000 | EUR/MW gadā |
| | Granules | 20.000 | EUR/MW gadā |
| | CO$_2$ taxes | | |
| | Natural gas | 15 | EUR/tCO$_2$ |
| | A splinter | 0 | EUR/MWh (saražoto) |
| | Granules | 0 | EUR/MWh (saražoto) |
| | Additional costs (not fuel) | | |
| | Natural gas | 20.0 | % |
| | A splinter | 50.0 | % |
| | Granules | 30.0 | % |

[1] x—technology capacity, kw. [2] x—pipeline diameter, mm. [3] The installed capacity of the technology.
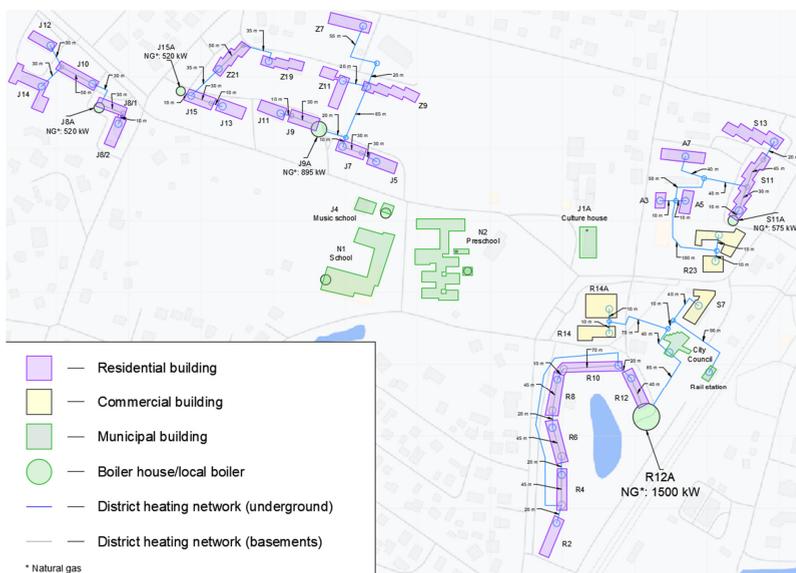
**Appendix B**



**Figure A1.** The area of Carnikava village, that falls within the scope of the study (created by authors).

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# Analysing Metal Melting Methods for Green Transformation of Scrap Metal: Case Study of Latvia using MCDA and SWOT Analysis

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*Abstract* – **Metal is one of the most widely used materials in the world. It was a crucial driving force in technological development since the industrial age and continues to push us forward to this day. As metal consumption grows, so does the amount of scrap metal generated. Proper utilization of this waste is crucial in mitigating the negative environmental impacts of the metalworking industry. The processing and use of raw materials is often associated with high resource consumption and high emissions. The utilisation of scrap metal instead of raw metal can lead to up to 10 times less electricity consumption and up to 30 times fewer $CO_2$ emissions. However, selecting the most suitable scrap metal processing technology is crucial, particularly in the case of the metal melting furnace which is the backbone of the industry. The efficiency of this process determines the environmental indicators for the entire scrap metal melting process. This paper conducts an analysis of 8 types of metal melting furnaces based on 11 environmental criteria. Furthermore, a SWOT analysis is conducted to evaluate the efficiency of the metal smelting process in Latvian metalworking enterprises and the potential for future expansion.**

*Keywords* – **Emissions; industry; Latvia; metallurgy; MCDA; scrap metal; smelting; sustainability; SWOT; waste management.**

## 1. INTRODUCTION

Metal is one of the most widely used materials in the world. It is present in many areas of life, including construction, the production of household items, technology industries, etc. Metal has played an essential role in technological development since the beginning of the Industrial Age and continues to be a key material in modern times. The crude steel produced constantly grows and reaches 1.958 billion tons in 2021 [1], [2].

Given the rising demand for metals, it is unsurprising that the metals sector is facing the challenge of meeting the Paris Accords to keep global warming below two °C below pre-industrial levels. As indicated in [3], the steel sector is responsible for 7 % of direct $CO_2$ emissions. Investors in this sector demand active action from companies and count on the maximum possible decarbonization of the industry. Considering the benchmarks set by the agreement, it can be assumed that the pressure exerted on the industry will only increase [4].

One of the ways to reduce emissions in the metallurgy sector without losing quality at the same time can be the complete or partial replacement of pure metal in production with scrap

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metal. According to [2], the demand for this resource has been steadily growing over the past decade, reaching 503.5 million tons in 2021, when a year earlier demand was 473.2 million tons.

Scrap metal is obtained from discarded material that still has a monetary value and can be recycled. It can be divided into categories depending on the products it was recovered from – it can be obsolete scrap if the source was used and/or end-of-life products. Scrap can also be primary/new if the source is from a manufacturing process that generates scrap metal, shavings, etc. As follows from such a division, obsolete scrap metal requires cleaning and recovery before processing, while the new one can be used almost immediately without significant technical investments [5]–[7].

Scrap metal recycling involves recovering material to the extent required for the specific manufacturing process in which the scrap metal will be used. With a reasonably well-established process, the processing of scrap metal requires less investment of resources than the use of primary materials. This is an essential advantage as it avoids the disposal of materials in landfills (and thus avoids the loss of a resource), which in turn is an effective and sustainable strategy to reduce emissions [8], [9].

Scrap metal recycling is usually divided into ferrous metals and non-ferrous. Some iron content distinguishes ferrous metals, while non-ferrous scrap metal contains aluminium, lead, copper and other valuable metals. Recycling scrap metal allows extracting many components from already created alloys – copper, aluminium, brass, etc., without damage and using them to produce new valuable products [3], [10].

Proper disposal (recycling) of metal and scrap metal can help reduce emissions and $CO_2$. This can be achieved in the following ways:

1. The use of scrap metal in production requires less energy compared to the production of products from "raw metals". As stated in [3], producing new metals requires ten times more electricity and creates 30 times more $CO_2$ emissions than working with scrap metal. If done so, metallurgists can partially replace coal with electricity – and reduce the share of fossil fuels from 75 % (2020) to 22 % by 2050 (assuming CCUS plants are also used). They are assuming that by 2030, technologies already on the market will be able to provide up to 85 % reduction in emissions in the sector. This is possible, provided that the share of scrap metal in the steel industry reaches at least 46 % by 2050. Recycling metals saves commonly used materials such as aluminium. Its processing into a new product requires 5 % less energy than making this product from scratch. Using steel and tin to manufacture containers/cans can save 60 to 74 % of energy compared to production from raw materials [11].

2. Quality collection, sorting and processing of scrap metal can reduce emissions from transportation and waste management processes. The chemicals used in mining pollute the air, reduce soil quality, and often end up in groundwater. Simultaneously, ore mining processes require massive amounts of energy. Even though ores can only be mined in certain places worldwide, metal production is carried out everywhere. This means that the mined ore must be delivered to the plant, which is associated with emissions from transportation processes. Using scrap metal can not only conserve natural resources (which are not increasing in amount), reduce emissions from ore mining and improve the environmental performance of the sight but also significantly reduce emissions from international logistics [12].

3. Compared to primary metals, scrap metal requires significantly fewer resources, producing fewer emissions. Another advantage is reducing the burden on mining enterprises, as the need for iron ore and coal, the primary materials in metal production,

is reduced [3]. Each used ton of scrap metal avoids an average of 1.7 tons of $CO_2$ emissions and saves up to 1.4 tons of iron ore, up to 0.8 tons of coal and up to 0.3 tons of limestone [13]–[15].

Thus, proper scrap management can reduce $CO_2$ emissions, conserve resources and contribute to a sustainable and circular economy. In such a way, using scrap metal can be considered a "green transformation" of this material – it is no longer a waste but a valuable resource for widely utilized material production. According to [1], [16], in 2020, more than 20 % of steel was produced from scrap metal, but 70 % was still produced from raw metal. Most of the production relates to Blast Furnaces, designed to smelt iron ore and produce pig iron, which is then used to make steel. About 5 % of steel from raw metal was produced in electric furnaces (EAF). However, it should be noted that electric furnaces, unlike Blast furnaces, can fully work with scrap metal, significantly reducing dependence on raw metal.

### 1.1. Metalworking in Latvia

According to Eurostat data [17], the amount of scrap metal collected in Latvia increased over time. Unlike ferrous metal, non-ferrous metal is not growing so noticeably – over ten years, the increase was slightly less than 3 %. The increase in collected ferrous metal showed its maximum in 2018 – the increase was 23 % compared to 2010.

In 2008, the European Parliament issued a directive under which member states undertake to develop a waste collection and management system. One of the tasks is to develop and improve the separate collection of waste, including the separate collection of metal and scrap metal, as well as the availability of such a service throughout the country [18]. As follows from the Ministry of Environmental Protection and Regional Development report, although the Directive set a deadline of December 31, 2014, even for 2019, this task still needs to be completed. Another target – to prepare for recycling and recycle at least 50 % (by weight) of waste, including metal/scrap – was also not fully achieved. However, from the amount of metal collected for 2018, 71.38 % was recovered, and 71.34 % was recycled with a target of 50 % (by weight, for both indicators), which is a good result. However, it should be pointed out that this target only applies to packaging materials and not to total metal waste per se [19], [20].

As part of the measures taken to increase the amount of collected metal in the country, collection points for metal and scrap metal were created, contributing to an increase in the amount of collected ferrous metal from 2016. The increase in the number of scrap metal collection points in 2021 increased the production rate in the metalworking sector by 18 % compared to a year earlier [21], [22].

In 2017, MASOC (Association of Mechanical Engineering and Metalworking Industries of Latvia) launched a project aimed at strengthening the cluster of metalworking enterprises, increasing efficiency and developing sales markets, as well as close cooperation with the scientific sector and collaborating partners (suppliers and buyers) [23]. This project aims to strengthen the manufacturing sector, which means an increase in turnover, and cooperation with the scientific sector potentially means testing new technologies for the processing and processing of metal and scrap metal, which will also positively affect the productivity and environmental friendliness of the metalworking sector.

## 2. METHODOLOGY

The purpose of this work is to conduct an in-depth analysis of metal smelting furnaces based on the technologies available in Latvia, as well as to determine the potential for the country to move towards more environmentally friendly methods of scrap metal processing.

To achieve this goal, a combination of two methods was chosen – SWOT and Multi-Criteria Decision Analysis (MCDA). In this paper, MCDA includes 8 alternatives based on 11 natural sector indicators. In turn, the SWOT analysis includes an analysis of ten Latvian metalworking/smelting enterprises.

### 2.1. Multi-Criteria Decision Analysis

The first task is to carry out a Multi Criteria Decision Analysis of the currently used metal melting furnaces and determine the most efficient furnace in terms of environmental impact. In order to reduce differences between indicators (for example, the amount of carbon dioxide produced and electricity consumption), the method involves normalizing the available data for all considered alternatives (i.e., in this case, different types of metal melting furnaces). Thus, the alternatives are ordered depending on the indicators of the criteria [24].

In this work, the following impact criteria are used for analysis:
  – Maximum capacity, t/d;
  – $SO_2$ amount, year average, mg/m³;
  – $CO_2$, kg/t;
  – Lead content in slag, %;
  – Energy consumption, MWh/t;
  – Oxygen, Nm³/d;
  – Gas, kWh/t;
  – Amount of total lead production, t/year;
  – Fuel consumption, kg/t;
  – Amount of $H_2SO_4$, kg/t;
  – Maximum temperature, °C/t.

The above indicators can be attributed to natural indicators and are based on open-access documents BAT (Best Available Technique) [25], technical descriptions of melting processes, as well as available literary sources [26]–[45]. The choice is justified by the fact that these indicators make it possible to compare scrap metal processing technologies from an environmental point of view.

If the process is well established, scrap metal recycling can have a positive impact on the environment, as well as be efficient and sustainable for the industry itself. The amount of lead in the slag is an essential indicator of processing efficiency. At the moment, lead slag is usually disposed of in landfills. As [46] indicates, considering the role of the metal industry in our lives, it can be assumed that the amount of space required for waste storage will only increase. Lead slag also contains toxic elements and compounds, creating environmental and human health risks.

The amount of carbon dioxide generated is directly related to the amount of energy consumed by the plant – gas, coal, coke and/or electricity. Modern metal-smelting furnaces consume significantly fewer fossil fuels than even half a century ago, and coal/coke is increasingly being replaced by more environmentally friendly fuels – gas and electricity. Increasingly, furnace fuel is supplied in pulverized form, improving combustion efficiency [47]. The maximum temperature in the furnace also depends on the amount of fuel supplied.

Insufficient temperature, or vice versa, its excess, can adversely affect either the metal melting quality or accelerate the furnaces' wear [48].

Thus, it is essential to consider the leading indicators of the metalworking industry, specifically the melting stage itself, and how effective this or that metal melting furnace is.

In this work, using the above indicators, the furnaces of the following type were studied:

- Flash smelting/QSL;
- Ausmet/ISASMELT furnace;
- Kaldo furnace;
- Kivcet furnace;
- Electric Arc furnace (EAF);
- Blast/Shaft furnace;
- Short Rotary furnace;
- Reverberator furnace.

It should be noted that the indicator values used in the study for each furnace are taken as an average of the sources found. More accurate values directly depend on the specific furnace and may vary depending on the conditions – the quality of the fuel, the quality of the metal being processed, the combustion conditions, etc. [49]–[51].

### 2.2. SWOT analysis

In order to determine the effectiveness, potential, and threats to the national metallurgy sector, a SWOT analysis (Strengths, Weaknesses, Opportunities, and Threats) was carried out in the work. SWOT is a method for identifying and formulating strategies for improving the performance of an enterprise, taking into account both external (opportunities and threats) and internal factors (weaknesses and strengths). Based on the analysis results, the enterprise can determine the development path, reduce the impact of potential threats, adapt to various factors and assign strategies for further work, development and/or behaviour in the context of the decision being made [52].

The SWOT analysis aims to determine the efficiency of 8 Latvian metallurgical enterprises. The analysis uses data provided by enterprises in reports for the State Environmental Service [53], as well as interviews with representatives of enterprises.

## 3. RESULTS

### 3.1. Multi-Criteria Decision Analysis

All values used in the multi-criteria analysis are referred to the production process and include either the consumption/emission per final product or amount of emission/waste in certain period of time. For the analysis the following indicator values were used.

Based on the values presented in Fig. 1, we find that the electric arc furnace (EAF) is the most efficient for the given values of the indicators. This result is consistent with the literature sources. This type of furnace is characterized by increased efficiency compared to the Blast furnace and the ability to use electricity generated from renewable energy sources, which reduces the total amount of emissions created from the entire process [54]–[57]. A significant advantage of EAF is the ability to work not only with raw metal but also with scrap metal, which in no way affects the quality of the final product. As indicated [58], compared to a Blast furnace, EAF can process up to 20 % more scrap metal, contributing to the sector's sustainability and circular economy.

TABLE 1. AVERAGE VALUES FOR THE ENVIRONMENTAL INDICATORS [25]–[45]

| Type of furnace<br><br>Indicator | Flash smelting/QSL | Ausmelt/ Isasmelt | Kaldo | Kivcet | EAF | Blast/Shaft | Short Rotary | Reverberator |
|---|---|---|---|---|---|---|---|---|
| Maximum capacity, t/d | 2200 | 1150 | 900 | 1800 | 600 | 13 000 | 3900 | 1000 |
| $SO_2$ amount, year average, $mg/m^3$ | 700 | 850 | 400 | 400 | 90 | 100 | 350 | 560 |
| $CO_2$, kg/t | 1700 | 1318 | 1500 | 2730 | 850 | 1214 | 9000 | 3000* |
| Lead content in slag, % | 5 | 1 | 3 | 2.5 | 1.5 | 3 | 4 | 5 |
| Energy consumption, MWh/t | 9 | 1.3 | 4.35 | 4.5 | 3 | 5.8 | 4.1 | 1.05 |
| Oxygen, $Nm^3/d$ | 138 889 | 41 667 | 91 667 | 11 100 | 1528 | 2778 | 10 278 | 1778 |
| Gas, kWh/t | 275 | 1120 | 450 | 670 | 540 | 300 | 280 | 800 |
| Amount of total lead production, t/year | 135 000 | 120 000 | 145 000 | 130 000 | 148 000 | 110 000 | 16 000 | 110 000 |
| Amount of $H_2SO_4$, kg/t | 700 | 400 | 500 | 1100 | 670 | 0 | 390 | 830 |
| Fuel consumption, kg/t | 110 | 405 | 100 | 110 | 12 | 720 | 710 | 25 |
| Maximum temperature, °C/t | 1400 | 1370 | 1400 | 1400 | 1450 | 1400 | 1370 | 2000 |

Note: * $kgCO_2eq/t$

Using the data from Table 1 in the MCDA analysis, we get the following resulting picture:
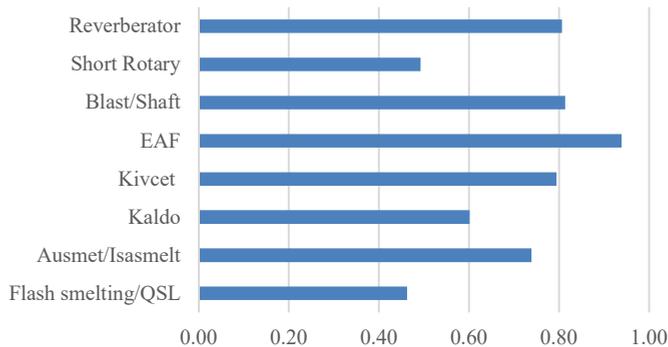


Fig. 1. Results of the MCDA analysis.

Next comes the Blast/Shaft furnace. This furnace consumes a significant amount of coal/coke, affecting $CO_2$ emissions. However, modern furnaces are equipped with technologies to reduce this amount. For example, the use of technologies for capturing, storing and/or utilization of carbon dioxide (CCUS), which can later be used to produce other valuable materials/products [59], or by using alternative fuels (the so-called bioreducers) – syngas, torrefied biogas, etc [60]. The advantage of Blast Furnace is its large capacity – the maximum load can hold up to 13,000 tons per day, allowing the production of a large amount of steel annually. Because the blast furnace can use low-quality ore as fuel, this furnace can be considered cost-effective [27].

In turn, the worst result compared to other observed furnaces was shown by the Flash smelting/QSL furnace. Although this process is characterized by a high degree of stability and productivity [61], at the moment, its performance is still inferior to more modern metallurgical furnaces, such as, for example, EAF. It should be noted that Ausmelt/Isasmelt furnaces also show excellent results. According to [26], [37], [43], [62], kilns of this type are especially remarkable for their high productivity and relatively low fuel costs. While Isasmelt stoves operate exclusively on solid fuels (coal, coke), Ausmelt can partially use electricity as fuel, significantly reducing the emissions created during fuel combustion. In the future, the Ausmelt process could eliminate the need for fossil fuels and become a greener technology [63].

### 3.2. SWOT analysis

Based on literary sources and descriptions of technological processes [53], [64]–[66] as well as on interviews with entrepreneurs, a SWOT analysis of Latvian metallurgical enterprises and the stage of melting of scrap metal in particular was carried out.

At the moment, nationwide metal processing enterprises rely on their strength and resources received from local sellers. The enterprises presented in the analysis are considered environmentally friendly. They use natural gas as fuel instead of coke (or the amount of coke is kept to a minimum, like in "Hidrolats", "Evan Group" and "Fonekss Metals" companies). In this way, the amount of $CO_2$ emissions from the melting process can be significantly reduced. The enterprises have developed a system for attracting experts. The hiring of young specialists and students is stimulated to improve the skills of employees and develop new ways to improve the efficiency of the enterprise. Ways are also being considered to obtain funding from EU funds, which could contribute to the development of factories.

The results of the analysis are presented in Table 2.

Despite well-established supply chains and product distribution, businesses feel market instability due to political and economic influences. These fears force companies to reasonably assess all the risks associated with any changes – the expansion of production, modernization, etc. However, decisions of this kind carry with them the risks of another aspect – the environmental one. European Union directives require businesses to reduce emissions and use renewable energy sources. However, enterprises often cannot meet such requirements on their own. State financial assistance or temporary tax assistance could help enterprises develop, contributing to the sustainable production of goods with increased added value and the country's economy.

TABLE 2. RESULTS OF THE SWOT ANALYSIS OF THE LATVIAN METAL PROCESSING COMPANIES

| Strength | Weaknesses |
|---|---|
| Good location of enterprises – reduction of logistics costs between the seller-buyer | Lack of skilled workers to operate and maintain complex equipment |
| Thanks to the replacement of obsolete equipment with more modern equipment nationwide, production can be considered efficient | Insufficient funding to purchase more efficient and sustainable equipment |
| Established and developed relationships with customers and the product sales market | Lack of available technologies for enterprise development. Stagnation of technological processes |
| Verified Suppliers | Work with material, the processing of which requires large energy investments and high capacities |
| Opportunity to use scrap instead of metal as a resource, contributing to the sustainability of the industry | At the moment there is no possibility to use alternative energy sources |
| Scrap metal delivery points, motivation of citizens to hand over scrap metal | Unstable financial growth, inability to predict long-term benefits |
| | Increasing demands on environmental "friendliness" of processes |
| | Undiversified energy supplier, dependence on one supplier |
| | Too small sales market |

| Opportunities | Threats |
|---|---|
| Opportunity to attract experts / working partners from other countries, thereby stimulating the development of the enterprise | Aging staff and lack of new skilled workers |
| Possibility to use foreign markets for sales/acquisition of products | An unstable economic and political environment, leading to instability in markets and established supply chains |
| Integrating new technologies that are more environmentally friendly, efficient and sustainable than those currently in use | Due to financial uncertainty, the impossibility of modernization and, as a result, the difficulty in meeting environmental requirements |
| The introduction of new technologies makes it possible to attract foreign investment | Instability of the political energy sector – there may be a need to change the energy supplier, which potentially entails increased financial costs |
| Installation of carbon dioxide capture systems, which will significantly reduce the amount of $CO_2$ emissions at the metal melting stage | Instability of the economic sector – the energy supplier can raise the price of energy, which leads to an increase in the price of the process and the final product |
| Attraction and use of alternative energy sources to improve the efficiency of the enterprise | Lack of funding and confidence in the stability of the enterprise |
| Cooperation with foreign enterprises in matters of technological and economic development | High raw material prices |
| The use of the latest melting furnaces allows to reduce the consumption of electricity without losing the efficiency of the process | The capture of sales markets by larger enterprises. The need to dump prices in order to obtain a sales market for products, which leads to a decrease in profits and illiquidity of the enterprise |

The modernization of production can be a vital step for the enterprise, although it is associated with risk. Efficiency gains could attract additional funding to support production. New markets can bring additional profit and stability as various buyers will be obtained. However, the main threats to enterprises are in the energy sector. The enterprises use mainly electric furnaces, and the metal melting process is highly energy-consuming. An increase in the price of electricity can be a critical or even decisive step in the functioning of the enterprise [53]. Diversifying energy providers can add stability to the process as it no longer depends on one particular energy seller. Using alternative energy sources or already independent energy production will significantly secure both the melting process and the enterprise.

Because enterprises use fuels with a lower carbon footprint, it can be assumed that the country's energy sector will reduce $CO_2$ emissions. As follows from the data [53] and [67], metalworking enterprises considered in the analysis in 2021 produced 8 % less $CO_2$ emissions than a year earlier.

## 4. CONCLUSIONS

As part of this work, a metal smelting furnace was analysed to determine the most effective in terms of 11 natural indicators. The analysis was carried out using MCDA analysis, which showed that the most efficient furnace can be considered an electric arc furnace at the moment. The main advantage of EAF is the ability to work with a large amount of scrap metal and the relatively low amount of lead produced in the waste, low $SO_2$ and $CO_2$ emissions. Due to the ability to use electricity, this furnace is also characterized by low consumption of fossil fuels. Given the ability to use electricity generated from renewable energy sources, EAF can be considered the most environmentally friendly among those analysed in this paper.

The second task of the study was to carry out a SWOT analysis of metalworking enterprises in Latvia. The study showed that the main threats to the sector are the uncertainty and instability of the market, both internal and external. While businesses have and are still upgrading processes and installing more efficient furnaces, this can also be risky – new furnaces consume electricity, making the process environmentally friendly but highly dependent on electricity prices. Because the electricity supplier is not diversified, enterprises expose themselves to certain risks associated with the supply of this type of fuel. This problem may be another field for researching technologies and innovations, as energy consumption created from renewable energy sources and the diversification of suppliers will secure enterprises. The use of electric ovens by local businesses could be a significant advantage in the future as with the development of the industry and the shift away from fossil fuels (coal/coke), as well as the drastic change in markets due to political factors, coal/coke prices may increase, which will make the metal recycling process illiquid.

In conclusion, the sector needs cleaner and more efficient scrap metal processing and utilization technologies. In this regard, further research is needed on furnaces for processing this resource, including more criteria and research methods.

## ACKNOWLEDGEMENT

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# From Cradle to Plate: Analysing the Life Cycle Sustainability of Fish Feed Composition

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*Abstract* – **Sustainability is defined as balancing environmental, economic and social factors, and various methodologies and tools are available to assess sustainability across sectors and scales. The demand for food has increased due to the increase in the population and the consumption of aquatic food in the world has increased significantly and is growing by an average of 3 % per year, while the population is growing by 1.6 % per year. As the aquaculture industry expands worldwide, it is important to consider the environmental impact of the industry and choose environmentally friendly alternatives to reduce its impact. The aim of this study is to assess the composition of five different fish feeds based on environmental, economic and social parameters using life cycle analysis (LCA), life cycle costing (LCC), social life cycle analysis (S-LCA) as well as technical considerations. The impact of alternatives to the main feed ingredients was analysed separately, while the development of fish feed focused on the protein source used in the feed and the oil used, as halieutic resources are used as raw material in their production, and alternatives are being considered. The best alternatives, considering all four dimensions, were the alternatives where fishmeal protein was partially replaced by Black Solder fly and Yellow Mealworm protein, as the proportion replaced is different for each alternative. By evaluating fish feed along several dimensions, the aim is to improve fish welfare while reducing the environmental impact of feed production.**

*Keywords* – **Assessment; environmental; economic; social; technical; fish feed.**

## 1. INTRODUCTION

It is expected that the world population will increase to 9 billion in 2050 and with it the demand for food will grow by 60 % and protein sources production grow will rise for meat nearly 70 %, aquaculture 90 % and dairy 55 %, but this challenge must be realized in a sustainable and safe way [1]. Over the past two decades, the industrial compound feed industry has experienced slow and steady growth, owing to market expectations from livestock and aquaculture farmers for effective compound feed that meets increasingly stringent performance and quality standards [2]. The Asia-Pacific region produces the most feed and in 2022 it was 37 % of the total feed production, followed by Europe with 21 % and North America with 21 % [1], see Fig. 1. However, most of the feed is consumed by poultry 44 % of the total amount of feed, followed by pigs 28 % [1], see Fig. 2.

The feed raw material production stage of animal products accounts for the largest share of GHG emissions, especially for pork, poultry, eggs, and farmed fish, where the share ranges

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from 70 % to 80 % [3]. The circular feed concept is based on the recovery and reduction of nutrient losses and can be divided into several dimensions that make up the circular feed – food/feed grade status; proximity to the feed mill; land use ratio; nutrient digestibility [4].
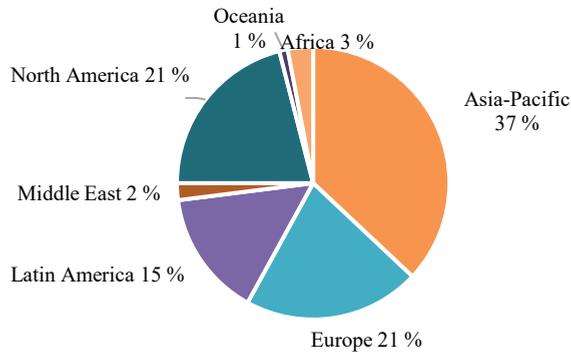


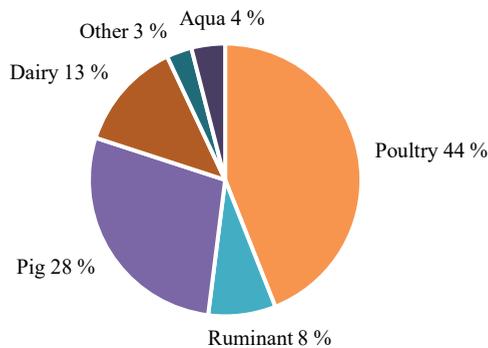Fig. 1. Feed production by region in 2022 [1].



Fig. 2. Global feed market by species – 2022 estimates [1].

The use of new feed ingredients and raw materials in feed production can create new challenges [5]. However, the safety of feed and ingredients can be determined by identifying inputs with potential hazards used in feed production, understanding the production process and conducting a risk characterization of the final product [5]. There are some regulations in the European Union related to feed, like Regulation (EC) No. 178/2002 on the marketing and use of feed with the aim of ensuring a high level of feed safety [6], as well as Regulation (EC) No 1831/2003 aimed at the use, marketing, supervision and labelling of feed additives and premixes in order to promote the use of high quality additives and premixes [7]. Also, Product Environmental Footprint Category Rules (PEFCR) Feed for Food-Producing Animals gives a set of guidelines on the environmental impact of feed production used by the food industry [8].

The industry is facing the challenge of improving feed compliance with fish production demand and improving feed sustainability is focused on partial replacement of marine resources with plant resources or another alternative [9]. The risk of halieutic resource depletion is related to fish feed, as traditional fish feed uses wild fish to produce fish meal and fish oil [10]. To reduce the environmental impact of fish farming, specific problems must

be considered, such as the use of traditional fish meal and fish oil in feed, increasing the use of by-products or using microorganisms and insects as raw materials for feed [3]. As well as preventing wastage of aquaculture feed, as uneaten/unconsumed fish feed is like a surplus that settles at the bottom of deep water [10]. In order to reduce the loss of nutrients, attention must be paid to the control of feed distribution, to improve the retention of feed in water, and the duration of flotation increases and the sedimentation of feed is delayed, as well as the recovery of nutrients, for example from fish feces, in order to grow algae that can then be used as feed [10]. Alternatives to avoid using aquatic alive resources in feed as raw materials [10]:

1. The first priority is to use the scraps of wild and farm-raised fish from the processing processes and there is a benefit in the circular bioeconomy.
2. The second priority is to use proteins, oils and fats from farmed insects that are fed with by-products and promote a circular economy.
3. The third priority is to use natural resources from lower trophic levels, but the use of these resources should be studied so as not to affect marine biodiversity and the balance of ecosystems.

The aim of this study is to assess the sustainability of different fish feed alternatives considering environmental, economic, social and technical parameters. Life Cycle Analysis (LCA) to assess environmental impacts, Life Cycle Costing (LCC) to assess economic impacts, Social Life Cycle Analysis (S-LCA) to assess social impacts and a technical dimension to assess the important parameters of fish feed. LCA complies with: ISO 14040 (2006) and ISO 14044 (2006) [11], [12]. LCC estimates the total costs over the life cycle - capital costs, consumption costs, operating costs, and the residual value of an asset at the end of its life cycle [13]. Social impact or risk can be assessed using a database method or according to the United Nations Environment Program (UNEP) guidelines method that is used for this study [14]. Technical parameters such as marine biodiversity, nutritional value of feed and origin of raw materials. Also, the MCDA method TOPSIS was used to perform a long-term assessment of the selected alternative according to environmental, economic, social and technical criteria.

## 2. METHODS

The development and improvement of fish feed must take into account that commercially produced fish feed must provide a comprehensive diet to support the optimal growth and health of the fish and most often fish feed consists of: proteins (18–50 %), lipids (10–25 %), carbohydrates (15–20 %), ash (<8, 5 %), phosphorus (<1.5 %), water (<10 %) and some vitamins and minerals [15]. Protein is one of the most expensive feed materials, and traditional feed used fish meal as a protein source, but land plants, single-cell proteins, microalgae, macroalgae and insect meal are used as alternatives [16]. Lipids are used to partially replace proteins and have almost twice the energy density of proteins [15]. Vegetable oil can be used as an alternative to fish oil - soybean, linseed, rapeseed, sunflower, palm oil and olive oil, and replacing fish oil with an alternative is not only an environmental benefit, but also an economic benefit [17]. Optimum use of carbohydrates in fish feed is a good source of energy and carbon, and optimal inclusion in fish feed increases protein and lipid retention, as well as improves stability and buoyancy of feed pellets [18]. However, an important component of the feed is the pigment that gives the colour of fish flesh and salmonids, and trout have a characteristic pink colour of fish flesh, which is mainly from the pigment astaxanthin [19]. This pigment must be obtained from the feed because fish do not synthesize carotenoids and astaxanthin has been a widely used feed additive for several decades in

aquaculture and commercially available astaxanthin (>90 %) is produced synthetically from a petrochemical source, but it is also possible to obtain this pigment from green algae, red yeast or from soil bacteria [19].

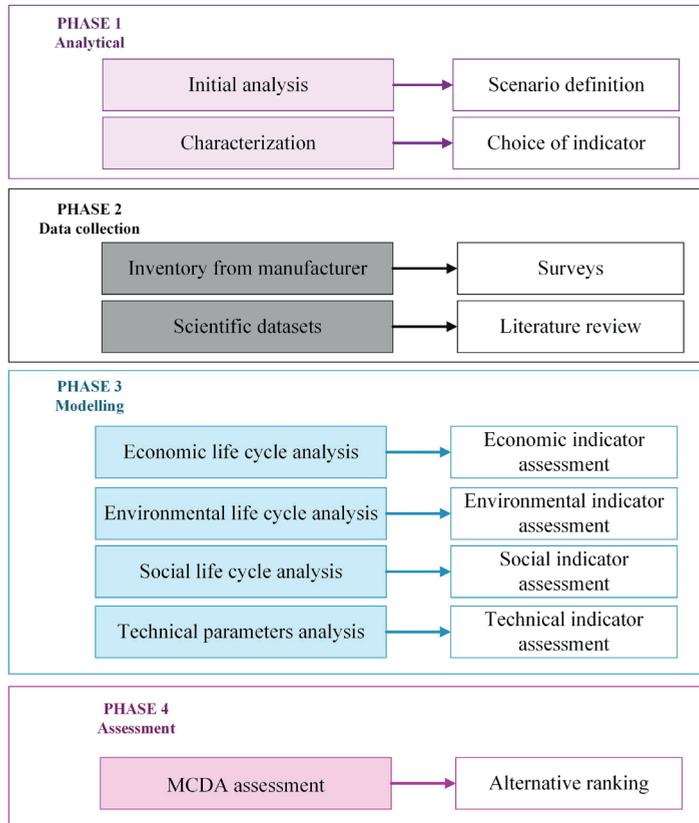The methodology for assessing the sustainability of fish feed (Fig. 3) consists of four phases.

Fig. 3. Fish feed sustainability methodology.

## 2.1. Analytical Phase

The first phase is the analytical phase, where parameters and criteria are selected to test the sustainability of the fish feed. In this case, five fish feeds are compared, where the proportion of the other fish feed ingredients varies according to the protein source:

- A1 – traditional protein – fish meal;
- A2 – traditional protein – fish meal and 5 % of traditional protein replaced by Black Solder fly protein;
- A3 – traditional protein – fish meal and 10 % of traditional protein replaced by Black Solder fly protein;
- A4 – traditional protein – fish meal and 15 % of traditional protein replaced by Yellow Mealworm protein;
- A5 – traditional protein – fish meal and 30 % of traditional protein replaced by Yellow Mealworm protein.

The five fish feeds are compared on environmental (results from LCA), economic (results from LCC), social (results from S-LCA) and technical (results from comparisons on marine biodiversity, feed nutritional value and raw material origin) parameters.

### 2.2. Data Collection Phase

During the development of the fish feed, several alternatives with alternative ingredients were developed, tested in the laboratory and tested on fish. The five fish feeds selected are those that performed best in the previous tests. All ingredient proportions of the fish feeds are commercially secret and are not published in this article. A comparison of alternative fish feed ingredients – protein (black soldier fly, yellow mealworm and soybean) [20], oil (microalgae, rapeseed and fish oil) [21] and pigment (microalgae and synthetic astaxanthin) [22] results are available, but publicly available data were used for modelling and expert comments were considered.

Necessary data to use for LCA, LCC, S-LCA and technical comparison were obtained from publicly available information – scientific articles, reports. The collected data is transformed into the necessary input data for the modelling phase.

### 2.3. Modelling Phase

The modelling of each dimension is slightly different and depends on the available data to make the assessment. LCA assesses the impact of the environment and is performed for all fish feed, LCC assess the economic impact and is performed for all fish feed, S-LCA assess social impact and is performed for protein and oil raw materials used in fish feed and technical dimension to evaluate the important parameters for fish feed and is performed for all fish feed.

#### 2.3.1. Environmental Assessment – LCA

Function unit for LCA is 1 tonne animal feed based on Product environmental footprint category rules (PEFCR) Feed for food-producing animals [8]. This LCA is "cradle to gate" and system boundaries the impact of raw materials is considered. Life cycle inventory data are collected from publicly available scientific articles as well as from the *Ecoinvent* 3.9 database.

Life cycle impact assessment is based on Product environmental footprint category rules (PEFCR) Feed for food-producing animals, where the necessary parameters are defined to characterize the environmental impact indicators. The method used in *SimaPro* 9.5 software is Environmental Footprint (EF) 3.0, which incorporates the PEFCR as an impact assessment method.

Result interpretation is based on environmental performance results for fish feed considering all input material flows. Weighted results for fish feed alternatives expressed in mPt value. Pt is the unit of the eco-indicator where one thousand of annual environmental load of an average European citizen is considered as 1 Pt [23].

#### 2.3.2. Economical Assessment – LCC

Function unit for conventional LCC is EUR to 1-tonne feed and system boundaries for conventional LCC is cost of raw input materials. Life cycle inventory data for conventional LCC is compiled from publicly available data. Life cycle impact assessment is based on cost (EUR) and amount (ton) of raw material.

The result interpretation is based just on raw material cost, EUR/t fish feed.

### 2.3.3. Social Assessment – S-LCA

The scope of the social risk assessment is based on two major ingredients that are used in fish feed because these raw materials make up at least half of the fish feed composition. Social risks were identified in the category of employees, local community, value chain participants and society. The categories of consumers and children were not considered, as the boundaries were only considered in the context of production and raw materials.

Life cycle inventory data is based on publicly available data about raw material production country for worker and society category and raw material industry reports on local community and value chain actor category. Impact assessment is evaluated as social performance evaluation scale from +2 to −2 [24]. The assessment of the social dimension was based on the countries from which the protein and oil for fish feed are sourced. The result interpretation is based on the obtained evaluations into subcategories and proportionally distributed according to the ratio of fish feed ingredients.

### 2.3.4. Technical Assessment

Technical parameters are important for fish feed, so this dimension has been added with criteria on marine biodiversity, nutritional value of feed and origin of raw materials. The marine biodiversity criterion considered whether marine species are produced as an ingredient in the fish feed, and this was analysed in the ingredients. The nutritional value criterion was taken from the results of fish feed tests. For the raw material origin criterion, it was examined from which resources the raw materials for fish feed production are obtained. The assessment of technical parameters was carried out by quantitative evaluation, but in the criteria where qualitative novelty was obtained this was converted to a qualitative evaluation – a scoring system.

### 2.4. Assessment Phase

In the fourth phase, the obtained results from the modelling phase are considered and for five fish feed assessment is used multi-criteria decision analysis (MCDA) method TOPSIS to determine the best fish feed according to environmental, economic, social, and technical parameters.

One of the input data in the TOPSIS method is the importance or weight of the selected criteria, and in this process the weights will be the same for all criteria: environmental criteria (25 %), economic criteria (25 %), social criteria (25 %) and technical criteria (25 %). It is also important to define the better value of the criterion (min or max) and in this process environmental criterion (min is the best value), economic criterion (min is the best value), social criterion (min is the best value), and technical criterion (min is the best value) values as input data in TOPSIS matrix is as ranking values from best to worst (1 to 5).

To obtain the results of the TOPSIS method, the normalized matrix, the weighted normalized matrix, the distance from the ideal and anti-ideal solution and the calculate the relative closeness to the ideal solution [25], [26]. As a result, in the TOPSIS method, the best result is with the result closest to the ideal. Also, sensitivity analysis was also performed for all criteria to determine which criterion had the greatest influence on the results.

## 3. RESULTS

Table 1 shows the results of the modelling phase by dimension. In the S-LCA and technical dimension, there is a ranking based on the number of points obtained.

TABLE 1. MODELLING RESULTS

|                    | A1       | A2       | A3       | A4       | A5       |
|--------------------|----------|----------|----------|----------|----------|
| LCA, mPt           | 2.10E+02 | 1.89E+02 | 1.67E+02 | 2.13E+02 | 2.40E+02 |
| LCC, EUR/t         | 9266     | 8346     | 7480     | 8146     | 9430     |
| S-LCA, ranking     | 5        | 4        | 3        | 2        | 1        |
| Technical, ranking | 4        | 1        | 3        | 2        | 3        |

Fig. 4 shows TOPSIS results for five fish feeds of different composition. Alternative A1 has the lowest rating in this case and this is the conventional fish feed composition. Alternative fish feed ingredients are used in the composition of A2, A3, A4, A5 fish feed composition. However, the best alternatives are A3 and A4, although slightly different proportions of ingredients and different alternative protein raw materials are used, but the same result was obtained.
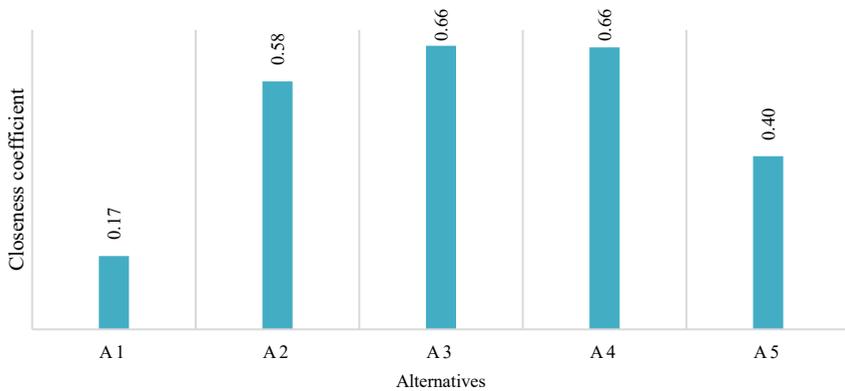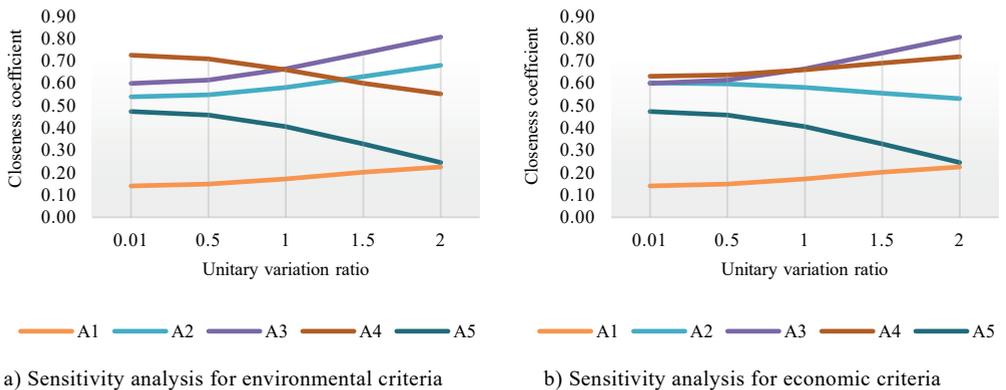


Fig. 4. TOPSIS results.



a) Sensitivity analysis for environmental criteria

b) Sensitivity analysis for economic criteria

c) Sensitivity analysis for social criteria        d) Sensitivity analysis for technical criteria
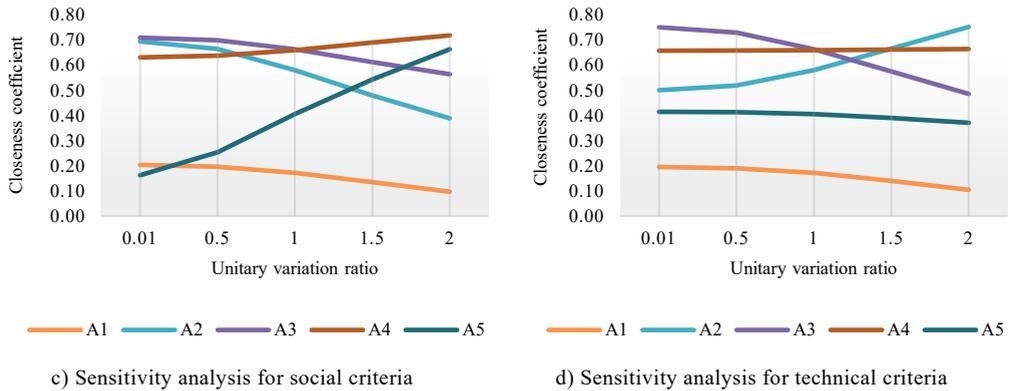
Fig. 5. Sensitivity analysis.

Fig. 5 shows the sensitivity analysis for environmental, economic, social, and technical criteria to clarify the most sensitive criterion. The biggest changes are in the sensitivity analysis of social criteria and the smallest change is in the technical criterion.

## 4. CONCLUSION

The aim of the study was to carry out a sustainability assessment considering the environmental, economic, social, and technical dimensions of several fish feeds with different compositions and to determine the best fish feed alternative. As a result, the two best fish feed alternatives were obtained, since the same results were obtained with the TOPSIS method. Alternative A3 showed the best results in the environmental and economic dimensions, but alternative A4 showed the second-best result in the economic, social, and technical dimensions. A sensitivity analysis was also performed, and the social dimension is more sensitive than all the dimensions. This shows that by choosing a different weight distribution for the dimensions, the results will be drastically different.

The obtained results show that making small changes in the composition and proportions of fish feed already has a positive effect on the environment, but it is necessary to consider all aspects, not only the effect of the environment or the composition of the feed on fish, which was not considered in this study. It is possible to improve the research and supplement the energy consumption and transportation stages considered to obtain a more comprehensive assessment of fish feed production, as well as to consider how fish take in and develop in the growth and development processes from a changed fish feed composition. Of course, the composition of fish feed depends on the species of fish and the phase of growth and development of the fish, therefore the composition of fish feed and the sustainability of the feed will differ.

Conventional fish feed is increasingly being replaced by sustainable alternatives, but the alternatives tend to have a negative impact on the development and growth of the fish, and a comprehensive analysis of possible alternatives is required for the fish feed to become even more sustainable and reduce the impact on the environment.

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# Environmental Life Cycle Assessment of Healthcare Waste Valorisation Alternatives

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*Abstract* – **Infectious healthcare waste (iHCW), after microbial inactivation treatment, primarily ends up in landfills. Although the morphological composition of iHCW depends on the type of health facility, predominantly HCW consists of plastic and textile waste. Furthermore, after the treatment iHCW is cleaner from a microbiological contamination perspective than household waste, making it a highly valuable resource. Recycling iHCW has environmental and economic benefits and by valorising iHCW, it would be possible to reduce the amount of landfilled waste and use it as a resource. The aim of the research is to understand the environmental consequences and potential benefits of treated iHCW valorisation scenarios through the 'gate-to-gate' (from iHCW generation at medical facilities to end-of-life or recovery) life cycle assessment framework and to compare it with the existing practice – landfilling with functional unit 1 ton of treated iHCW and using ReCiPe 2016 (Midpoint, Hierarchist perspective) method. Valorisation scenarios (VS) analysed the use of treated HCW as a substitute of feedstock for reinforced asphalt, reinforced cement, RDF, syngas, acoustic panel and plastic components used for hydroponics. The results of the LCA demonstrate that from the environmental impact perspective, the best scenarios are syngas production (VS4) with cumulative result −11Pt and −237 kg $CO_2$ eq for global warming impact category and RDF (VS3) with result −5Pt and −195 kg $CO_2$ eq for global warming impact category, as the entire iHCW flow is recycled into energy. However, when recycling waste, the most valuable product must be created, and then the best results from plastic recycling are plastic components for hydroponics (VS6) with result 50Pt and 1181 kg $CO_2$ eq for global warming impact category and reinforced asphalt (VS1) with result 53 Pt and 1246 kg $CO_2$ eq for global warming impact category. From textile recycling acoustic panels (VS5) with result 55 Pt and 598 kg $CO_2$ eq for global warming impact category and reinforced cement (VS2) with result 55 Pt and 603 kg $CO_2$ eq for global warming impact category. Therefore, additional scenario was created where plastic, textile and residual iHCW streams are fully recycled and fully eliminating landfilling. The results show that BAU with result 75 Pt and 1509 kg $CO_2$ eq for global warming impact category has the greatest environmental impact compared to any of the VS considered in this research. Of the total scenario impacts, the largest impact is caused by waste disposal, followed by transport, which has a similar impact in all scenarios due to assumptions about the distance to be transported, and iHCW treatment also has a similar impact in all scenarios, but the bigger difference is the environmental benefit from recycled waste. Based on the LCA results, recommendations for the stakeholders are developed.**

*Keywords* – **Chemical treatment; damage; environmental impacts; LCA; medical waste; scenarios; thermal treatment.**

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## 1. INTRODUCTION

The healthcare sector contribution to global warming continues to grow and reaching 4–5 % of the total global greenhouse gas (GHG) emissions [1], [2], which makes it comparable to the effect generated by global food industry [2] and aviation sectors [3]. This statement has finally reached policy-makers reaction at the level of COP28 Declaration on Climate and Health [4]. In addition, the healthcare sector is a significant waste producer [5], originating from a variety of single-use and non-recyclable materials – the problem which was plainly presented during COVID-19 pandemics.

More than 80 % healthcare waste (HCW) is not hazardous waste, and approximately 15 % of HCW is classified as hazardous waste [6]. Hazardous HCW can be infectious, toxic or radioactive [7], thus is obliged to be properly managed avoiding impacts linked with its hazardous nature [8], [9]. To ensure microbial inactivation of infectious HCW (hereinafter iHCW) various thermal (autoclaving, incineration, microwaving) and chemical methods are used and requires different resources such as energy, water, chemical compounds [10]. Once iHCW is treated, from microbiological contamination perspective they are cleaner than household waste [11] giving a strong foundation to be recycled and valorised to added-value products.

Waste valorization, the process of giving value to waste materials, increases environmental, economic and social benefits of waste by advancing circular economy and reduction of environmental impact [12]. Currently, landfilling and incineration of HCW, are the most commonly used technologies due to low capital expenses and well-known technological pathways, while recycling of HCW offers environmental and economic benefits [13]. The valorisation of HCW remains underexplored research field so far [14]–[23] and most studies are mostly focusing on energy recovery from HCW. This trend also fair in regard to life cycle assessment (hereinafter LCA) studies on valorization scenarios [24], [25].

To fill this research gap and to guide the decision makers (policy makers, investors, waste management company operators, grant developers, etc.) the current study is developed. The aim of the research is to understand the environmental impacts generated during the iHCW current management strategy and potential environmental benefits of iHCW valorisation scenarios through the "gate-to-gate" (from HCW generation at medical facilities to end-of-life or recovery) life cycle assessment framework.

## 2. METHODOLOGY

This LCA examines the current situation and potential valorization scenarios for treated iHCW. A total of seven scenarios are analysed in this study: the 'business as usual' (BAU) scenario and seven treated iHCW valorization scenarios (VS). The BAU scenario reflects a linear economy approach, where treated iHCW is disposed of in sanitary landfills. Alongside incineration, landfilling remains one of the most widely used methods for managing treated healthcare waste globally [10]. VS1–VS6 (Table 1) represent circular economy approaches where six distinct products are derived from treated iHCW: reinforced asphalt, reinforced cement, RDF, syngas, acoustic panels and plastic components for hydroponics. These products were selected based on factors such as their added-value potential, the maturity of recovery technologies and their industrial symbiosis potential under Latvian conditions. The materials utilized in the product development (plastics, textiles or all iHCW) and their proportions in the final products vary across scenarios as depicted in Table 1.

TABLE 1. VALORISATION SCENARIOS AND iHCW SHARE IN THE PRODUCT

| Scenario | Waste hierarchy approach | iHCW share used | iHCW material type used |
|---|---|---|---|
| VS1: reinforced asphalt | Recycling | 34 % | Plastics |
| VS2: reinforced cement | Recycling | 31 % | Textile |
| VS3: RDF | Energy recovery | 100 % | All iHCW |
| VS4: syngas | Energy recovery | 100 % | All iHCW |
| VS5: acoustic panel | Recycling | 31 % | Textile |
| VS6: plastic components used for hydroponics | Recycling | 34 % | Plastics |
| VS7: combination of products | Max. recycling, min. energy recovery | 100 % | All iHCW |

A substitution approach is applied in all valorization scenarios, where virgin raw materials are replaced with iHCW-recovered materials. These approaches are based on two waste management strategies: recycling and energy recovery. According to the waste management hierarchy [9], recycling is prioritized after waste prevention and reuse, whereas energy recovery is considered a less favourable option, positioned just above landfill disposal. Consequently, energy recovery should be applied only to non-recyclable or hard-to-recycle waste. Treated iHCW is frequently classified as non-recyclable due to processes like soaking and post-shredding. However, modifications to these processes – such as avoiding shredding – and enhanced segregation practices (e.g., sorting waste into specific fractions or materials at the source) can improve alignment with the waste hierarchy, thereby promoting recycling and material recovery. Building on this framework, an additional scenario (VS7) will be developed as an optimized solution. This scenario aims to maximize the use of recycling strategies with the lowest LCA results while incorporating the energy recovery strategy with the lowest LCA impact for the remaining fractions of treated iHCW (e.g., metals, wood, mixed waste and rubber) – see Table 2.

TABLE 2. RECIPE 2016 MIDPOINT INDICATORS USED WITHIN THE CURRENT STUDY [30], [31]

| Impact indicator | Abbreviation and unit | Description of indicator | Damage field |
|---|---|---|---|
| Particulate matter | PM, kg PM2.5 eq | Impact of PM2.5 on health, including lung cancer and cardiovascular risks, using global and region-specific factors. | Human health |
| Ozone formation (hum) | OFHH, kg $NO_x$ eq | Impact of ground-level ozone on human health, particularly respiratory issues, using global and region-specific characterization factors. | Human health |
| Ionizing radiation | IR, kBq Co-60 eq | Impact of radiation exposure on human health, considering different types of cancers and using time-horizon-specific characterization factors. | Human health |
| Stratospheric ozone depletion | SOD, kg CFC11 eq | Impact of ozone layer depletion on human health, particularly focusing on risks like skin cancer and cataracts across various time horizons. | Human health |

| Impact indicator | Abbreviation and unit | Description of indicator | Damage field |
|---|---|---|---|
| Human cancerogenic toxicity | HCT,kg 1,4-DCB | Impact of chemical exposure on cancer risk in humans, using specific characterization factors for different chemicals. | Human health |
| Human non-cancerogenic toxicity | HNCT, kg 1,4-DCB | Impact of chemical exposure on non-cancer health effects, using specific characterization factors for various substances. | Human health |
| Global warming | GW, kg $CO_2$ eq | Impact of greenhouse gas emissions on climate change, expressed as $CO_2$ equivalents over various time horizons. | Human health Ecosystems |
| Water consumption | WC, $m^3$ | Impact of water consumption on human health and ecosystems using region-specific characterization factors. | Human health Ecosystems |
| Freshwater ecotoxicity | FEc, kg 1,4-DCB | Impact of toxic substances on freshwater ecosystems, using characterization factors that reflect the potential harm to aquatic life. | Ecosystems |
| Freshwater eutrophication | FE, kg P eq | Impact of nutrient enrichment, particularly phosphorus, on freshwater ecosystems, leading to issues like algal blooms and oxygen depletion. | Ecosystems |
| ozone formation (eco) | OFE, kg $NO_x$ eq | Impact of ground-level ozone on terrestrial ecosystems, focusing on damage to plant life and overall ecosystem health. | Ecosystems |
| Terrestrial ecotoxicity | TEC, kg 1,4-DCB | Impact of toxic substances on terrestrial ecosystems, using characterization factors to assess potential harm to soil organisms and plant life. | Ecosystems |
| Terrestrial acidification | TA, kg $SO_2$ eq | Impact of acidifying emissions, such as $SO_2$, on soil quality and plant life, leading to potential ecosystem degradation. | Ecosystems |
| Land use/transformation | LU, $m^2$ a crop eq | Impact of land occupation and conversion on biodiversity, focusing on species loss and ecosystem disruption. | Ecosystems |
| Marine ecotoxicity | MEC, kg 1,4-DCB | Impact of toxic substances on marine ecosystems, using characterization factors to assess potential harm to marine life. | Ecosystems |
| Marine eutrophication | ME, kg N eq | Impact of nutrient enrichment, particularly nitrogen, on marine ecosystems, leading to issues like algal blooms and oxygen depletion. | Ecosystems |
| Mineral resources scarcity | MRS, kg Cu eq | Impact of mineral extraction on resource scarcity, expressed in terms of increased future extraction costs. | Resource availability |
| Fossil resources scarcity | FRS, kg oil eq | Impact of fossil fuel extraction on resource scarcity, focusing on the depletion of reserves and increased future extraction costs. | Resource availability |

### 2.1. Goal and Scope

The goal of this environmental LCA is to define the environmental impacts associated with the management of infectious HCW (hereinafter iHCW) under both linear economy conditions (treatment and landfilling) and circular economy conditions (treatment of iHCW and its subsequent use as a raw material for the development of new products).

### 2.2. Functional Unit

The study considered two functional units: 1 ton of treated iHCW and the annual amount of treated HCW generated in Latvia. 1 ton of treated iHCW is a well-established unit for measuring waste generation, allowing for comparisons across regions. On the other hand, focusing on the annual quantity of treated HCW generated in Latvia is particularly valuable for policymakers and potential investors at the local scale, as it helps assess the availability and management of such resources on a broader, more practical level.

While both functional units were considered in the study, the focus on 1 ton of treated iHCW was particularly relevant given the variability in waste generation over recent years. This variation is reflected in the data summarized below (see Fig. 1).
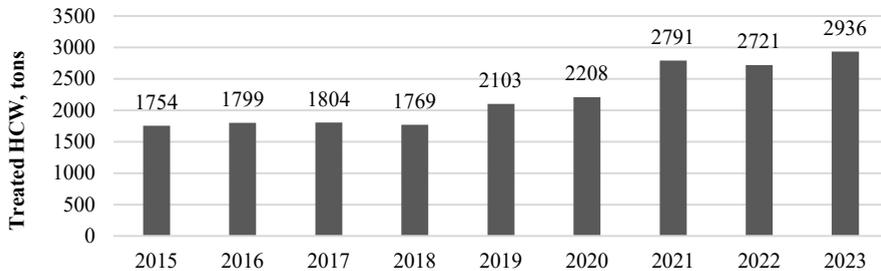


Fig. 1. Annual amount of treated iHCW in Latvia [26].

The data on treated iHCW (180103, 180202, 180207) in Latvia from 2015 to 2022 shows an average of 2209 tons of treated waste per year. Volumes on iHCW have been relatively similar between 2015 and 2019 but have become more variable since the start of the COVID-19 pandemic. All scheduled healthcare services were suspended at the beginning of the pandemic, and therefore there is less treated waste in 2020 than in 2021 and 2022, when planned services were restored. Since iHCW volumes have been so variable in recent years, then in this environmental LCA functional unit (FU) is 1 ton of treated iHCW.

### 2.3. System Description

The technological system boundaries of the present environmental LCA are 'gate-to-gate': from generation of the iHCW in hospitals to end-of-life stage of the iHCW – landfilling or one of the six valorization scenarios (see Fig. 2). The time boundaries of the present LCA are October 2022 – September 2023, a period when the inventory data collection was performed. Geographical boundaries of the LCA cover Latvia.

The definition of the scenarios to be analysed was based on several key considerations. First, the composition of iHCW, which is heterogeneous and varies depending on factors such as seasons, disease outbreaks, location, type of healthcare facility, and the economic and social conditions of a country [27]. Notably, iHCW is predominantly composed of plastic waste (e.g., polypropylene, nylon, polyester), followed by various textiles (e.g., cotton and

cellulosic materials) [28]. Second, the mass characterization of iHCW after treatment at iHCW treatment plants was considered. Both technologies involve shredding the treated waste into particles ranging from 13 to 55 mm in size. Third, the presence of symbiotic enterprises in the region – such as energy plants, cement and concrete factories, or asphalt plants – near the iHCW treatment facilities was also considered. A detailed description of the valorization scenarios is provided in the inventory section.
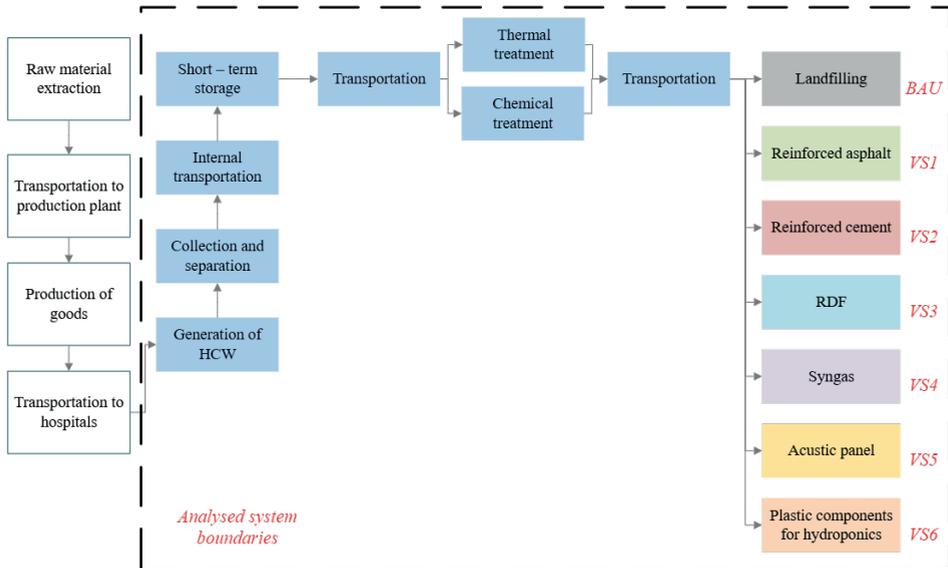


Fig. 2. Technological system boundaries of the analysed scenarios.

## 2.4. Life Cycle Impact Assessment Method

Life cycle assessment modelling software 'SimaPro' v9.5 [29] was used for the study. ReCiPe 2016 (Midpoint, Hierarchist perspective) was applied as an impact assessment method [30] which includes 18 midpoint indicators (see Table 2) covering three damage fields – damage to human health, damage to ecosystems and damage to resource availability.

The Hierarchist perspective reflects a cultural viewpoint, aiming to achieve consensus while adopting a 100-year timeframe.

## 2.5. Environmental Life Cycle Inventory

### 2.5.1. Overall Approach on Data Collection and Limitations

Inventory data required for the survey was collected from Latvian companies involved in the iHCW supply chain, including hospitals, iHCW transportation providers and iHCW treatment companies, as well as a landfill operator. Since none of the analysed valorization scenarios (VS1-VS6) have been implemented in practice, inventory data for the end-of-life stage was sourced from scientific papers (referenced in the corresponding "Results" section) and adjusted to match the analysed supply chain conditions.

In addition, some generalised assumptions are defined:
   – The separation of iHCW into fractions (refer to Table 3) is performed at the point of generation, in hospitals, immediately after the product is used. All these fractions are

considered infectious and needed to be treated to assure microbial inactivation, as described in Section 2.2.3.

– iHCW is collected from healthcare institutions across Latvia, encompassing both human and veterinary healthcare facilities. While the maximum distance from an iHCW generation point to a treatment plant is 302 km, most healthcare institutions utilizing these services are concentrated within a 60 km radius of the treatment plant. Based on this, the levelized distance from an iHCW generation point to the treatment plant is assumed to be 100 km.

– The valorization scenarios (VS1-VS6) include the transportation of treated iHCW to a production plant. Given the variety of products to be generated from treated iHCW and the varying locations of the associated production sites, a market analysis was conducted to identify the closest feasible options. This analysis prioritized economic considerations, which are a core factor for iHCW treatment companies during the selection process. Consequently, 50 km was established as the assumed distance from the iHCW treatment plant to a production plant.

– Supply chain actors' (hospitals, transportation and treatment companies, landfill management companies) provided data is used as much as possible within the life cycle inventory. However, if no proper qualitative data was able to be submitted by the companies, relevant data was used from 'Ecoinvent' database, specifically related to Latvian parameters. If such data is not available, then data related to RER (Europe) parameters is used. This ensures a hierarchy in data preference, choosing the most relevant and specific information whenever possible.

– Energy (for mechanical separation in fractions) and consumables (additional bins, bags, etc.) used to segregate iHCW streams according to material type are excluded from the inventory. These simplifications are possible because the most proper segregation method for the iHCW is segregation at generation points, i.e. in healthcare facilities, instead of segregation at waste treatment plants or recycling companies.

### 2.5.2. iHCW Generation at Healthcare Institutions and Transportation

The composition of iHCW generated in healthcare facilities varies and depends on such factors as hospital service profile, segregation practices applied in a specific facility as well as behaviour of medical personnel in the provision of qualitative segregation.

In the current research, a levelized composition of iHCW is utilized for inventory purposes. The compositional data (refer to Table 3) was obtained through experimental testing of mixed iHCW collected from various healthcare institutions across Latvia and delivered to two centralized iHCW treatment facilities in the country. This data was previously reported by Zlaugotne *et al*. [28].

Generated iHCW from healthcare facility rooms is collected in waste bins and subsequently transferred, with both infectious waste and sharps discarded into 1.1 m³ containers. This mixed iHCW is then transported to treatment plants using specialized trucks owned by iHCW treatment companies. These trucks have a load capacity of 15 tonnes and comply with EURO 6 emission standards, which regulate vehicle emissions by category and engine type.

TABLE 3. LEVELIZED COMPOSITION OF HCW GENERATED IN LATVIAN HEALTHCARE FACILITIES [28]

| Fraction | Share in total mass, % |
|---|---|
| Plastic | 34 |
| Cotton | 31 |
| Latex, rubber, nitrile | 19 |
| Mix of different fraction | 12 |
| Aluminium | 3 |
| Wood | 1 |

### 2.5.3. iHCW Treatment

Considering the nature of iHCW, it required to be treated assuring the microbial inactivation reduction of various bacteria, viruses, parasites and other microorganisms present at least at a 6Log10, as well as inactivation of *B. atrophaeus* and *G. stearothermophilus* spores at a 4Log10 reduction or more [32]. In Latvia, treatment of iHCW is provided by two centralised iHCW treatment companies – thermal and chemical treatment companies.

Thermal waste treatment plant uses a thermal treatment technology to treat iHCW from many healthcare facilities in the country (market share based on collected iHCW mass balance is 48 %). The thermal treatment unit is an integrated steam treatment system that uses an inclined horizontal stainless steel pressure vessel with a rotating inner drum containing vanes in the internal surface of the drum. iHCW is piled into 660-litre wheeled red bins. The waste is then loaded into the treatment unit's drum by means of an automatic loader. After the iHCW is introduced into the drum and the vessel door is sealed, a steam jet ejector system is used to pull a vacuum after which steam is introduced to treat the waste. The system is computer controlled. During the treatment process (at proper temperature (up to 132 °C) and pressure levels, the inner drum rotates causing bags and containers to be ruptured and their contents mixed inside the vessel. After a sufficient steam exposure time (from 30 to 60 minutes based on the amount of waste treated), a post-treatment vacuum cycle removes the steam and reduces the moisture content. The vessel door is then opened, and the treated waste is then ejected onto a conveyor which brings the waste into the hopper of a heavy-duty shredder. The finely shredded treated waste (microbial inactivation efficiency of the treatment unit is tested regularly) is then ejected into another series of conveyors into a compactor and roll-off container.

The chemical iHCW treatment plant utilizes a technology that uses $ClO_2$ to treat iHCW (their market share based on the treated iHCW amount is 52 %). iHCW containers (660 litres) are first lifted and their contents deposited into a hopper. Once waste is dropped into the hopper, shredding of material occurs. During the shredding process, air from the hopper is extracted through a HEPA filtration process. A four-shafted shredder reduces the waste to small particles. This particalized waste falls into a chamber below the shredder which contains a liquid solution of $ClO_2$ (cold water and $ClO_2$). A probe monitors the $ClO_2$ concentration. The entire treatment process is monitored by a control panel that provides the operator with the $ClO_2$ concentrations as well as a video of the interior of the hopper. If more $ClO_2$ is required, staff inject the chemical until acceptable levels are reached. After the treatment process (15–25 minutes long) the treated waste is conveyed from this chamber via a screw conveyor to be discharged into a collection bin. The treated waste (microbial inactivation efficiency of the treatment unit is tested regularly) has a moisture content of

approximately 50–60 %. As a result, it is stored in specialized containers for several hours to reduce the moisture level to 40–42 % through the passive deliquification process.

Lastly, in both companies, the treated iHCW is transported to the 'end-of-life' or recovery site via specialised iHCW treatment companies' owned trucks (load capacity – 15 tonnes, EURO 6 (emission limits by vehicle category and engine type)).

Considering the shared market of the iHCW treatment activities between two iHCW treatment companies and the selected FU, the mass allocation (52 %:48 %) is performed to demonstrate the proper HCW treatment conditions in Latvia.

### 2.5.4. iHCW end-of-life

The conventional method for managing treated HCW in Latvia is landfilling, which is also applicable to the BAU scenario. The BAU scenario inventory for both Latvian companies managing iHCW is presented in Table 4.

TABLE 4. LIFE CYCLE INVENTORY FOR BAU SCENARIO

| Parameter | Unit | Value |
|---|---|---|
| Thermal iHCW treatment | | |
| iHCW subjected to chemical treatment | t | 0.48 |
| Water | $m^3$ | 0.4 |
| Electricity | kWh | 0.07 |
| Gas | t | 0.02 |
| Transport | tkm | 100 |
| Waste scenario – landfill | % | 100 |
| Chemical iHCW treatment | | |
| iHCW subjected to chemical treatment | t | 0.52 |
| Sodium chloride | t | 0.0001 |
| Sodium thiosulfate | t | 0.00002 |
| Water | $m^3$ | 0.9 |
| Electricity | kWh | 18.5 |
| Transport | tkm | 100 |
| Waste scenario – landfill | % | 100 |

While the processes of iHCW generation, transportation, treatment, and the transportation of treated iHCW to the end-of-life point are consistent across all analysed scenarios, the end-of-life outcomes for the treated waste varies between the scenarios, as detailed in the description of each scenario below.

### VS1: Feedstock for reinforced asphalt

Treated iHCW is transported to an asphalt production plant. In the production of asphalt, the raw materials are natural aggregates (gravel), aggregates and asphalt binding agent (bitumen), and after crushing and grinding the raw materials, the asphalt mixture is produced [33]. Different research has examined the use of various plastics in the production of asphalt, the most popular plastics being high-density polyethylene (HDPE), low-density polyethylene (LDPE), polypropylene (PP), polyethylene terephthalate (PET), ethylene-vinyl acetate (EVA), polyvinyl chloride (PVC), polyethylene (PE) and polyethylene terephthalate (PTP)) [34]. Research shows that adding plastic waste improves the strength and stiffness of

asphalt, but it is important to understand the morphology of plastic waste because it affects the asphalt production method (dry or wet method) and the performance of the resulting asphalt mixture) [34]. In the research different percentage values are mentioned for the addition of plastic waste to asphalt mixture – 5.7 % of the total asphalt weight [35], 6 % of the bitumen weight [36], [37] and 6.5 % of the bitumen weight [38]. In this scenario, it will be used that 6 % of bitumen is replaced by plastic waste from the treated iHCW, while other iHCW fractions are landfilled. In Table 5 the inventory for VS1 is summarised.

TABLE 5. LIFE CYCLE INVENTORY FOR VS1

| Parameter | Unit | Value |
|---|---|---|
| Treatment (chemical: thermal = 52:48) of iHCW[1] | t | 1 |
| Transport (healthcare facility – treatment plant – production plant – landfill) | tkm | 200 |
| iHCW to recovered product | t | 0.34 |
| Substitution of bitumen | t | 0.0009 |
| iHCW to be landfilled | t | 0.66 |

[1]inventory of treatment process is given in Table 4

*VS2: Feedstock for reinforced cement*

Treated iHCW is transported to a concrete production plant, where raw materials such as cement, water, aggregates (sand, gravel, crushed stone and additives) are used [20], [21]. Waste materials, including glass, polypropylene, carbon, polyester and textile fibres, can be incorporated into concrete as reinforcement agents [22]. In VS2, it is assumed that treated iHCW textile waste will partially replace the sand used in concrete, with the previous research [23] noting that replacing 20 % of sand with textile waste yields optimal results. The remaining iHCW fractions are landfilled. The inventory for the value-added product, reinforced concrete, is provided in Table 6.

TABLE 6. LIFE CYCLE INVENTORY FOR VS2

| Parameter | Unit | Value |
|---|---|---|
| Treatment (chemical: thermal = 52:48) of iHCW[1] | t | 1 |
| Transport (healthcare facility – treatment plant – production plant – landfill) | tkm | 200 |
| iHCW to recovered product | t | 0.31 |
| Substitution of sand | t | 0.02 |
| iHCW to be landfilled | t | 0.69 |

[1]inventory of treatment process is given in Table 4

*VS3: Feedstock for RDF*

Treated iHCW is transported to an energy generation plant from refuse derived fuel (RDF) generated from treated iHCW. RDF is a specific type of alternative fuel with a high calorific value (on average 16–18 MJ/kg) and uniform particle size [39]. RDF is obtained from non-hazardous waste and is most often composed of 10–75 % high- and low-density plastic waste, 12–85 % paper and cardboard waste, 5–66 % textile waste, 5–30 % organic waste and up to 10 % non-combustible fraction waste [40]. To recover the valuable material, partially homogenize and eliminate water, $CO_2$ and the non-combustible fraction from waste, the waste are mechanically (crushing, sorting, drying, shredding) or biologically (mechanical treatment with additional biostabilization and biodrying) processed [40]. Within VS3 all treated iHCW

is used to produce RDF and replaces natural gas used for heat production. Inventory for VS3 is given in Table 7.

TABLE 7. LIFE CYCLE INVENTORY VS3

| Parameter | Unit | Value |
|-----------|------|-------|
| Treatment (chemical: thermal = 52:48) of iHCW[1] | t | 1 |
| Transport (healthcare facility – treatment plant – production plant) | tkm | 150 |
| iHCW to recovered product | t | 1 |
| Substitution of heat | MWh | 1 |

[1]inventory of treatment process is given in Table 4

### VS4: Feedstock for syngas production

Treated iHCW is transported to a syngas production plant. Syngas can be produced from various carbon sources – fossil fuel (coal gasification, natural gas, oil), but it is also possible to use waste gasification to obtain syngas [41]. Gasification is a process when insignificant materials (including waste) are converted into gaseous products with usable heat capacity and after purification processes, syngas can be used as an alternative fuel to produce thermal energy and electricity [42]. All treated iHCW will be used to produce syngas, which will then be used to generate electricity, and it will replace electricity from the grid. VS4 inventory is in Table 8, value added product produced syngas from the treated iHCW.

TABLE 8. LIFE CYCLE INVENTORY FOR VS4

| Parameter | Unit | Value |
|-----------|------|-------|
| Treatment (chemical : thermal = 52 % : 48 %) of iHCW[1] | t | 1 |
| Transport (healthcare facility – treatment plant – production plant) | tkm | 150 |
| iHCW to recovered product | t | 1 |
| Substitution of electricity | MWh | 0.64 |

[1]inventory of treatment process is given in Table 4

### VS5: Feedstock for acoustic panel

Treated iHCW is transported to an acoustic panel production plant. Sound absorption panels (or acoustic panels) are made from porous synthetic materials such as stone wool, glass wool, polyurethane, polyester and others [43]. The use of waste in the production of sound-absorbing panels is a possible alternative, as they can have good acoustic properties and are like traditionally used materials [43]. It is concluded that the recycled textile waste has good acoustic properties to be used in the production of panels [44]. Research on thermal and acoustic panels from recycled materials, where the main raw materials are wastepaper and textile waste [45]. To produce 1 m$^2$ of insulation panel, a total of 5.2 kg of raw materials are required – 3.4 kg of wastepaper and 0.4 kg of textile waste, as well as 1.4 kg of glue [45]. All textile waste from the treated iHCW is used to produce acoustic panels, others iHCW fractions are landfilled. Value added product produced acoustic panel from the treated iHCW and inventory data is in Table 9.

TABLE 9. LIFE CYCLE INVENTORY FOR VS5

| Parameter | Unit | Value |
|---|---|---|
| Treatment (chemical : thermal = 52 % : 48 %) of iHCW[1] | t | 1 |
| Transport (healthcare facility – treatment plant – production plant – landfill) | tkm | 200 |
| iHCW to recovered product | t | 0.31 |
| Substitution of foam glass | t | 0.0084 |
| iHCW to be landfilled | t | 0.69 |

[1]inventory of treatment process is given in Table 4

### VS6: Feedstock for plastic components in hydroponics

Treated iHCW is transported to hydroponic systems production plant. Hydroponics and aquaponics are closed environments where plant crops and/or aquatic animals are grown under optimized conditions using soilless systems [46]. A vertical farm system combines hydroponics, aeroponics or aquaponics systems [47]. The technological infrastructure of these systems uses many different plastic products, such as different types of containers and connecting tubes [47]. Plastic waste from iHCW can thus be recycled into various plastic products [48]. Plastic products that would be suitable for a vertical farm are various garden items such as growing containers, water system pipes and others. In this scenario, plastic waste from the treated iHCW is replaced by plastic pellets, while remaining iHCW fractions are landfilled. VS6 inventory data is in provided Table 10.

TABLE 10. LIFE CYCLE INVENTORY FOR VS6

| Parameter | Unit | Value |
|---|---|---|
| Treatment (chemical : thermal = 52 % : 48 %) of iHCW[1] | t | 1 |
| Transport (healthcare facility – treatment plant – production plant – landfill) | tkm | 200 |
| iHCW to recovered product | t | 0.34 |
| Substitution of plastic | t | 0.34 |
| iHCW to be landfilled | t | 0.66 |

[1]inventory of treatment process is given in Table 4

## 3. RESULTS

### 3.1. Life Cycle Impact Assessment Results

Table 11 shows the results of the life cycle impact assessment using ReCiPe 2016 Midpoint (H) method, where the scenario results indicated in numbers (a positive result indicates that the system influences the given environmental indicator, while a negative result signifies an avoided impact, thereby providing an environmental benefit). The results also are marked with colours on a scale from very low environmental impact (bright green) to very high environmental impact (orange).

As seen from Table 11, the environmental impacts in VS3 and VS4 are entirely negative due to the high share of iHCW being recycled rather than landfilled.

TABLE 11. ReCiPe 2016 Midpoint (H) results for BAU and VS1–VS6

| | BAU | VS1 | VS2 | VS3 | VS4 | VS5 | VS6 |
|---|---|---|---|---|---|---|---|
| GW, kg CO$_2$ eq | 1.51E+03 | 1.25E+03 | 6.03E+02 | −1.95E+02 | −2.37E+02 | 5.98E+02 | 1.18E+03 |
| SOD, kg CFC11 eq | 8.08E−05 | 8.21E−05 | 8.89E−05 | −2.14E−05 | −1.87E−04 | 8.73E−05 | 6.02E−05 |
| IR, kBq Co-60 eq | 2.77E+00 | 2.66E+00 | 2.93E+00 | −7.60E−01 | −4.33E+01 | 2.58E+00 | 1.45E+00 |
| OFHH, kg NO$_x$ eq | 2.98E−01 | 1.96E−01 | 2.19E−01 | −1.65E−01 | −5.39E−01 | 2.07E−01 | 3.11E−02 |
| PM, kg PM2.5 eq | 8.76E−02 | 7.02E−02 | 7.71E−02 | −2.80E−02 | −2.89E−01 | 6.96E−02 | −4.53E−02 |
| OFT, kg NO$_x$ eq | 3.13E−01 | 2.11E−01 | 2.37E−01 | −1.88E−01 | −5.71E−01 | 2.24E−01 | 4.18E−02 |
| TA, kg SO$_2$ eq | 1.91E−01 | 1.49E−01 | 1.64E−01 | −7.37E−02 | −5.68E−01 | 1.51E−01 | −2.22E−02 |
| FE, kg P eq | 9.86E+00 | 4.62E+00 | 6.56E+00 | −3.33E−03 | −4.94E−02 | 6.55E+00 | 4.57E+00 |
| ME, kg N eq | 2.06E+00 | 6.10E−01 | 1.81E+00 | −2.35E−03 | −5.31E−03 | 1.80E+00 | 6.06E−01 |
| TEC, kg 1,4-DCB | 9.98E+02 | 1.20E+03 | 1.30E+03 | −4.02E+02 | −3.82E+03 | 1.27E+03 | 9.56E+02 |
| FE$_C$, kg 1,4-DCB | 5.18E+02 | 3.58E+02 | 4.59E+02 | −4.49E−01 | −6.52E+00 | 4.59E+02 | 3.51E+02 |
| MEC, kg 1,4-DCB | 6.87E+02 | 4.73E+02 | 6.12E+02 | −1.16E+00 | −1.20E+01 | 6.12E+02 | 4.63E+02 |
| HCT, kg 1,4-DCB | 2.04E+01 | 1.89E+01 | 2.17E+01 | −8.87E+00 | −3.23E+01 | 2.10E+01 | 1.10E+01 |
| HNCT, kg 1,4-DCB | 1.23E+04 | 8.07E+03 | 1.12E+04 | −2.50E+00 | −1.22E+02 | 1.12E+04 | 7.97E+03 |
| LU, m$^2$a crop eq | 5.72E+00 | 4.81E+00 | 4.70E+00 | −2.56E−01 | −2.52E+01 | 4.48E+00 | 3.68E+00 |
| MRS, kg Cu eq | 1.50E−01 | 1.57E−01 | 1.79E−01 | −1.05E−01 | −4.58E−01 | 1.62E−01 | 5.76E−02 |
| FRS, kg oil eq | 2.09E+01 | 2.09E+01 | 2.43E+01 | −7.43E+01 | −7.48E+01 | 2.29E+01 | 6.74E+00 |
| WC, m$^3$ | −5.67E+00 | −3.11E+00 | −6.07E+00 | −1.58E−01 | −2.06E+00 | −6.09E+00 | −3.35E+00 |

| Colour scale | Very low | Low | High | Very high |
|---|---|---|---|---|

Overall, the lower environmental impact results were achieved in the VSs, where the entire iHCW stream was recycled for energy recovery (VS3 and VS4), but this does not properly align with the circularity principles where the focus needs to be given on re-use, recycling and recovery. To keep the focus on circularity, VS7 was created: it represents an integrated recycling and energy recovery process – plastic and textile fractions of iHCW are recycled, the remaining fraction (rubber, metals, wood and mix of fines), which cannot be yet recycled to any of the analysed recycling scenario, is transferred to energy recovery. Based on the LCA results (see Table 11), this includes plastics recovery via VS5, textiles recovery via VS7 and the remaining treated iHCW directed to syngas production through VS4. The impact of transportation is similar in all considered scenarios (from 0.4 Pt to 1.5 Pt) due to the distance assumptions made, and the impact of the iHCW treatment process as well as – being in the range from 0.29 Pt to 0.44 Pt.

For better representation of BAU and VS results, Fig. 3 provides the results in single score manner and the values are expressed in EcoPoints (Pt). The single-point results are formed from three main groups: iHCW treatment, transportation and end-of-life. As can be seen, the greatest impact is caused by landfilling iHCW, while the impact of transport and iHCW treatment has similar Pt values in all scenarios.
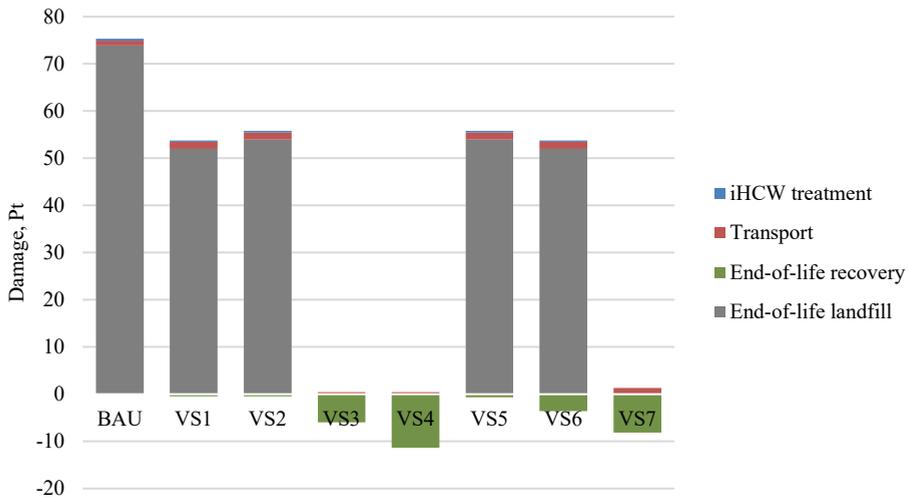
Fig. 3. Single score results for BAU and VS1–VS7 (ReCiPe 2016 Midpoint (H)) method.

## 4. DISCUSSION AND CONCLUSIONS

The annual generated amount of treated iHCW in Latvia accounting for close to 3000 tonnes and comprising such fractions as textiles, plastics, metals, wood and other. Despite the high microbiological cleanness and relatively stable annual quantities of treated iHCW, the recovery of it to new materials and products is still underdeveloped nationally and regionally. To guide the potential waste management companies, investors and policymakers in this direction, along the economic benefits, the environmental benefits need to be highlighted particularly considering the EU circular economy and decarbonization targets. This study provided the LCA based ('gate-to-gate' analysis) comparison of end-of-life stages between one BAU scenario (landfilling) and seven VSs for the iHCW generated in Latvian healthcare sector.

The results of the LCA specifies the following recommendations:

- Landfilling of treated iHCW should be minimized as much as possible as it creates a double-negative effect: spending (1) resources and generating environmental impacts related to iHCW microbial inactivation and (2) afterwards again generating environmental impacts through landfilling of treated iHCW.
- The analysis of VSs with varying proportions of iHCW integrated into the production of new products shows that valorizing the majority of the treated iHCW fractions is advantageous.
- While energy recovery valorization strategies properly ensure recovery of all treated iHCW fractions and, as indicated in the results of the study, can even generate the negative environmental impact, this approach does not fully align with the core objective of the EU circular economy framework – recovering the waste into materials rather than energy. From the business perspective, the energy recovery from treated iHCW may become risky in long-term due to future stricter EU regulations in circular economy field. When generating a VS, along the environmental performance results, a special attention should be also put on generation of high-added value products.

– Following the circular economy targets, the healthcare sector is also starting to be oriented on even the higher concepts of waste hierarchy beyond recovery, i.e. waste minimisation and re-use. This shift has been properly addressed by leading healthcare organisation, such as, for example, World Health Organisation and Health Care without Harm [49]–[52] implementing strategies for effective waste separation at source, monitoring waste volumes, integrating sustainability of products and services into procurement processes, reduce unnecessary use of medical consumables, replacing single use materials with reusable ones, and others. These strategies effectively reduce the environmental impacts from the HCW sector. While, from the business perspective, this also eliminates the amount of potential waste recovered resources for entrepreneurs. Therefore, when planning the HCW-derived businesses, high level of flexibility in regards to alternative feedstocks, aside HCW, should be integrated to ensure long-term economical viability.

As far as for recommendations to the future research, the authors recommend to extend the next LCA to broader system boundaries – as a minimum 'gate to grave' and as a best – 'cradle to grave'. This broader perspective would encompass additional life cycle stages and potentially reveal different insights about the environmental benefits and burdens of iHCW valorisation.
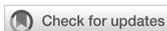
## ACKNOWLEDGEMENT

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# Fishing net waste management: quantification and valorization

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Abandoned, lost or discarded fishing gear harms marine ecosystems by releasing microplastic waste from synthetic materials, reducing biodiversity, spreading invasive species and causing long-term damage to fragile habitats. Therefore, it is essential to evaluate fishing gear waste quantities and establish efficient waste management strategies focused on reuse, recycling and recovery. This research develops a methodology to assess the quantity of discarded fishing nets and scrap waste from Latvia's fishing gear industries, explores potential waste valorization scenarios and evaluates them based on the country-specific circular economy principles. The study employs environmental life cycle assessment (avoided burden approach) and environmental damage cost methods to evaluate different waste management scenarios for discarded fishing nets in Latvia. Findings show that manufacturing scraps exceed discarded fishing nets, with Latvia averaging 53 tons of fishing net waste annually from 2018 to 2023, and a notable drop in manufacturing during COVID-19. The assessment of valorization scenarios demonstrates that recycling fishing nets for nylon production and asphalt reinforcement significantly reduces both environmental impact and costs. Specifically, recycling for nylon production avoids 7850 kg of $CO_2$ eq. and reduces environmental damage costs by 2947 Euro per tonne of discarded fishing nets. For asphalt reinforcement, it avoids 636 kg of $CO_2$ eq. and results in a cost reduction of 407 Euro per tonne of discarded fishing nets. In contrast, the less environmentally feasible options, syngas production and landfilling, show higher environmental footprints. Syngas production generates 156 kg $CO_2$ eq. per tonne of fishing nets and incurs an additional environmental damage cost of 31 Euro per tonne, but it is still a preferable alternative to landfilling. Landfilling has the most severe impact, generating 12100 kg $CO_2$ eq. and costing 29609 Euro per tonne, making it the least favorable option and one that should be avoided. Research underscores the necessity for uniform data collection on fishing net waste and enhanced collaboration among stakeholders to facilitate valorization and investment efforts.

# 1 Introduction

Marine ecosystems are highly vulnerable to human pollution, which is worsening as populations and generated waste increase (Dabrowska et al., 2021). Significant form of marine pollution is abandoned, lost or discarded fishing gear (ALDFG), known as ghost gear which also includes ghost nets, which is a global transboundary plastic pollution problem (World Wide Fund, 2020; Mengo et al., 2023). At least 46% of the Great Pacific Garbage Patch consists of ghost gear and in Europe this waste is among the 10 most common types of debris found on coasts and beaches (World Wide Fund, 2020; Juan et al., 2021). Ghost nets occur under various circumstances such as when fishing nets become entangled with marine obstacles, are lost during fishing operations or interact with other fishing gear (Thomas and Lekshmi, 2017; Kozioł et al., 2022; Hodgson, 2022). The impact and longevity of ghost nets depend on their material properties, with more durable nets causing prolonged harm to marine life and ecosystems (Thomas and Lekshmi, 2017; Kozioł et al., 2022; Stephen Hodgson, 2022). Fishing nets are classified as textiles with various physical (construction, density, durability, strength and resistance) and chemical properties (composition) (Farah et al., 2021; Karadurmuş and Bilgili, 2024). The structural characteristics significant for fishing nets are summarized in Figure 1.

Fishing nets tend to have different composition due to the different applications and types of materials used (see Figure 2). Overall, synthetic fibers dominate, mostly polyamide, incl. nylon, in modern fishing nets due to their durability in marine environments (Karadurmuş and Bilgili, 2024).

Synthetic fishing nets, as a type of plastic waste, causes not only environmental harm but also economic and social damage (Juan et al., 2021). The nets tend to drift freely in the initial stages and then become entangled, passively capturing and killing aquatic life, but these nets also tend to damage coral reefs and become entangled in ship propellers (Kozioł et al., 2022; Defraeye and Shoji, 2024). The research of A. R. Gajanur and Z. Jaafarresearch demonstrates that in shallow waters nets stop capturing marine organisms after 224 days, but in deeper waters, marine organisms are captured for

more than three years (Gajanur and Jaafar, 2022). In additon, fishing nets impact biodiversity by introducing alien and invasive species into new areas, causing physical damage to marine habitats and animals (Gunasekaran et al., 2024). Aquatic creatures may also ingest net fragments, which can then enter the human food chain (Kozioł et al., 2022; Kannan et al., 2023). Given the significant multiplicative impact of discarded fishing nets on various enviromental issues, their proper management – through recycling, upcycling and sustainable disposal – can contribute to achieving multiple Sustainable Development Goals (SDGs), see Figure 3.

However, to achieve the SDGs related to discarded fishing nets and gear, several uncertainties must be addressed, including the amount lost, the rate of microplastic degradation and their impact on the marine environment and seafood consumers. Other challenges include the loss of fishing time due to damage or loss of gear, the effect on ecosystem services, and the unclear distribution of responsibility and financial burden for cleaning up marine debris and abandoned waters (Apete et al., 2024).

Estimates of the amount of fishing net or gear litter generated vary between studies and Table 1 some examples of data collection methods are summarized. Due to the diversity of materials, recycling of fishing nets is complicated by disassembly, high organic pollution and logistical problems, which, as a result, often lead to energy recovery from fishing nets rather than recycling, although it is technically possible (Juan et al., 2021; Basurko et al., 2023). Fishing net recycling is possible by mechanical methods, chemical methods and thermal methods, but in all the cases fishing net waste requires pre-treatment to be cleaned from organic impurities (Sala and Richardson, 2023). Then this fishing net waste is sorted and, if necessary, shredded and then processed to more valuable products (Sala and Richardson, 2023). Methods such as incineration and landfilling of fishing nets waste are unsustainable and are classified as downcycling (Kim et al., 2022). Recycled fishing nets can be reused for accessories, clothing, footwear, home furnishings and leisure goods, as well as for industrial applications such as building materials, where they help reduce early shrinkage cracking and improve the mechanical



**FIGURE 1**
Fishing nets structural characteristics (Thomas and Lekshmi, 2017; Farah et al., 2021; Karadurmuş and Bilgili, 2024).
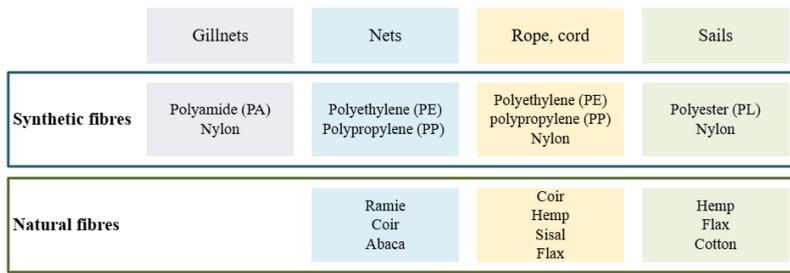
FIGURE 2
Synthetic and natural fibres widely used in fisheries (Singha and Singha, 2012; Thomas and Lekshmi, 2017; Sato and Shishido, 2020; Juan et al., 2021).

properties of cement, plaster and earth materials (Mondragon et al., 2020; Charter and Carruthers, 2022; Bertelsen et al., 2023; Sala and Richardson, 2023). Although, the industrial and large-scale use of discarded nets as a raw material for new products is hampered by the lack of reliable data and methodology on the definition of the amount of net waste generated annually.

As shown in Table 1, the primary approach to gathering information on the amount of discarded fishing nets is through interviews with fishermen, port workers and waste managers. The data collected is usually approximate and often relies on assumptions to estimate amounts. Also, no record of discarded nets is done during fishing, either on ships or in ports, which would certainly help determine a more accurate amount of discarded fishing nets.

The aim of this study is to develop a methodology to assess the amount of discarded fishing nets and manufacturing scraps, as well as to propose and assess valorization scenarios for discarded fishing nets and fishing net production scrap.

## 2 Methodology

This study concentrates on Latvia (Europe) and the corresponding fishing area of the Baltic Sea (refer to Figure 4). The Baltic Sea shoreline of Latvia stretches for 497 km, which constitutes roughly 0.7% of the overall coastline within the European Union. Furthermore, the inland waterways – including

lakes and rivers – encompass an area of 2340 km², which accounts for approximately 3.6% of Latvia's entire land area.

The research encompasses the years 2018 to 2023, a timeframe distinguished by two significant occurrences that profoundly impacted fishing operations. The first, the COVID-19 pandemic, and the second, Russia's war in Ukraine, disrupted both fishing activities and the manufacturing of fishing equipment. In an effort to alleviate the repercussions of the pandemic, a sum of 2.8 million Euro in public funding was allocated across all sectors of the fishing industry (Ministry of Agriculture of the Republic of Latvia, 2022). Furthermore, an additional 5 million Euro in assistance was designated to counterbalance the ramifications of the conflict, encompassing the escalation of energy and raw material expenses, as well as the diminishment of export markets in Ukraine, Belarus and Russia (Ministry of Agriculture of the Republic of Latvia, 2022). Both occurrences also played a role in the decline of fishing net production and a reduced prevalence of discarded nets in the Baltic Sea, attributable to diminished fishing intensity and catch rates.

## 2.1 Quantification of discarded fishing nets

The methodology is based on three data collection approaches. The first is statistical data collection on import and export of fishing nets, the second is interviews with fishing net manufacturers and retailers, fishermen and association of fishermen, port authorities, waste management companies, national authorities (State
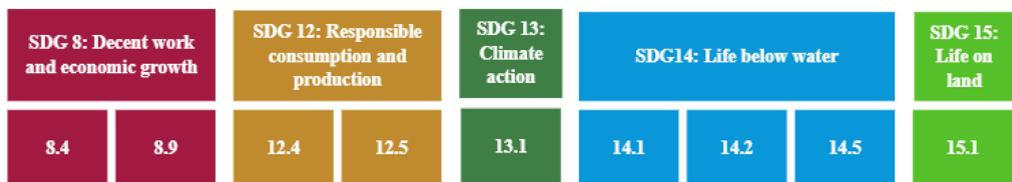


FIGURE 3
SDG indicators related to discarded fishing nets (United Nations Sustainable Development, 2017).

TABLE 1 Existing methodologies for quantification of discarded fishing nets and gears.

| Research object | Methodology |
|---|---|
| Post-consumption end-of-life fishing gear (Spain) (Basurko et al., 2023) | Interviews with port representatives and fishermen to quantify discarded fishing gear based on type of vessel and type of gear (bottom otter trawl, purse seine, pole and line, longline, gillnet/trammel net) as well as waste managers on overall quantity of gear managed. Results obtained quantifies specific fishing gear used per specific vessel and the total amount in seven Spanish coastal regions. |
| Mainly pre-consumption fishing gear (Sweden, Norway, Denmark, Finland and Aland islands, Iceland, Faroe, Greenland) (Unsbo et al., 2022) | Initial data collection via literature review combined with interviews with manufacturers and retailers on identification of sales statistics, national import and export data as well as a web-based survey on fishing gear losses in targeting sport and recreational anglers. The result is an estimate of annual fishing net losses and annual quantities of fishing gear placed on the market. |
| Mainly pre-consumption fishing gear (Denmark, Estonia, Finland and Aland islands, Germany, Latvia, Lithuania, Poland, Sweden) (Unsbo et al., 2023) | Initial statistical data collection via literature review (statistics and customs service data, research articles, reports) followed by interviews with fishing net manufacturers, retailers, marine processing centres and relevant authorities as well as an open web-based questionnaire for fishermen. The result is an estimate of annual fishing net losses and annual quantities of fishing gear placed on the market. |
| Mainly post-consumption fishing gear (global practice) (Richardson et al., 2019) | A literature review (research articles and technical reports) was conducted and statistical data on fishing gear volumes, scales, time periods, geography and characteristics collected and processed via statistical data assessment models. The result provides annual gear loss by gear type and provision of the most suitable gear loss prediction model. |
| Post-consumption end-of-life marine litter (Baltic Sea) (Kammann et al., 2023) | Data on marine litter was gathered during three seabed surveys employing 65 bottom trawls. The debris, collected from authentic marine environments, was sorted, classified, weighed, measured and photographed following the International Council for the Exploration of the Sea protocols. Items exceeding 2.5 cm were incorporated into the analysis and organized by material type. Items related to fishing gear were designated as ALDFG, with fishing nets recognized as the primary subcategory. Plastic items underwent subsampling and were analyzed for polymer composition through Attenuated total reflectance-Fourier transform infrared spectroscopy spectroscopy. |

*(Continued)*

TABLE 1 Continued

| Research object | Methodology |
|---|---|
| Post-consumption end-of-life fishing gear (Sri Lanka) (Gallagher et al., 2023) | Data gathering was carried out through interviews with fishermen, emphasizing their fishing methods, the kinds of gear utilized, and approaches for handling worn or broken equipment. The findings reveal that the yearly life cycle of fishing gear has been measured, with most of the gear being mended or repurposed across five districts in Sri Lanka. |

Environmental Service, the Ministry of Agriculture of the Republic of Latvia Fisheries Department) and the third – extrapolation of missing data.

The interviews with fishermen revealed that retrieved from waters, but not ghosted, fishing nets are as long as possible repaired and reused directly for fishing or in other application, for example, farming, thus avoiding discarding. However, when nets become unusable, they are often discarded in mixed municipal waste rather than being sorted for recycling. Waste managers also confirmed that fishing nets appear irregularly in waste sorting facilities. Therefore, to enable the valorization of unusable fishing nets, a proper collection system must be developed and implemented.

Fishing nets suitable for valorization can also be sourced by retrieving ghost nets and historically lost nets from the sea. However, their quantity and material composition remain unpredictable, leading to periodic fluctuations in the availability of resources for valorization. To establish a more stable resource supply, fishing net production companies operating in Latvia could play a key role. These companies generate production scraps that are well-suited for recycling alongside discarded fishing nets, as they are made of the same material. Additionally, the quantity of these scraps is documented in company reports and remains stable, making them a reliable resource for waste recycling.

Figure 5 presents the methodology for quantifying manufacturing scraps (pre-consumption) and discarded fishing nets (post-consumption) across all material types. Combining both pre-consumption and post-consumption waste ensures a sufficient and stable supply of resources for recycling.

The study has certain methodological limitations, primarily related to the availability and quality of current data and assumptions made. Where data on generated and managed ALDFG waste amount was missing or incomplete, assumptions were made based on information provided by industry representatives, which may be specific to the Latvian context and not directly transferable to other regions. For example, estimates regarding the replacement frequency of fishing gear, total quantities in use in Latvia and characteristics of the most used equipment. These limitations should be considered when interpreting the findings and assessing their generalizability.

**FIGURE 4**
Map of the study area – Latvia and the Baltic Sea.

## 2.2 Assessment of valorization of fishing net waste

Effective waste management is necessary to prevent the environmental impact of discarded fishing nets. They can be reused and recycled through mechanical or/and chemical recycling, prioritizing recycling over landfilling (Van den Tempel and Picchioni, 2025). To assess the effectiveness of fishing net recycling, the study evaluates three valorization scenarios alongside a business-as-usual scenario – landfilling of fishing net (see Table 2). Additionally, it is important to note that only synthetic (nylon) fishing nets are analyzed in the valorization scenarios due to their predominant market presence, widespread use and significant environmental impact.
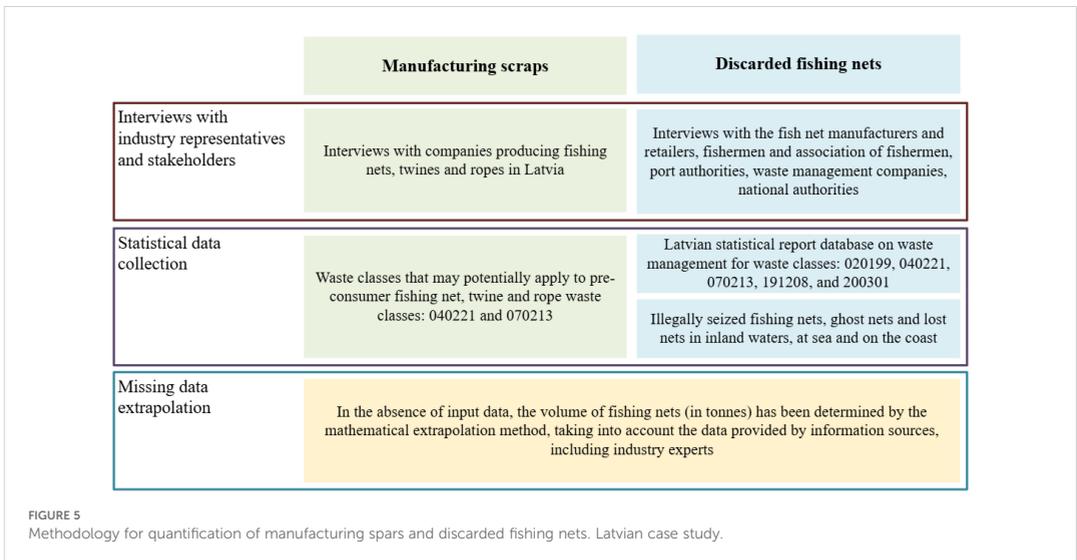


**FIGURE 5**
Methodology for quantification of manufacturing spars and discarded fishing nets. Latvian case study.

| | |
|---|---|
| Scenario 1 (S1) | Fishing nets made primarily of nylon can be thermomechanical processed to recover the same material without any loss of properties, making it suitable for reuse in similar products (Tonsi et al., 2023). Tensile test results confirm that the recycled nylon exhibits mechanical properties comparable to commercial nylon (Mondragon et al., 2020). In this scenario, the **replacement of new nylon with recycled fishing net waste** is analysed. |
| Scenario 2 (S2) | The physico-mechanical properties of nylon fibers make them suitable for use as reinforcement fibers, and fishing net fibers serve as a viable alternative to commercially available reinforcing fibers (Bertelsen et al., 2023). Consequently, recycled fishing net waste can be used as reinforcement in asphalt mixture because nylon filament improves the high-temperature stability, low-temperature crack resistance and toughness of asphalt mixture (Yin, 2020). In this scenario, fishing net waste are used as **reinforcement in asphalt materials replacing glass fibre reinforcement.** |
| Scenario 3 (S3) | Fishing net waste is made of different types of plastic, so energy can be obtained from plastic waste as syngas (Choi et al., 2021). In this scenario, fishing net waste is converted into **syngas.** |
| Scenario 4 (S4) | Collected fishing nets are not recycled and are **landfilled**, which is the current fate of fishing net waste. |

The defined valorization scenarios will be assessed through life cycle assessment (LCA) and environmental damage cost methods.

## 2.2.1 Environmental assessment

The principles and framework for LCA, as defined in ISO 14040:2006 and ISO 14044:2006 (International Organization for Standardization, 2006a, 2006b) are followed in this study. LCA can be used to access the impact of recycling processes through three main approaches: the cut-off approach, the partitioning approach and the avoided burden approach (Liu et al., 2022). In this research,

the avoided burden approach is used to evaluate the environmental impact of different fishing nets waste management scenarios.

### 2.2.1.1 Goal and scope

The goal of the study is to evaluate and compare the environmental impact of discarded fishing net management scenarios. The functional unit selected for the LCA study is 1 ton of discarded fishing net after pre-treatment (i.e., after the separation of unnecessary fractions, such as organics, from the nets).

### 2.2.1.2 System boundary

The LCA system boundaries (see Figure 6) defined in the study are "cradle-to-cradle" (for S1-S3) and "cradle-to-grave" (for S4) and as the avoided burden approach is applied it is modelled that the discarded fishing net as a resource completely or partially replaces the traditional raw materials used in production of nylon or asphalt additive. The installation and transportation stages as well as the use phase (including maintenance, reuse, repair and replacement of fishing nets) are excluded from the assessment due to their similarity across different types of synthetic fishing nets (thus negligible) and the lack of reliable inventory data for these stages.

### 2.2.1.3 Inventory

Relevant inventory data, including data on fishing net production (Karadurmuş and Bilgili, 2024), fishing net waste management scenario data (Schneider et al., 2023) is obtained from literature review and "Ecoinvent" database (see Table 1 and Table 2 in Supplementary Material).

### 2.2.1.4 Impact assessment

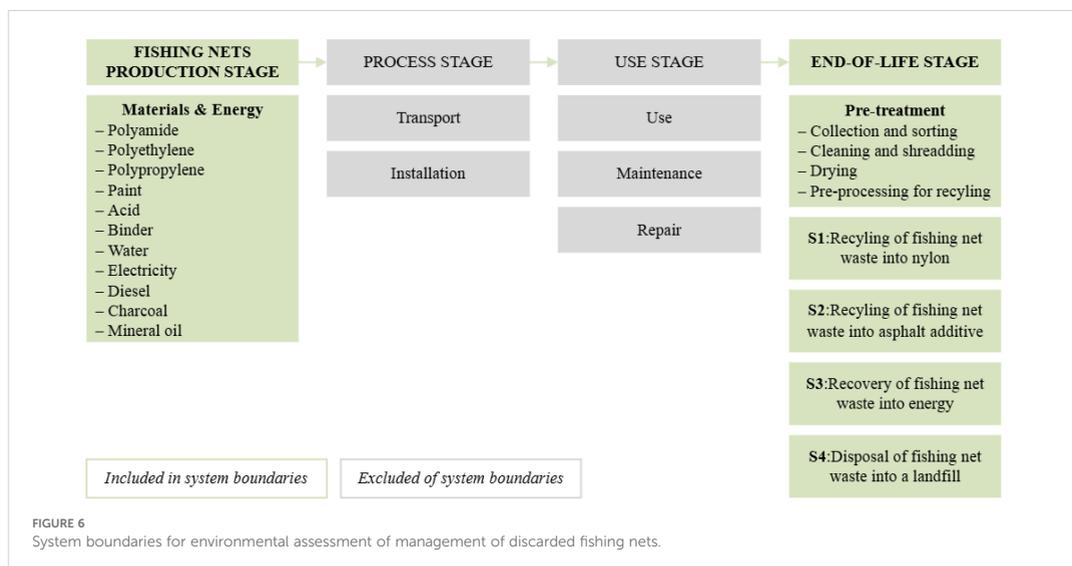The ReCiPe 2016 midpoints method has been chosen for the LCA impact assessment. The ReCiPe 2016 midpoints method has

16 impact categories, according to which the environmental impact assessment is also performed (Huijbregts et al., 2017).

## 2.2.2 Economic indicators

There are several methods to assess the economic aspect, such technical-economic assessment *via* CAPEX and OPEX (also called conventional life cycle costing), cost-benefit analysis, environmental life cycle costing and societal life cycle costing (PRé Sustainability, 2022). However, there are also environmental damage cost method, which determine the damage caused by specific pollution as euros per unit of pollutant (De Vries et al., 2024). Since environmental damage cost is not directly observable, they must be calculated based on damage assessments and economic impact studies (De Vries et al., 2024).

This study will use LCA results and convert them into monetary values Environmental damage costs are updated periodically with the latest release being from 2021 (De Vries et al., 2024). To obtain environmental prices that reflect 2025 values, an adjustment for environmental cost inflation was made using World Bank data and forecasts for 2025 (Directorate General for Economic and Financial Affairs, 2024; World Bank, 2024). The adjusted environmental damage costs by impact category are presented in Table 3.

# 3 Results

## 3.1 Quantification of fishing nets in Latvia

In 2023, a total of 1659 illegal fishing gear was confiscated in inland waters of Latvia. The most confiscated items were fishing lines (613 pieces), followed by fishing nets (355 pieces) and crayfish traps and chalks (334 pieces). In marine and coastal waters, 121 illegal fishing gear were seized. Among these, the most frequently confiscated were fishing nets (110 pieces), along with herring nets (3 pieces), fish traps (1 piece), longline (1 piece), bream traps (3 pieces) and other type of gears (3 pieces) (Latvian Rural Consulting and Education Center, 2024). Figure 7 illustrates the amount of Latvia's import and export fishing nets, twine, ropes and sails. As shown, these volumes fluctuate significantly from year to year, with 2022 recording the lowest export volume and the highest import volume, and on average, the import volume is twice as large as the export volume. The net domestic trade, therefore, ranges from 9 to 435 tons.

Previous research (Rijkure et al., 2024), which estimated gear losses in coastal fisheries in the Baltic Sea based on national statistics and literature review, has highlighted a significant accumulation of abandoned fishing gear, particularly gillnets, entangling nets and traps, over the past 10 years. Another study quantified marine litter on the Baltic Sea floor, identifying fishing gear as a main source. This study, which involved collecting litter as part of the catch, found an average litter volume of 9.2 L/km², with polyethylene being the most common polymer (Kammann et al., 2023).

Latvian ports accept ship waste in accordance with the legislation, which includes a category for fishing gear in the corresponding form. However, this type of waste is rarely transferred at Latvian ports. It is licensed that in 2025, 42 vessels

TABLE 3 Environmental damage costs, Euro per unit of pollutant (De Vries et al., 2024).

| Impact category | Environmental damage price, €$_{2025}$ per unit |
|---|---|
| Climate change | 0.16 |
| Ozone depletion | 34.76 |
| Ionising radiation | 0.0052 |
| Oxidant formation, human health | 2.76 |
| Oxidant formation, terrestrial ecosystems | 0.51 |
| Particulate matter formation | 121.95 |
| Acidification | 6.47 |
| Freshwater eutrophication | 4.59 |
| Marine eutrophication | 17.53 |
| Terrestrial ecotoxicity | 0.00079 |
| Freshwater ecotoxicity | 0.0257 |
| Marine ecotoxicity | 0.00393 |
| Human toxicity, cancer-related | 4.9 |
| Human toxicity, non-cancer-related | 0.0873 |
| Land use | 0.1216 |
| Mineral extraction | 0.0172 |
| Fossil extraction | 0.0344 |
| Water consumption | 0.5002 |
| NO$_2$ addition | 7.83 |

will carry out industrial fishing in the Gulf of Riga (The Ministry of Agriculture of the Republic of Latvia, 2025). For industrial fishing in inland waters, coastal waters and at sea as well as for self-consumption fishing, the fishing nets and lines with limited lengths are used. According to the regulations set up in Latvia (Cabinet of Ministers of the Republic of Latvia, 2014), the allowed annual length of inland water (lakes) fishing nets is 142–000 m, in coastal waters – over 350–000 m (Cabinet of Ministers of the Republic of Latvia, 2007, 2014). This type of data provides the maximum annual net length allowed in the national waters.

Historical data on the amount of fishing nets in national waters can only be found by cleaning up the waters. Finnish oil refining company Neste in collaboration with partners from Latvia (Latvian Maritime Academy and Science and Innovation Center of the Riga Technical University), Lithuania (Nardymo Academy) and Estonia (Teeme Ära) is working to clean up the Baltic Sea from ghost nets, develop innovative technological solutions for cleaning the sea pollution and recycling it (Neste, 2025). In the summer of 2023, a tugboat sunk during World War II was cleared near a small port town in Latvia, and within two days, 1 m³ of nylon nets, consisting of 1970s lute trawls and 40-year-old herring trawls, were brought to shore (Neste, 2023). In 2024, fishing gear with a total length of 280 m was found near a small Latvian port city lying 5–10 m deep at the sea
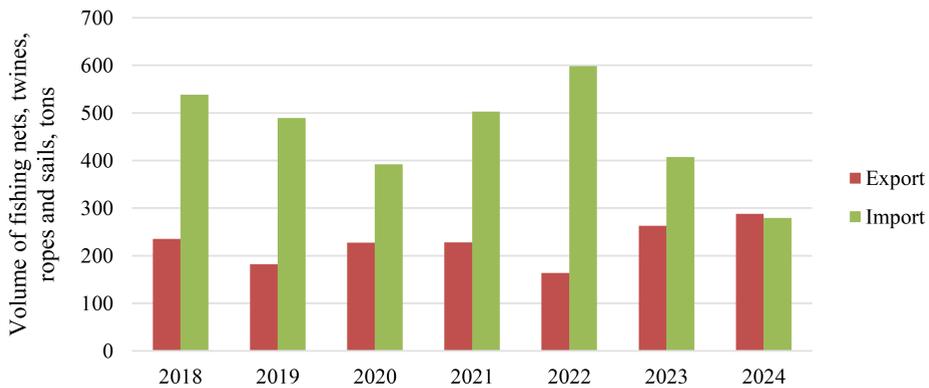
bottom (Neste, 2024a). Industry professionals have reported numerous new shipwrecks in the Gulf of Riga, many of which are surrounded by ghost nets. Efforts to survey and map these wrecks will continue until 2026. Meanwhile, divers predict that approximately 2 tons of ghost nets will be removed, marking a significant increase compared to the previous year (Neste, 2024b) (an example of abandoned fishing gear collected from the Latvian shores of the Baltic Sea is presented in Figure 8).

## 3.2.1 Discarded fishing nets

Discarded fishing net, twine and rope waste is generated after fishing and accurate data of this type has not been yet collected for Latvia. Therefore, interviews with stakeholders were held to estimate the data. In addition, the data from the state authorities, who regularly carry out inspections in inland waters, seas and coasts and remove illegal fishing gear, was collected (see Figure 9).

Although the number of inspections in Latvia's inland and marine waters varies from year to year, there is a slight overall trend of decline. Inspection practices are evolving through the adoption of innovative technologies such as drone surveillance, echo sounders, GPS navigation devices, thermal imaging cameras, and night vision equipment. In addition to technological advancements, administrative changes have expanded the authority to remove illegal fishing gear. This responsibility is no longer limited to inspectors from the State Environmental Service, but also includes public environmental inspectors, municipal police, municipal environmental control officers, the State Police, the State

Border Guard and the Coast Guard Service of the National Armed Forces Navy. Moreover, international cooperation plays a crucial role in marine fisheries control. Inspectors from the Latvian State Environmental Service actively participate in international inspection missions. However, this cooperation was disrupted by the COVID-19 pandemic, and in 2020, Latvian inspectors took part in fewer international missions as a result.

The discarded fishing net, twine and rope waste amounts were calculated considering the volume of seized illegal fishing nets and the amount of discarded fishing nets. The following framework for the calculation is designed:
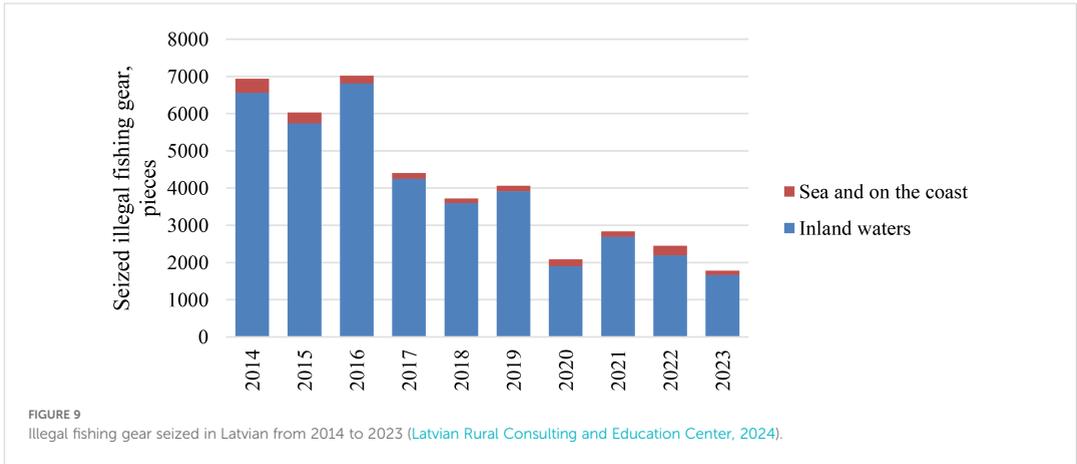
- the average weight of one net is 5 kilograms (the weight of the most used commercial fishing net).
- 40% of fishing nets are replaced once a year and 60% of fishing nets – once every 4 years.
- the total length of nets – 490–000 m annually.
- the most used fishing net type (0.17 mm nylon net, 30 m, wall height – 1.8 m, mesh size – 40 mm, weight – 0.5 kg) was used to calculate the volume of waste. Thus, the total estimated volume is 5 tonnes annually.

## 3.2.2 Fishing net manufacturing scraps

Latvia has companies that produce various types of fishing gear. Nylon, polyester, polyamide and polypropylene tows, cords, ropes

**FIGURE 9**
Illegal fishing gear seized in Latvian from 2014 to 2023 (Latvian Rural Consulting and Education Center, 2024).

are produced, as well as fishing threads from polyamide fibre and polyester fibre. These companies generate production scraps and residues, which are managed in accordance with regulatory enactments, and this type of waste is managed by companies in Latvia and neighbouring countries.
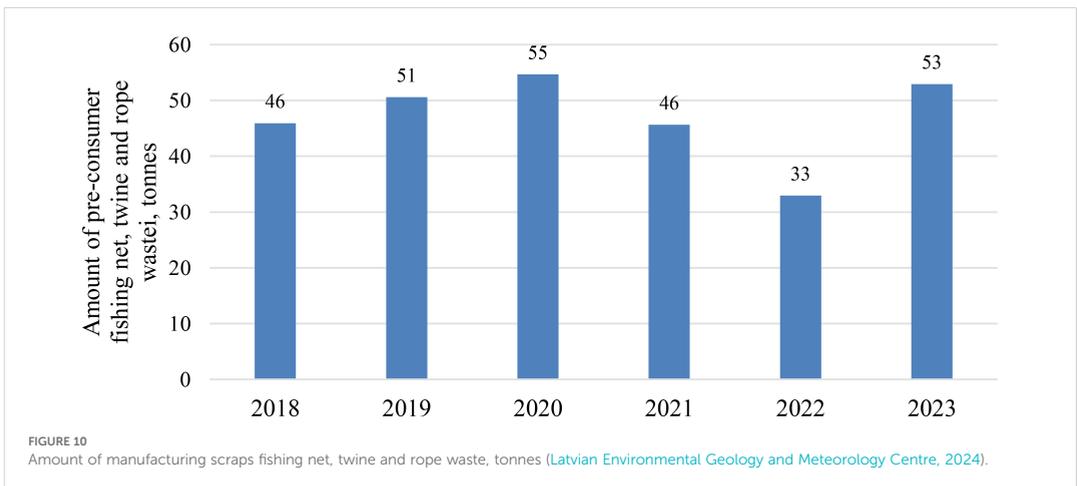
In Figure 10, the data about the waste generated in Latvia under the waste classes 040221 "Wastes from unprocessed textile fibres" and 070213 "Wastes from the MFSU of plastics, synthetic rubber and man-made fibres" according to the European waste catalogue (European Commission, 2000) are summarised. The average amount for 2018–2023 is 47 tons of manufacturing scrap waste.

### 3.2.3 Amount of discarded fishing nets and manufacturing scraps

Figure 11 illustrates the estimates regarding the total amount of fishing net waste, which includes both discarded fishing gear and manufacturing by-products. As depicted, the annual volume

remains consistent, except for the years 2021 and 2022, when a significant decrease in fishing net waste was noted. This decline is probably associated with the effects of the COVID-19 pandemic, which disrupted the activities of fishing vessels and manufacturing firms – especially in areas heavily impacted by serious outbreaks.

Looking at the amount of manufacturing scraps and discarded fishing nets waste provides insight into the waste dynamics of the sector and the opportunity to assess waste management options. Amount of manufacturing scraps are important because they are off-cuts from the fishing net manufacturing processes and are therefore clean waste that can be subsequently recycled into a high-value product and do not require a major waste treatment step. Discarded fishing nets data are not systematically recorded and are based on estimates, but the management of this waste is also important, although the amounts in Latvia are smaller than the manufacturing scraps amount in Latvia. However, Latvia generates an average of 53 tonnes of fishing net waste that needs to be managed effectively.
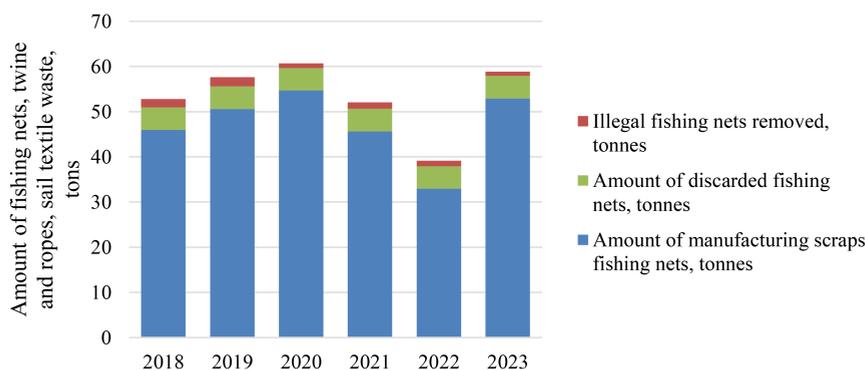


**FIGURE 10**
Amount of manufacturing scraps fishing net, twine and rope waste, tonnes (Latvian Environmental Geology and Meteorology Centre, 2024).

**FIGURE 11**
Quantification on fishing net waste in Latvia for 2018-2023.

## 3.2 Fishing net waste valorization scenarios

The results from the "ReCiPe 2016" midpoints method are reflected in Table 4. The negative values are considered as benefits to the environment and the positive values – as negative impacts to the environment.

The environmental damage costs per impact category is reflected Table 5. The most expensive environmental damage categories are particulate matter and ozone depletion. In this case, the impact of ozone depletion and particulate matter is related to electricity consumption and fishing net production. Similarly, to the LCA results, some of the environmental damage costs results are negative, thus presenting economic benefits (revenues) for the environment and society.

LCA and environmental price assessment study showed significant environmental benefits from recycling fishing nets. Valorization scenario results:

- S1: replacement of new nylon with recycled fishing net waste resulted in an environmental benefit of -7–850 kg $CO_2$ eq. and an environmental cost of -2–947 Euro.
- S2: reinforcement in asphalt materials replacing glass fibre reinforcement resulted in an environmental benefit of -636 kg $CO_2$ eq. and an environmental cost of -407 Euro.
- S3: fishing net waste is converted into syngas resulted as a positive environmental impact of 156 kg $CO_2$ eq. and an environmental cost of 31 Euro.
- S4: fishing nets are landfilled resulted as the highest environmental impact of 12–100 kg $CO_2$ eq. and an environmental price of 29–609 Euro, making it the least sustainable option.

The results show the importance of avoiding landfill and instead prioritizing recycled fishing nets as replacements for new nylon (S1) and asphalt reinforcement (S2) to provide the greatest environmental benefit. Although synthesis gas production (S3)

has a greater impact than S1 and S2, it is still a desirable secondary waste management option.

## 4 Conclusions

Abandoned, lost or otherwise discarded fishing gear becomes a serious problem in marine and coastal areas as litter and continues to passively trap aquatic organisms, affecting the environment and biodiversity. The research proposes a methodology for determining the amount of fishing nets in Latvia. It considers the number of discarded nets that is considered as post-consumer amount, as well as data from fishing net manufacturers on the amount of waste that remains from production processes and is considered as manufacturing scrap or pre-consumer waste. Valorization scenarios for discarded nets and manufacturing scrap are also examined, where an environmental performance assessment is performed for scenarios where a higher value-added product, energy, or landfilling is obtained.

The fishing industry needs to create a unified system that would monitor the amount of manufacturing scraps, as well as the number of discarded nets. To have the opportunity to use this type of waste as a resource in a circular economy. This path towards sustainability aimed on reduction and elimination of ALDFG waste should be based on involvement from multiple stakeholders. Education and awareness-raising are crucial for both the public and the fishing industry to encourage responsible gear usage and foster a greater understanding of the environmental consequences of ALDFG on marine and coastal ecosystems. This shift should also promote the use of more resilient and biodegradable materials in the production of fishing gear to mitigate long-term environmental pollution. Furthermore, targeted initiatives must concentrate on enhancing gear recovery systems and encouraging recycling practices, thereby diminishing the amount of gear waste that is deposited in landfills. To bolster these efforts, clear and comprehensive policy guidelines must be established by policymakers to guarantee effective implementation and compliance across the sector.

TABLE 4  LCA characterization results.

| Impact category | Unit | S1 | S2 | S3 | S4 |
|---|---|---|---|---|---|
| Climate change | kg $CO_2$ eq | -7847.76 | -636.36 | 156.10 | 12080.46 |
| Ozone depletion | kg CFC-11 eq | 0.000003 | -0.000048 | 0.000003 | 0.000024 |
| Terrestrial acidification | kg $SO_2$ eq | -26.69 | -2.06 | 0.39 | 28.24 |
| Freshwater eutrophication | kg P eq | -0.39 | -0.02 | 0.02 | 1.18 |
| Marine eutrophication | kg N eq | -8.95 | -0.06 | 0.02 | 30.99 |
| Human toxicity | kg 1,4-DB eq | -65.14 | -38.04 | 6.37 | 5105.51 |
| Photochemical oxidant formation | kg NMVOC | -19.99 | -7.95 | 0.51 | 29.09 |
| Particulate matter formation | kg PM10 eq | -8.01 | -0.66 | 0.19 | 9.36 |
| Terrestrial ecotoxicity | kg 1,4-DB eq | -0.06 | -0.09 | 0.02 | 2.54 |
| Freshwater ecotoxicity | kg 1,4-DB eq | -6.97 | -1.70 | 2.09 | 1481.87 |
| Marine ecotoxicity | kg 1,4-DB eq | -3.92 | -1.84 | 1.85 | 1193.81 |
| Ionising radiation | kBq U235 eq | 43.03 | 32.07 | 42.59 | 128.51 |
| Agricultural land occupation | $m^2a$ | 60.03 | 56.39 | -443.56 | 1591.82 |
| Urban land occupation | $m^2a$ | -0.93 | -7.67 | -2.56 | 61.73 |
| Natural land transformation | $m^2$ | 0.02 | -0.48 | 0.01 | -2.61 |
| Water depletion | $m^3$ | -228.18 | 18.07 | -0.89 | 96.98 |
| Metal depletion | kg Fe eq | 1.10 | -29.30 | 5.45 | 64.55 |
| Fossil depletion | kg oil eq | -273.71 | -9.18 | 4.13 | 322.40 |

[1]Colour scale    Low impact    Medium impact    High impact

TABLE 5  Environmental damage costs for fishing net waste management scenarios based on 2025 monetary values.

| Impact category | S1 | S2 | S3 | S4 |
|---|---|---|---|---|
| Climate change | -1255.64 | -101.82 | 24.98 | 1932.87 |
| Ozone depletion | 0.00010 | -0.00166 | 0.00011 | 0.00082 |
| Ionising radiation | 0.22 | 0.17 | 0.22 | 0.67 |
| Oxidant formation, human health and terrestrial ecosystems | -65.37 | -26.01 | 1.65 | 95.14 |
| Particulate matter formation | -977.32 | -81.00 | 23.45 | 1142.00 |
| Acidification | -172.66 | -13.34 | 2.55 | 182.72 |
| Freshwater eutrophication | -1.78 | -0.09 | 0.08 | 5.44 |
| Marine eutrophication | -156.88 | -1.14 | 0.31 | 543.29 |
| Terrestrial ecotoxicity | -0.00005 | -0.00007 | 0.00001 | 0.00201 |
| Freshwater ecotoxicity | -0.18 | -0.04 | 0.05 | 38.08 |
| Marine ecotoxicity | -0.02 | -0.01 | 0.01 | 4.69 |
| Human toxicity, cancer-related and non-cancer-related | -324.85 | -189.72 | 31.78 | 25462.73 |
| Land use | 7.19 | 5.92 | -54.25 | 201.07 |
| Total | -2947 | -407 | 31 | 29609 |

The creation of data passports or waste passports would also be useful. Data passports provide detailed information about a product, its raw materials and energy consumed, helping consumers make decisions with sustainability in mind, waste passports ensure proper waste management, considering materials for possible resource recycling or regeneration.

Development of symbiotic centres that would create new opportunities to use waste as a valuable resource. Promote the use of fishing nets not only in the production of decorative products but also find new and innovative solutions to obtain innovative high-value products from fishing net waste, as this will help reduce the volume of fishing nets stored in landfills and will promote the collection of these discarded fishing nets from the waters.

## Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author/s.

## Author contributions

BZ: Writing – original draft, Methodology, Formal Analysis, Visualization, Data curation, Conceptualization, Investigation, Writing – review & editing. JP: Writing – original draft, Data curation, Conceptualization, Validation, Writing – review & editing. JG: Writing – original draft, Conceptualization, Validation, Writing – review & editing.

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## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## Generative AI statement

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## Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2025.1607436/full#supplementary-material

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