RIGA TECHNICAL UNIVERSITY
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ALGAE USE EVALUATION FOR BIOGAS PRODUCTION IN LATVIA

Summary of the Doctoral Thesis

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To be granted the scientific degree of Doctor of Science (Ph. D.), the present Doctoral Thesis has been submitted for the defense at the open meeting of RTU Promotion Council on September 3, 2020 at 2 p.m. at the Faculty of Electrical and Environmental Engineering of Riga Technical University, 12 k-1 Āzenes Street, Room 115.

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DECLARATION OF ACADEMIC INTEGRITY

I hereby declare that the Doctoral Thesis submitted for the review to Riga Technical University for the promotion to the scientific degree of Doctor of Science (Ph. D.) is my own. I confirm that this Doctoral Thesis had not been submitted to any other university for the promotion to a scientific degree.

……………………………. (signature)

Date: ………………………

The Doctoral Thesis has been written in English. It consists of an Introduction; 4 Chapters; Conclusions; 17 figures; 16 tables; 7 appendices; the total number of pages is 136. The Bibliography contains 191 titles.

TABLE OF CONTENTS

INTRODUCTION

Actuality

Even though there are many theories about the amount of available fossil fuels, they all have the same tendency – the amount is limited and will suffice for a limited period of time (50–100 years, depending on the resource and aspects taken into account) (Aurora Liquefied Natural Gas Ltd., 2013). In order to meet the growing demand for energy resources new, preferably renewable energy resources (RES) must be considered within the energy source mix. Renewable resources could meet the long-term demand and they are also carbon neutral. Carbon dioxide and other greenhouse gas (GHG) effect on climate change and global warming is a highly discussed topic worldwide. Even though there still are some debates among international leaders, European Union (EU) has already set targets to reduce greenhouse gasses, as well as increase the share of renewable resources in final consumption. EU goals for year 2020 (also known as '20-20-20') have set three main targets for climate change and energetic sectors:

- GHG emission amount reduced by 20 % (compared to the level of year 1990);
- share of renewable energy in final energy consumption comprises 20 %;
- increase of 20 % in energy efficiency (European Commission, 2019).

For the next planning period from 2021 until 2030, European Union has set higher targets for climate change and energetic sectors:

- GHG emissions reduced by at least 40 % (compared to the level of year 1990);
- share of renewable energy in final energy consumption reduced by at least 32 %;
- at least 32.5 % increase in energy efficiency (European Commission, 2019).

The EU member states also have the option to set their target to a higher value by developing national renewable energy action plans with specific plans and actions on how to achieve the targets. The Latvian National Energy and Climate Plan (NECP) 2021–2030 sets the increase of renewable energy resource share in final energy consumption by 45 % (compared to year 1990). The main courses of action in order to achieve the NECP targets are RES technology promotion, sustainable resource promotion, and the promotion of efficiency management for different sectors (Kauliņš, 2019).

The Sustainable Development Strategy of Latvia until 2030 and Latvian Bioeconomy Strategy 2030 identified the need for a more sustainable use of locally available nature resources. It includes several renewable resources that are already used, as well as support for research. These documents also mention the use and need for research on washed out marine algae as one of the least researched resources in Latvia (Latvijas Republikas Saeima, 2010; Latvijas Republikas Zemkopības Ministrija, 2017).

Every year on the shores of the Baltic Sea large amounts of washed out macroalgae are observed. The washed out and non-harvested algae can have a negative impact on tourism (due to unpleasant smell) as well as environment (eutrophication, coastal area habitat changes). Every year several thousand tons of algae are washed out and could be potentially used as renewable resources. EU Directive EC 2006/7 mandates the pick-up of washed-out algae in recreational areas during swimming season. Currently this problem is solved at a municipality level. Each municipality deals with this problem in a different way – collecting and discarding the washed-out algae as waste, collecting and discarding of algae in dune area by burying them or by not collecting and letting them undergo aerobic biodegradation process (Brūniņa, 2018; European Commission, 2006).

As macroalgae growth rates are higher than terrestrial plant growth rates and algae natural growing and cultivation does not require fertile arable land, they have a high potential for being used as energetic resource.

Current research in renewable energy production from algae is focused on finding the most suitable energetic product and its production method. Most of the research points out weak spots like high energy intensity production phases and high capital and investment costs of these technologies. On the other hand – applying existing and potentially cost-effective technology like biogas production reduces the production phases and lowers the investments (Wiley, Campbell, & McKuin, 2011).

Based on this information, biogas production from washed out algae could be a potential solution both to the algae as waste problem and increase of renewable energy sources in the final energy consumption. Current research is fragmented and while it is possible to evaluate the algae use projects from economic perspective or to evaluate the environmental impacts of such projects, there is a lack of evaluation methodology that would take into account both the economic and environmental aspects. As available algae species and characteristics differ in each region, there is also a lack of reliable energetic data for locally available species. Experimental determination of energetic data for new substrates is a crucial part of their overall use evaluations. An evaluation methodology that would take into account the energetic, environmental and economic aspects of new substrate would fill the research gap for evaluating such projects.

Based on the EU targets set for renewable energy and the action plans of Latvia to achieve those targets, the author of study sets the aim of the Doctoral Thesis to develop methodology for evaluating algae use for biogas production taking into account several aspects. The evaluation methodology includes energetic (evaluation of energetic potential), environmental (environmental impact assessment) and economic (life cycle cost analysis) aspects.

Research Aim and Tasks

The aim of the study is to develop and test a methodology for evaluating algae use for biogas production taking into account three aspects – energetic, environmental, and economic. Testing of the developed methodology is based on a case study of locally available algae species in Latvia. In order to achieve the goal, several tasks are set.

1. Research the processes of algae collection, pre-treatment, anaerobic digestion and biogas production and use.
2. Develop a methodology for algae use for biogas production evaluation and develop scenarios for the case study of Latvia.

2.1. Develop the design of experiment for methane potential determination in a laboratory setting and perform the experiments with locally available algae species.
2.2. Perform life cycle assessment and evaluate the environmental impact of developed scenarios.
2.3. Perform life cycle cost analysis and evaluate the total costs of the developed scenarios.
2.4. Perform multi-criteria analysis.
3. Evaluate and compare the developed scenarios and evaluate the developed methodology itself.

Research Methodology

The basis of the Doctoral Thesis is the development and testing of a methodology for evaluating algae use for biogas production. In order to develop the methodology and test the case study scenarios, theoretical research methods, analytical research methods and practical research methods were used (Fig. 1).

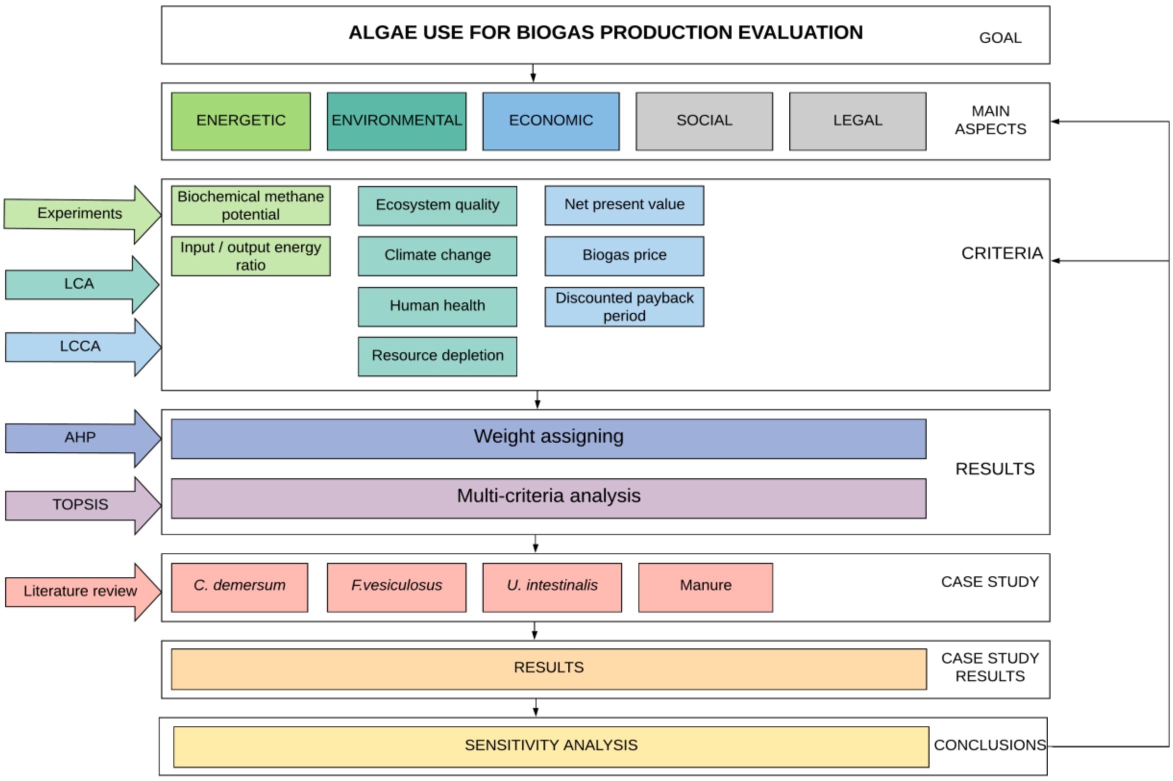

Fig. 1. Main methods used within the developed methodology.

Design of experiment is used to set-up experimental plan and statistical methods, like analysis of variance (ANOVA) is used to analyze the results. Anaerobic digestion batch scale experiments are based on Moller method. Other experimental research methods are applied. Life cycle assessment modeling in program *SimaPro* is used to determine the environmental impact in 4 damage categories – ecosystem quality, climate change, human health, and resource depletion. For economic criteria, the basis of life cycle assessment is used within life cycle cost analysis to calculate the economic criteria – net present value, biogas price, and discounted payback period. The analytic hierarchy process methodology is used to assign weights to each criterion. Multi-criteria analysis with *TOPSIS* methodology is used for calculation of evaluation results. Sensitivity analysis is used to test the methodology robustness.

Scientific Significance

The Doctoral Thesis has a high scientific significance as a novel methodology for evaluating algae use for biogas production has been developed. The methodology combines the experimental energetic value determination of algae with the evaluation of environmental impact (LCA) and cost-effectiveness (LCCA) of biogas plant operation. The combination of experimental research with biogas plant life cycle modeling is a novel approach in evaluation of algae as a new substrate for biogas production. The methodology combines 9 criteria across three aspects (energetic, environmental, and economic) taking into account weights assigned by decision-makers.

The developed methodology can be used in the Baltic Sea region countries and internationally as well to evaluate the potential of different local algae species use for biogas production.

The use of experimental energetic value determination within the methodology fills in the missing data of energetic values for algae species not studied for biogas production before.

The developed methodology is approbated in a case study of 3 locally available algae species in Latvia.

Practical Significance

The development of new renewable resources is of high importance in order to achieve the goals of the European Union as well as its member states like Latvia for year 2030 in climate change and energy sectors. Renewable energy resource use can help cover the increasing energy demand or completely replace fossil fuel use. As most renewable resources are used locally, the increase of renewable resource use also increases energetic independence of countries and regions. The developed methodology and the results from it can be used at municipal, national or regional level policy planning as it gives insight into algae use for energy production in aspects like energy efficiency, environment and economics. As the methodology combines several important aspects, it can save time and resources for a large-scale evaluation of possible scenarios. The methodology is flexible and allows the stakeholders to put emphasis on specific criteria or aspects of the overall evaluation based on their goals and needs. The use of this methodology for project evaluation also gives detailed insight in into the projects, allowing to determine the weak spots or areas that need improvement at the municipal or governmental level.

The outcomes of evaluations give more information on the subject not only for the contractor but also for neighboring municipalities, countries and regions.

The methodology can be supplemented and approbated for use with different substrates to evaluate their potential as biogas production feedstock.

Approbation of the Research

Publications on the topic of the Doctoral Thesis

1. Pastare, L., Romagnoli, F. Life Cycle Cost Analysis of Biogas Production from Cerathophyllum demersum, Fucus vesiculosus and Ulva intestinalis in Latvian Conditions. "Environmental and Climate Technologies", 2019, Vol. 23, No. 2, pp. 257–270. Available: doi: 10.2478/rtuect-2019-0067.
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3. Romagnoli, F., Pastare, L., Sabūnas, A., Bāliņa, K. Effects of pre-treatment on Biochemical Methane Potential (BMP) testing using Baltic Sea Fucus vesiculosus feedstock. "Biomass and Bioenergy", 2017, Vol. 105, pp. 23–31. Available: doi: 10.1016/j.biombioe.2017.06.013.
4. Pastare, L., Aleksandrovs, I., Lauka, D., Romagnoli, F. Mechanical pre-treatment on biological methane potential from marine macro algae: results from batch tests of Fucus vecisulosus. "Energy Procedia", 2016, Vol. 95, pp. 351–357. Available: doi: 10.1016/j.egypro.2016.09.021.
5. Pastare, L., Romagnoli, F., Ruģele,K., Dzene, I., Blumberga, D. Biochemical methane potential from anaerobic digestion of the macrphyte Cerathophyllum demersum: a batch test study for Latvian conditions. "Energy Procedia", 2015, Vol. 72, pp. 310–316. Available: doi: 10.1016/j.egypro.2015.06.045.
6. Pastare, L., Romagnoli, F., Lauka, D., Dzene, I., Kuznecova, T. Sustainable Use of Macro-Alagae for biogas Production in Latvian Conditions: a Preliminary Study through an Integrated MCA and LCA Approach. "Environmental and Climate Technologies", 2014, Vol. 13, pp. 44–56. Available: doi: 10.2478/rtuect-2014-0006.
7. Pastare, L., Romagnoli, F., Baltrenaite, E. The methodology of evaluating different macroalgae biogas production scenarios with multi-criteria analysis. "Proceedings of the 17th Conference for Junior Researchers "Science – Future of Lithuania"", 2014, No.5, pp. 1–8. eISBN: 978-609-457-538-9

Other publications

1. Sabunas, A., Romagnoli, F., Pastare, L., Balina, K. Laboratory Algae Cultivation and BMP Tests with Ulva intestinalis from the Gulf of Riga. "Energy Procedia", 2017. Vol. 113, pp. 277–284. Available: doi: 10.1016/j.egypro.2017.04.066.

2. Balina, K., Romagnoli, F., Pastare, L., Blumberga, D. Use of macroalgae for bioenergy production in Latvia: review on potential availability of marine coastline species. “Energy Procedia”, 2017, Vol. 113, pp. 403–410. Available: doi: 10.1016/j.egypro.2017.04.022.
3. Lauka, D., Pastare, L., Blumberga, D., Romagnoli, F. Preliminary analysis of anaerobic digestion process using Cerathophyllum demersum and low carbon content additives: a bacth test study. “Energy Procedia”, 2015, Vol. 72, pp. 142–147. Available: doi: 10.1016/j.egypro.2015.06.020.
4. Pastare, L., Ozoliņa, L., Blumberga, D. Production of Foliage Extracts. In: International Scientific Conference “Environmental and Climate Technologies”: Abstract Book, Latvia, Riga, 14–16 October 2013. Riga: RTU Press, 2013, pp. 30–31. ISBN 978-9934-8302-9-7
5. Pastare, L., Žandeckis, A. Mitruma noteikšana dūmgāzēs (Moisture content evaluation in fluegases). 53rd RTU Student scientific and technical conference proceedings, 2012, pp. 83–84.

Reports at international scientific conferences

1. Pastare, L., Romagnoli, F. Life Cycle Cost Analysis of Biogas Production from Cerathophyllum demersum, Fucus vesiculosus and Ulva intestinalis in Latvian Conditions. International Scientific Conference “Environmental and Climate Technologies”, CONECT 2019, 15–17 May 2019, Riga, Latvia.
2. Pastare, L., Romagnoli, F., Blumberga, D. Comparison of biomethane potential lab tests for Latvian locally available algae. International Scientific Conference “Environmental and Climate Technologies”, CONECT 2018, 16–18 May 2018, Riga, Latvia.
3. Sabunas, A., Romagnoli, F., Pastare, L., Balina, K. Laboratory Algae Cultivation and BMP Tests with Ulva intestinalis from the Gulf of Riga. International Scientific Conference “Environmental and Climate Technologies”, CONECT 2016, 12–14 October 2016, Riga, Latvia.
4. Pastare, L., Aleksandrovs, I., Lauka, D., Romagnoli, F. Mechanical pre-treatment on biological methane potential from marine macro algae: results from batch tests of Fucus vecisulosus. International Scientific Conference “Environmental and Climate Technologies”, CONECT 2015, 14–16 October 2015, Riga, Latvia.
5. Balina, K., Romagnoli, F., Pastare, L., Blumberga, D. Use of macroalgae for bioenergy production in Latvia: review on potential availability of marine coastline species. International Scientific Conference “Environmental and Climate Technologies”, CONECT 2016, 12–14 October 2016, Riga, Latvia.
6. Pastare, L., Romagnoli, F., Ruģele, K., Dzene, I., Blumberga, D. Biochemical methane potential from anaerobic digestion of the macrphyte Cerathophyllum demersum: a batch test study for Latvian conditions. International Scientific Conference “Environmental and Climate Technologies”, CONECT 2014, 14–16 October 2014, Riga, Latvia

7. Pastare, L., Romagnoli, F., Lauka, D., Dzene, I., Kuznecova, T. Sustainable Use of Macro-Alagae for biogas Production in Latvian Conditions: a Preliminary Study through an Integrated MCA and LCA Approach. International Scientific Conference "Environmental and Climate Technologies", CONECT 2014, 14–16 October 2014, Riga, Latvia
8. Lauka, D., Pastare, L., Blumberga, D., Romagnoli, F. Preliminary analysis of anaerobic digestion process using Cerathophyllum demersum and low carbon content additives: a batch test study. International Scientific Conference "Environmental and Climate Technologies", CONECT 2014, 14–16 October 2014, Riga, Latvia.
9. Pastare, L., Romagnoli, F., Baltrenaite, E. The methodology of evaluating different macroalgae biogas production scenarios with multi-criteria analysis. Proceedings of the 17th Conference for Junior Researchers "Science – Future of Lithuania": 17th Conference for Junior Researchers "Science – Future of Lithuania" = Aplinkos apsaugos inžinerija. 17-osios Lietuvos jaunųjų mokslininkų konferencijos "Mokslas – Lietuvos ateitis" straipsnių rinkinys, 10 April 2014. Vilnius, Lithuania.
10. Pastare, L., Ozoliņa, L., Blumberga, D. Production of Foliage Extracts. In: International Scientific Conference "Environmental and Climate Tehnologies", 14–16 October 2013, Riga, Latvia
11. Pastare, L., Žandeckis, A. Mitruma noteikšana dūmgāzēs (Moisture content evaluation in fluegases). In 53rd RTU Student scientific and technical conference, 10–12 May 2012, Riga, Latvia.

Monographies

1. Bažbauers, G., Blumberga, D., Njakou-Djomo, S., Dzene, I., Gušča, J., Kazulis, V., Kļaviņa, K., Kuzņecova, T., Ķeirāne, E., Lauka, D., Muižniece, I., Pastare, L., Piļicka, I., Pubule, J., Rēpele, M., Romagnoli, F. Ecodesign Solutions for Climate Technologies. Riga, RTU Press, 2019. 156 p. ISBN 978-9934-22-104-0.

Structure and Outline of the Research

The basis of the Doctoral Thesis is 7 thematically unified scientific publications that have been published in different scientific journals available in scientific information storages and international scientific databases. The aim of these publications is to transfer and approbate the developed methodology for algae evaluation for use in biogas production.

The Doctoral Thesis contains Introduction, 4 chapters, Conclusions, Bibliography, 7 appendices, 17 figures, 16 tables, it comprises 136 pages. Bibliography contains 65 titles but as the Thesis is a thematically unified 7 publications, the total number of used references is 191. The literature analysis chapter is not included in this summary.

1. DEVELOPENT OF EVALUATION METHODOLOGY

It is possible to evaluate the algae use opportunities from economical perspective or to evaluate the environmental impacts of such projects, but there is a lack of evaluation methodology that would consider several aspects of such projects at once. Thus, emerges a need for an evaluation methodology for new substrates that would evaluate the main aspects of biogas production. Development of such methodology would decrease the time and resources needed.

As algae is a relatively new and unused substrate for biogas production, there is limited information about the energetic values of different species. Even when the energetic value is determined in one region, it might not be the same in another region if the salinity level of water is different, if the weather conditions or available nutrients are different. For this reason, an analysis of locally available species should be carried out. As the energetic value is a crucial aspect of any substrate used in biogas production, its determination is the first step in the evaluation process. The energetic value can be expressed as specific biogas yield, but as the amount of methane in biogas can vary, pure methane content gives more precise information about the energetic content. Biochemical methane potential (BMP) is the amount of methane that is produced from 1 kg of volatile solids of substrate. See Chapter 1.1 for more details.

For many new renewable energy projects, input–output energy ratio (ER) is a crucial point and should be taken into account to make sure that more energy is produced than consumed. See Chapter 1.1 for more details.

New renewable energy projects are often evaluated based on environmental aspects. In order to consider the impacts on environment during the whole production phase, life cycle analysis (LCA) is carried out. LCA considers all processes from the production phase and gives the result in several damage criteria categories. The calculation method IMPACT2002+ allocates environmental impacts in 4 end-point (damage) categories – ecosystem quality, climate change, human health, and resource depletion. See Chapter 1.2 for more details.

There are several methods how to evaluate the cost-effectiveness of a project, but life cycle cost analysis (LCCA) allows for a detailed and precise evaluation of all production stages of a project. Cash flow of the whole project timeline is modeled. With outcomes from the LCCA, net present value (NPV) and discounted payback period (DPB) can be calculated. Biogas price (BP) is a criterion that shows the costs of biogas production per unit of biogas. These 3 criteria give a wide enough scope on the project to determine its feasibility and to be able to compare it with the selected scenarios and with other already existing projects. See Chapter 1.3 for more details.

Social and legal aspects are not included in this study for several reasons. There is no available method to quantify the legal restrictions and prohibitions. The legal aspects should be analyzed separately and should include both the biogas plant operations and the collection of washed out marine algae or freshwater algae from natural waterbodies. The social aspects are not included as the locations of the biomass collection and the biogas plant were not selected during this evaluation methodology. If the results of the evaluation are satisfactory and there is a potential for algae use and biogas plant successful operation, the social aspects should be considered and evaluated in the next stage of project development.

As some of the aspects taken into account can be more important than others, weights are assigned to each of the criteria with analytical hierarchy process (AHP) methodology. See Chapter 1.4. for more details.

With the selected 9 criteria from three main aspects, the multi-criteria analysis is applied. The multi-criteria analysis is chosen as a base for its simplicity, the possibility to apply criteria weights, the multi-dimensionality and transparency of it. Multi-criteria methods allow addressing real world problems through integrated, flexible, and realistic methodological approaches. They have been developed to support the decision makers in their decision-making process which more or less is unique every time. When there are alternatives to assess, the multi-criteria analysis (MCA) provides basis and techniques for finding the best solution. It must be taken into account that the best solutions mean the most appropriate from the analyzed solutions, it may in fact not be even close to the best possible solution if it is not suggested as an alternative. See Chapter 1.5. for more details.

Based on the assigned weights and criteria values, the chosen scenarios can be compared with each other with TOPSIS (technique for order preference by similarity to ideal solution). See Fig. 1.1 for the full developed methodology scheme.

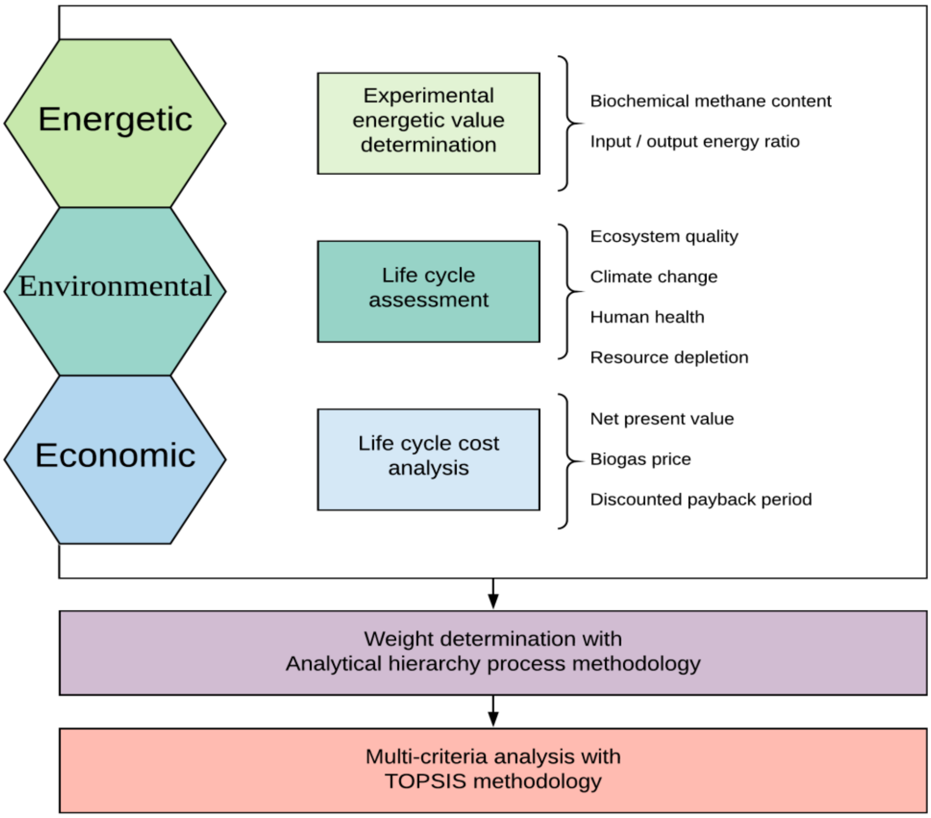

Fig. 1.1. Overall methodology development scheme.

The in-depth methodology of each method used for criteria value determination is described further.

1.1. Energetic Criteria

In order to determine the biomethane potential (BMP) of selected algae species, series of experiments must be conducted. The experiments should examine not only the BMP values of feedstock but also their characteristics, the most suitable pre-treatment methods, most favorable feedstock to inoculum ratio, and the need for additives.

The series of experiments were carried out in stages – experimental planning, biomass parameter determination, biogas experiments, and data analysis. Biomass parameters like moisture content, volatile solids (VS), and total solids (TS) are determined prior to each biogas experiment for both the feedstock and inoculum. Experiment planning was carried out using the design of experiment methodology (Eriksson, Johansson, Wold, Wikstrom, & Wold, 2001).

Total solid, volatile solid and fixed solid content was determined by method 1684 developed by the United States Environmental Protection Agency 1684 “Total, Fixed and Volatile Solids in Water, Solids, and Biosolids” (US Environmental Protection Agency, 2001).

The biogas yield tests were carried out in small-scale batches recreating the conditions of a mesophilic (37 °C or 98.6 °F) biogas production. The experiments were carried out using Moller method, measurements were made with syringe and the adsorption of CO_2 to determine methane content was used (Hansen et al., 2004; Møller, Sommer, & Ahring, 2004; Pham, Triolo, Cu, Pedersen, & Sommer, 2013; VDI, 2006) The batches contain water, inoculum (wastewater treatment plant sludge), biomass, and buffer and are flushed with either CO_2 or N_2 gas. The measurements were taken using a syringe with a movable plunger, filled with 3M NaOH solution (to dissolve the CO_2 from biogas). See Fig 1.1 for the schematic representation of the BMP measurements.

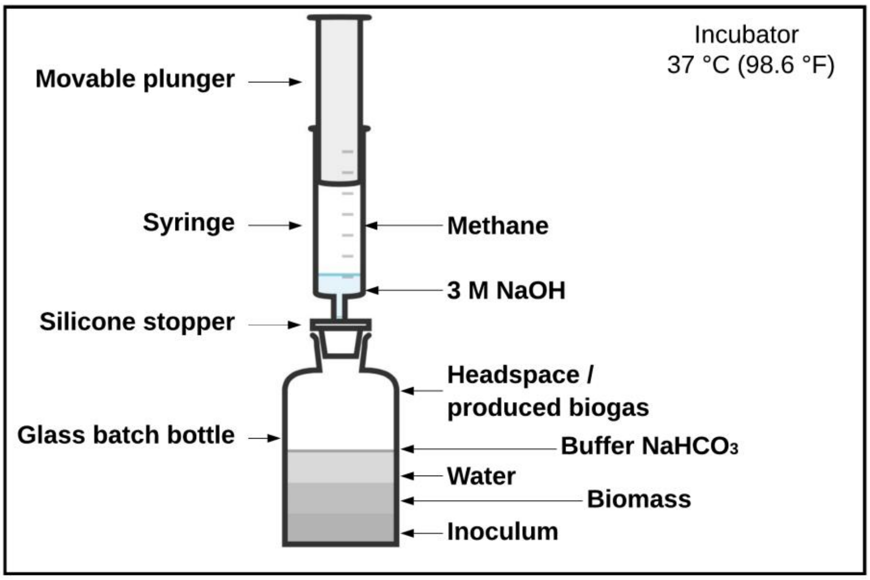

Fig. 1.1. Scheme of biogas batch test and measurement of BMP.

The BMP value calculations after the measurements are shown in Eq. (1.1).

$$B_{\text{SAMPLE}} = \frac{B_{\text{TOAL}} - B_{\text{INOCULUM}}}{1000VS_{\text{SAMPLE}}}, \tag{1.1}$$

where

B_{SAMPLE} – biochemical methane potential of sample, L CH_4 / kg_{VS};

B_{TOTAL} – measured total methane amount of batch, mL CH_4;

B_{INOCULUM} – measured inoculum methane amount of blank batch, mL CH_4;

VS_{SAMPLE} – volatile solid content of measured sample in batch, kg.

The results of experiments were afterwards analyzed using ANOVA statistical testing (Smalheiser, 2017). More details about experiments can be found in these publications – Pastare, Aleksandrovs, Lauka, & Romagnoli (2016); Pastare, Romagnoli, & Blumberga (2018); Pastare, Romagnoli, Rugele, Dzene, & Blumberga (2015); Romagnoli, Pastare, Sabūnas, Bāliņa, & Blumberga (2017).

Based on the BMP experiment results life cycle of scenarios can be modeled for both the environmental criteria determination and economic criteria determination. Based on these models the input/output energy ratio (ER) can be calculated, taking into account the energetic need for all phases of operation (Eq. (1.2)).

$$ER = \frac{E_{\text{STORAGE}} + E_{\text{PRE-TREATMENT}} + E_{\text{DIGESTION}} + E_{\text{CLEANING}} + E_{\text{CHP}}}{E_{\text{PRODUCED}}}, \tag{1.2}$$

where

E_{STORAGE} – total electrical and heat energy used for storage, MWh per year;

$E_{\text{PRE-TREATMENT}}$ – total electrical and heat energy used for pre-treatment, MWh per year;

$E_{\text{DIGESTION}}$ – total electrical and heat energy used for digestion, MWh per year;

E_{CLEANING} – total electrical and heat energy used for biogas cleaning, MWh per year;

E_{CHP} – total electrical and heat energy used for operating CHP unit, MWh per year;

E_{PRODUCED} – total electrical and heat energy produced, MWh per year.

The fuel needs for transportation are not included in the ER calculation.

1.2. Environmental Criteria

Life cycle assessment is an environmental management tool that helps to understand and quantify the complicated relationships of environmental impacts of all production stages of a product. In order to quantify the environmental impacts of the study, the *SimaPro* 8 program has been used.

Within the program the chosen calculation method is *IMPACT 2002+*. This method combines 14 mid-points and 4 damage categories. The damage categories and their units are:

- Ecosystem quality (EQ) expressed in potentially disappeared fractions of species per m^2 per year (PDF/m^2 per year). The score of 0.2 PDF/m^2 per year implies the loss of 20 % of species of 1 m^2 of earth surface during one year.
- Climate change (CC) in kg of CO_2 equivalents.

- Human health (HH) expressed in disability-adjusted life years (DALY) characterizes the disease severity taking into account both the years of life lost and the years of life with lowered quality of life. The score of 3 DALYs implies the loss of three life years over the overall population (not per person).
- Resource depletion (RD) in MJ measures the energy needed for extracting resources (Althaus et al., 2007; Goedkoop, Oele, de Schryver, & Vieira, 2008).

See Fig. 1.2 for overall scheme of LCA methodology *IMPACT 2002+* framework.

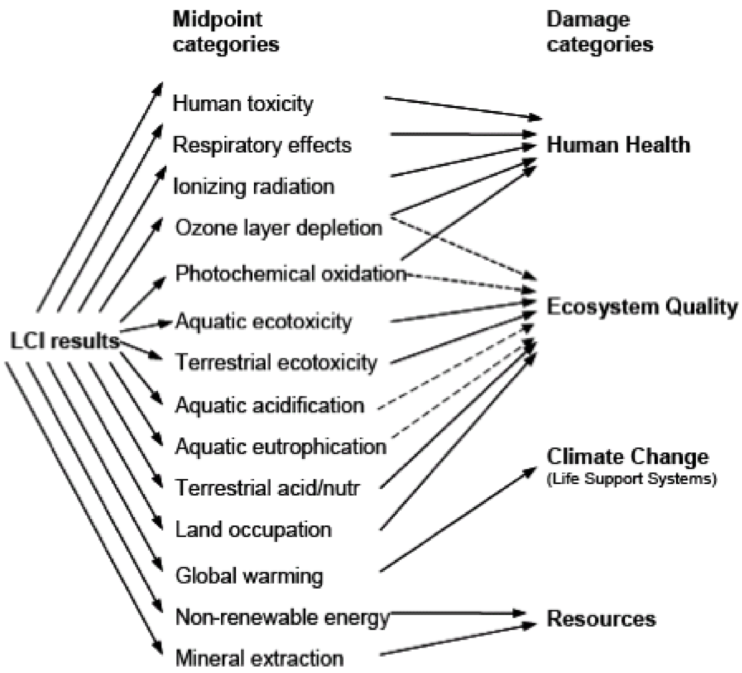

Fig. 1.2. Overall scheme of LCA methodology *IMPACT 2002+* framework (Goedkoop et al., 2008).

The main boundaries and assumptions for scenarios are set in Chapter 2, as well as in papers Pastare & Romagnoli, 2019; Pastare, Romagnoli, Lauka, Dzene, & Kuznecova, 2014. The functional unit is operation of biogas plant and the CHP unit for 1 year producing 2190 MWh of electricity and 3942 MWh of heat. The total amount of algae needed for each scenario will be different as the characteristics of algae are different (BMP, VS, TS values).

1.3. Economic Criteria

The proposed concept of a life cycle cost analysis is widely used to analyze and evaluate various kinds of project alternatives on their profitability over the whole life span. The purpose of the life cycle cost analysis (LCCA) methodology is to provide basis of economic study to evaluate discounted cash flows of a project proposed over its life span.

The basic metric of LCCA is net present value (NPV) or in other words the difference between the present value of cash inflows and present value of cash outflows (including initial cost).

Another metric used for comparing and evaluating the different biogas production scenarios is the produced biogas price (BP). The biogas price is calculated considering the costs and the revenues from other products, averaged for the full life cycle of 20 years. As the biogas price is calculated, the costs of CHP unit and its operation are not taken into account.

An additional supplementary measure is discounted payback (DPB). DPB measures the time necessary to recover initial investment costs using discounted cash flows. The measure can be used to accept or reject a certain project.

The main relevant costs are design & licensing, capital investment, and O&M. See Fig. 1.3 for main operational and maintenance costs for algae scenarios.

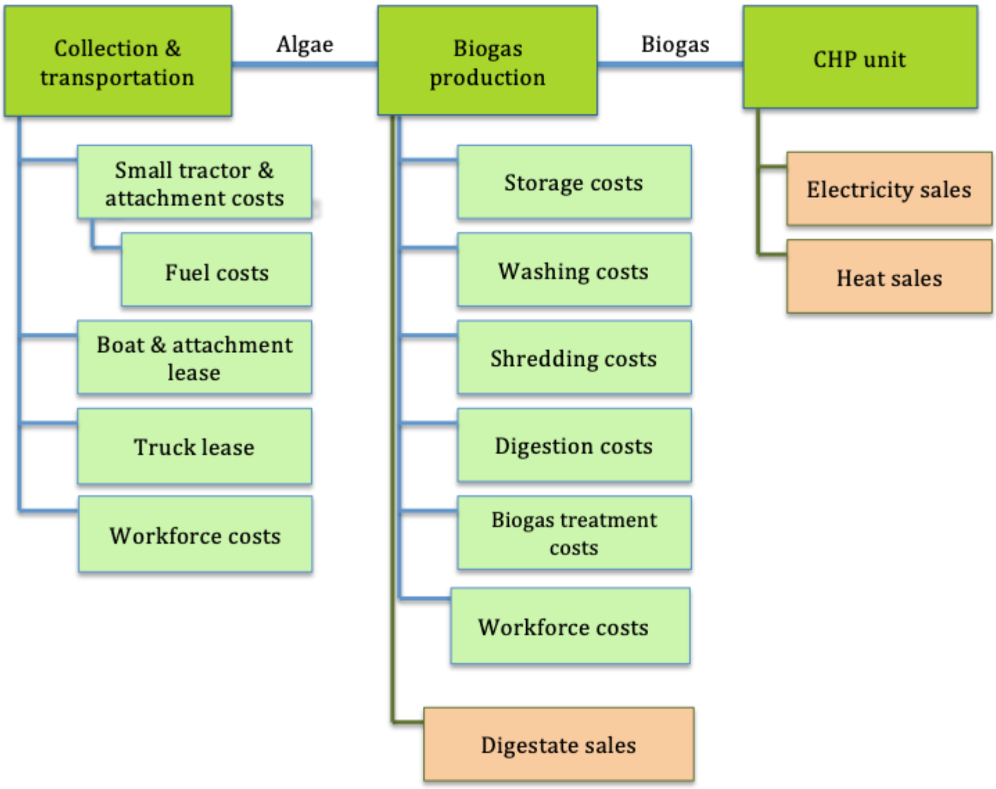

Fig. 1.3. Main operational and maintenance costs for algae scenarios.

The revenues come from selling the excess electricity, heat and, digestate. For the first 10 years of the project, electricity is sold at a feed-in tariff. The main boundaries and assumptions for scenarios are set in Chapter 3, as well as in publication Pastare & Romagnoli (2019).

1.4. Criteria Weight Determination

The criteria weights are an important part of the overall MCA, as each selected criterion presents a different level of importance for each decision-maker. The analytic hierarchy process (AHP) is a decision-making process that has been developed in the 1970s by mathematician Thomas L. Saaty. AHP is a participatory and multi-criteria decision-making approach in which the relative importance of a factor or indicator is derived from pairwise comparisons data. The AHP allows making relative independent judgments to be used in a more formalized way (Triantaphyllou & Mann, 1995).

A pair-wise comparison of criteria is carried out in a table – an orthogonal array. Each pair is then rated based on a preference scale of 1 to 9, where 1 is equal importance and 9 is absolute preference over the other criteria. After the ranking and comparison of the criteria, the weightings are then normalized and averaged in order to obtain an average weight for each criterion (Munier, 2004; Saaty, 1990).

1.5. Multi-Criteria Analysis

TOPSIS (technique of order preference similarity to the ideal solution) is an MCA methodology developed by Hwang and Yoon (1981). TOPSIS defines the relative closeness to positive-ideal solution and the remoteness from the negative-ideal solution. From these distances best alternative is chosen based on the maximum similarity to the positive-ideal solution.

TOPSIS method is based on five computation steps. The first step is to gather information of the alternatives on the chosen criteria. These data should be normalized in the second step. Next steps are to weight the normalized values and calculate the distances to positive- and negative-ideal values. Finally the closeness is given as the relation of these distances (Ishizaka & Nemery, 2013; Kahraman, Yasin Ateş, Çevik, Gülbay, & Ayça Erdoğan, 2007; Lu, Zhang, Ruan, & Wu, 2007).

The closeness coefficient is always in a range of 0 … 1, where 1 is the preferred action. If the action is closer to 1, it is closer to the ideal solution than the anti-ideal solution, and the other way round (Ishizaka & Nemery, 2013).

2. CASE STUDY

Many Baltic See rim countries face the problem of eutrophication in the coastline. The seaweeds are washed out seasonally and the affected countries must find ways to remove it as it can have an adverse effect on the coastline ecosystem (Brūniņa, 2018). After collecting and transporting the seaweeds away from the coast, there are several options on how to dispose of the biomass – in Latvia in some cases it is composted, but mostly it is disposed in landfills. In locations where the amounts are small, the washed-out algae are either buried or left as is.

Eutrophication in freshwater bodies is also a large problem in areas with developed agriculture. The excess biomass (algae and macrophytes) does not wash out the shore and may need to be removed manually to maintain the ecosystem in the water body.

As eutrophication is an ongoing problem in many countries and does not have a quick solution, the excess of marine and freshwater biomass should be not only disposed of, but also used to its advantage. Based on literature analysis, biogas production from washed out or collected algae could be a potentially beneficial option. In order to evaluate the opportunity of excess algae use for biogas production, a methodology and scenarios to test the methodology have been developed. The chosen scenarios and methodology development are described in further subchapters.

The scenarios have been developed based on the situation in Latvia for both the marine water washed out algae and freshwater algae. The scenarios are developed based on the technologies available and currently used regionally, as well as on assumptions. Based on the study by Balina et al. on the marine coastline, algae species *Fucus vesiculosus* and *Ulva intestinalis* were chosen as most suitable species to be evaluated further (Balina, Romagnoli, Pastare, & Blumberga, 2017). As freshwater bodies also tend to have a problem with overgrown algae, one scenario is chosen with a freshwater species. Based on literature analysis the chosen macrophyte is *Cerathophyllum demersum*. The 3 selected species will be the basis for further analysis and evaluations. A base scenario of manure use for biogas production is also analyzed and evaluated. It will be used as a benchmarking scenario to evaluate how algae perform as feedstock against a more traditional and widely used feed.

The boundaries of evaluation start with collection of algae and end with the production/selling of produced heat and electricity. The construction and teardown phases are not taken into account.

In all three scenarios algae are supposed to be naturally grown and are collected either directly from water bodies (in case of freshwater species) or from the shores of the Baltic Sea or the Gulf of Riga. The collection of algae is carried out after the bloom period (usually starting in July, until November). Marine algae are supposed to be collected with specialized small tractors with comb type attachments for algae collection from the ground or shallow waters (max 1.2 m from the shore). A boat and a trawler attachment are used for collecting biomass from freshwater bodies. In the baseline scenario, the collection of manure is not taken into account as this action is performed regardless of the existence of biogas plant. In all scenarios the average distance from algae collection to biogas production site is assumed to be

100 km. A diesel-powered truck with a capacity of 10–20 tones is leased for transporting algae. For all transportation it is assumed that the load factor is 50 %. It is assumed that a cattle farm is less than 1 km away from the biogas plant. A pipeline system is used for manure transportation, thus diminishing the need for motorized transportation vehicles.

After transportation to the site, algae are stored in a storage unit with a maintained temperature of 4 °C (39 °F) before being treated and used for biogas production. The feedstock and digestate are stored in two separate units. Only the feedstock storage unit is cooled. The manure is stored in concrete storage units without cooling. Pre-treatment includes washing of excess salt and sand for marine algae species. Washing is carried out in water tanks with sieves using freshwater as cleaning medium. Shredding is carried out for all algae species as part of pre-treatment. There is no pre-treatment for manure.

Algae are co-digested with cattle farm manure (ratio 1 : 5 based on volatile solids) to improve the overall feasibility and digestion rate. The temperature in the digestion reactor is 37 °C (98.6 °F). The electricity and heat need for biogas digestion is included in the parasitic energy use (7 % for electricity and 30 % for heat of total produced amount). It is assumed that 1 % of total produced biogas escapes as emissions during biogas production phase. After digestion process there is leftover digestate that can be used as liquid fertilizer. Digestate contains 1.8 % of nutrient nitrogen (as N_2), 1.0 % of nutrient phosphate (as P_2O_5) and 0.9 % of nutrient potassium (as K_2O) in digestate compared to input.

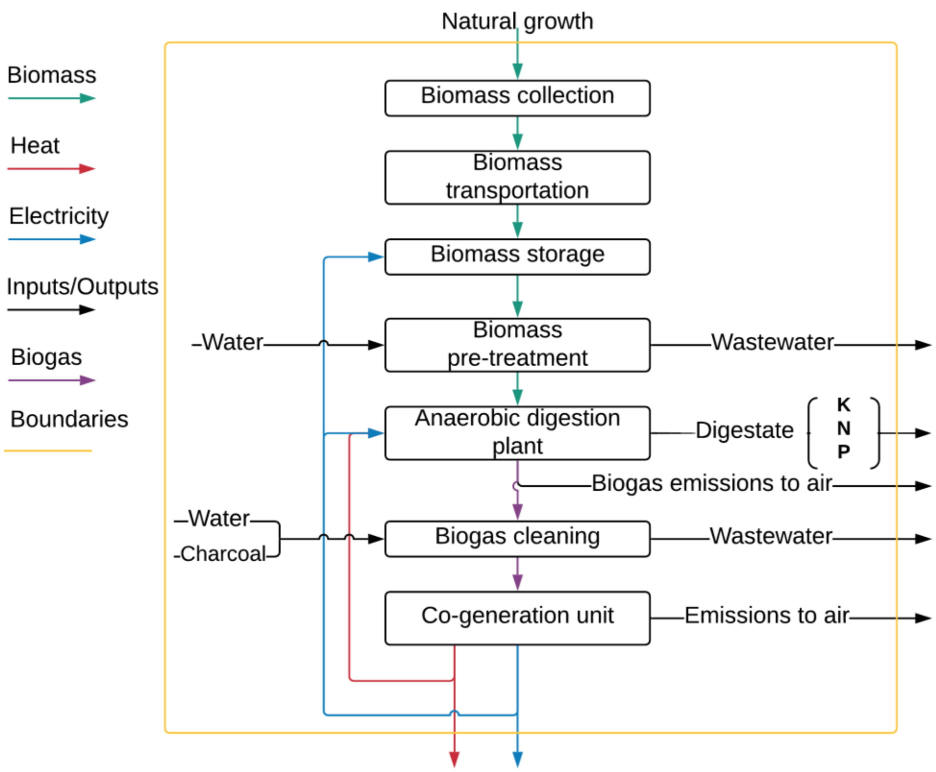

Fig. 2.1. Overall scheme of algae use scenarios for biogas production.

After biogas production it goes through a cleaning process to remove excess moisture, sulfur compounds, and other impurities. Wet scrubbing adsorption method with activated carbon is used. After the cleaning, biogas can be used in a combined heat and power (CHP) unit with heat to electricity production ratio 1.8 : 1 (64 % of produced energy is heat, 36 % is electricity).

As the chosen biomass is growing naturally and is collected directly from nature, there is a limit in the amounts available for collection each year. As the marine algae are washed out, the available amount is calculated based on the average load-size per meter of coastline (25 kg/m) and the length of available coastline (Holden et al., 2018). It is assumed that freshwater macrophytes are also available in the same amount. It is assumed that biomass is homogenous throughout the year. More details about the inputs and assumptions of the scenarios can be found in publications – Pastare & Romagnoli (2019); Pastare, Romagnoli, & Baltrenaite (2014); Pastare, Romagnoli, Lauka et al. (2014).

3. RESULTS AND ANALYSIS

3.1. Energetic Criteria

Several rounds of experiments have been carried out in order to find the best combination of factors for the tested species. The tested factors were biomass to inoculum ratio (variations 1 : 3, 1 : 5, 1 : 10) and different pre-treatment options (washing, cutting, pesteling, microwaving or a combination). The results of these experiments can be found in detail in publications - Pastare et al., 2016, 2015; Pastare & Romagnoli, 2019; Romagnoli et al., 2017.

The experiments on inoculum ratio change showed, that in the samples of *C. demersum* higher ratios of inoculum produced more biogas. With significance level of $\alpha = 0.05$, the BMP value increase of +20 L CH_4 / kg_{VS} from ratio 1 : 3 to 1 : 5 is statistically significant ($p = 0.0455$), but the BMP increase from ratio change from 1 : 5 to 1 : 10 is not statistically significant ($p = 0.056$). The results from experiments with *F. vesiculosus* showed similar results – BMP value increase of +45 L CH_4 / kg_{VS} from ratio 1 : 3 to 1 : 5 with $p = 0.049$. Looking at the speed of biogas production, the samples with 1 : 3 and 1 : 5 ratio produced at least 50 % of total yield in the first 5 to 7 days, while samples with ratio 1 : 10 produced 50 % of total yield in 7 to 12 days. Based on the results, the algae : inoculum ratio used further in experiments and calculations is 1 : 5.

The effects of microwaving as a pre-treatment option showed increase in a range of 7.8–43.7 % for 1.5-minute application and increase in a range of 37.2–45.2 % for 3-minute application for *F. vesiculosus* samples. The 1.5-minute application influence was not statistically significant ($p = 0.702$ with $\alpha = 0.05$), while 3-minute application was statistically significant ($p = 0.011$ with $\alpha = 0.05$).

The influence of washing and mechanical pre-treatment (cutting) is different for selected algae species. See Fig. 3.1 for BMP values of scenarios with influences from pre-treatments.

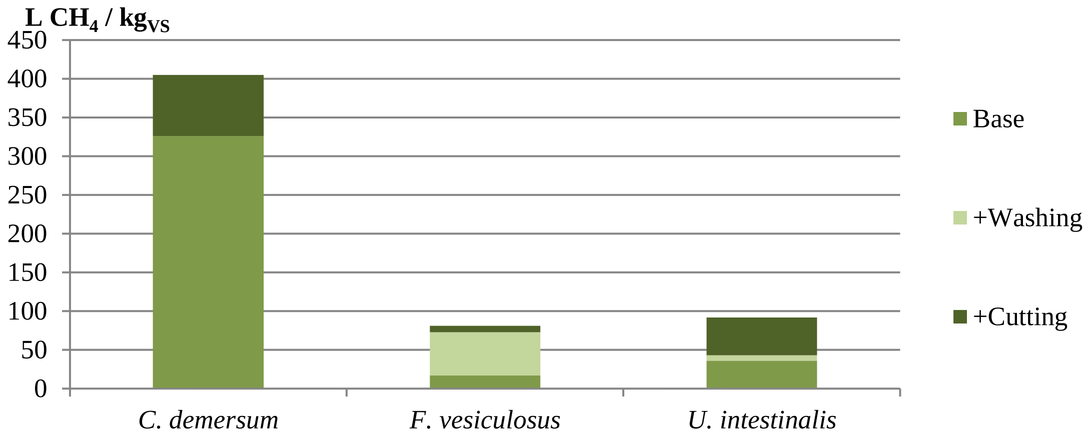

Fig. 3.1. BMP values of scenarios with influence from pre-treatment.

Factorial analysis of averaged experimental data was performed to determine how each of the factors (cutting and washing) influences the results. For freshwater *C. demersum* there is no impact from washing but cutting increases the BMP by +79 L CH_4 / kg_{VS} ($T_{test} = 0.292$,

$p = 0.387$), there is no interaction between factors. For marine *F. vesiculosus* washing has a positive influence of +56 L CH_4 / kg_{VS} ($T_{test} = 0.170$, $p = 0.434$) and from cutting +8 L CH_4 / kg_{VS} ($T_{test} = 0.196$, $p = 0.424$), there is no interaction between factors. For marine *U. intestinalis* cutting has a positive influence of +49 L CH_4 / kg_{VS} ($T_{test} = 0.071$, $p = 0.472$), while washing has an influence of +7 L CH_4 / kg_{VS} ($T_{test} = 0.1655$, $p = 0.435$), there is no interaction between factors. Even though the influences from different pre-treatment methods are not statistically significant, the total obtained values of each test are statistically significant. For all algae types any use of mechanical pre-treatment (cutting, chopping or crushing) was beneficial to enhancing biogas yields and reducing retention times.

Based on these experiments the values used further in the methodology evaluation are listed in Table 3.1. Values for manure are taken from literature. Based on the experimental results of *F. vesiculosus, U. intestinalis,* and *C. demersum* biogas yield, volatile solids (VS), and total solids (TS) a digestion tank with a capacity of 1500 m^3 and CHP unit with 250 kW electrical capacity are chosen. This is considering a retention time of 20 days as well as the daily load of algae and inoculum needed to operate the plant.

Table 3.1

Feedstock Parameters for Biogas Production

Parameter	Unit	*C. demersum*	*F. vesiculosus*	*U. intestinalis*	Manure
BMP	L CH_4 / kg_{VS}	405.3	81.1	92.1	300
VS	%	78.3	78.5	78.5	79.0
Moisture	%	94.9	82.2	78.7	85.0
TS	%	5.1	17.8	21.3	15.0

Based on experimental values and literature analysis it is assumed, that biogas contains 65 % of methane.

Based on the BMP values, chosen biogas plant, CHP unit size, and other assumptions, it is possible to calculate how much energy is spent in order to generate heat and electricity from algae derived biogas. The summary of all spent and produced energy in each of the scenarios can be seen in Table 3.2.

Table 3.2

Energy Input/Output Ratio Calculation

Process	*C. demersum* MWh	*F. vesiculosus* MWh	*U. intestinalis* MWh	Manure MWh
Total input	**1407.93**	**1435.31**	**1407.93**	**1335.90**
Electricity for storage unit	17.28	17.28	17.28	0
Electricity for pre-treatment	54.75	82.13	54.75	0
Electricity for digestion, biogas cleaning and CHP unit operation	153.30	153.30	153.30	153.30
Heat for digestion	1182.60	1182.60	1182.60	1182.60
Total output	**6132**	**6132**	**6132**	**6132**
Electricity output	2190	2190	2190	2190
Heat output	3942	3942	3942	3942
Ratio	**0.2296**	**0.2341**	**0.2296**	**0.2179**

It should be noted that energy spent for transportation is not taken into account.

3.2. Environmental Criteria

Environmental impacts are calculated in *SimaPro* program using *IMPACT2002+* as the calculation method. The results are in 4 damage categories further divided into mid-point impact categories (see Table 3.3 for the main results in damage categories).

Table 3.3

Environmental Impact of Scenarios in Damage Categories

	C. demersum	*F. vesiculosus*	*U. intestinalis*	Manure	Unit
Ecosystem quality	136 566	193 827	143 330	4 250	PDF per m^2
Climate change	280 313	359 182	291 188	105 239	kg CO_2 equivalent
Human health	0.273	0.333	0.267	0.087	DALY
Resource depletion	3 599 703	4 719 593	3 755 142	1 124 616	MJ

The results for algae scenarios are overall very similar within 15 % range for each category, but manure scenario impact is lower as it is regarded as a by-product of cattle farming. The impact on human health and ecosystem quality category is mainly due to transportation emissions. Transportation emissions also comprise around 80 % of climate change and resource depletion categories for algae scenarios.

In order to be able compare the results within different damage categories, they are converted to a point system via normalization step in *SimaPro* (see *IMPACT2002+* methodology for more details (Goedkoop et al., 2008)).

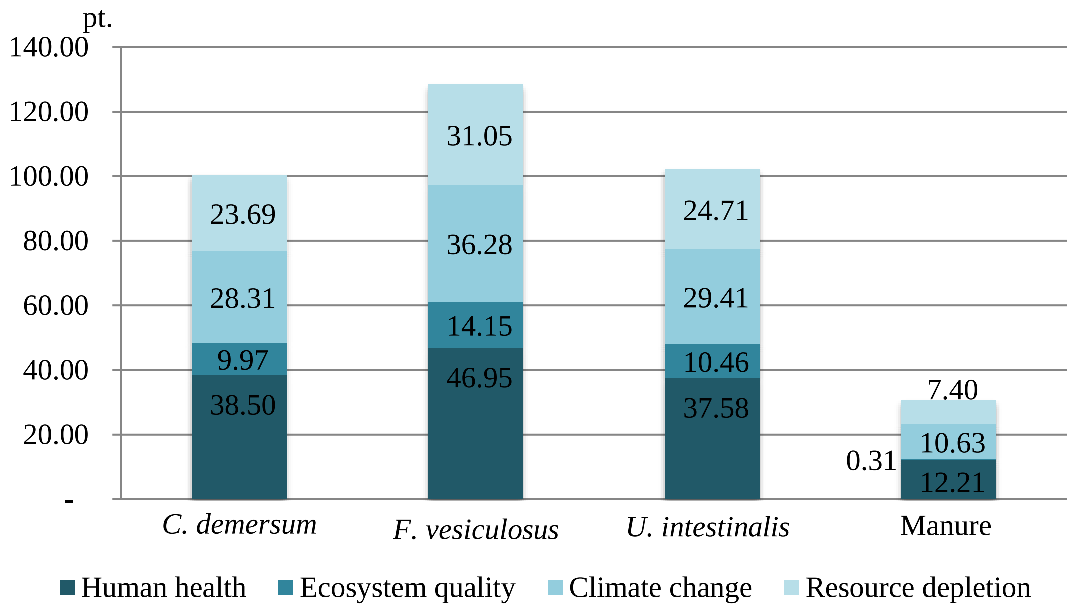

Fig. 3.2. Normalized environmental impact per damage categories in each scenario in points.

As it can be seen in Fig 3.2, the biggest damage is from the human health and resource depletion category.

Not many biogas stations tend to use storage with cooling, as it adds additional costs to the whole process. A sensitivity analysis was carried out to determine how the environmental impact would change considering biomass degradation rate of 0 %, 10 %, 20 % and 30 %. As the functional unit is operation of biogas plant and the CHP unit for 1 year (producing 2190 MWh of electricity and 3942 MWh of heat), it is assumed that respectively more biomass should be collected to make up for the loss of biomass during storage. Regressions analysis shows that there is a strong correlation, meaning the more biomass is needed to operate the same biomass plant and CHP unit, the higher are environmental impacts – by 30 % increase of biomass, environmental impacts are increased by 26 % on average. This means that by excluding a storage unit with cooling, the environmental impacts would increase proportionally to the amount of biomass lost from degradation. In case of preferable climate conditions (mild summers, colds winters, generally lower temperatures) the impact could be small, but as the general tendency in last 5–10 years for climate is to get warmer it is very likely that through a life cycle of biogas production plant the increased environmental impacts could reach up to 30 % or higher due to biomass degradation.

3.3. Economic Criteria

Cash flow was modeled based on the assumptions mentioned before. The NPV, BP, and DPB values can be seen in Table 3.4.

Table 3.4

NPV, BP, DPB Values for Scenarios

	C. demersum	*F. vesiculosus*	*U. intestinalis*	Manure	Unit
Net present value	51 008	–505 683	–219 061	916 864	EUR
Biogas price	355	389	373	304	EUR / t. m^3
Discounted payback period	11	20	11	2	Years

As it can be seen from NPV, only the algae scenario of *C. demersum* as a feedstock would give a positive cash flow in a 20-year span. Even though *U. intestinalis* discounted payback period is the same as *C. demersum* (11 years), the biogas price is slightly lower for *C. demersum.* Based on just this information, even with a positive NPV value *C. demersum* scenario would not be as good of an investment as just a manure biogas plant. The most critical costs are capital good and maintenance costs for all scenarios and either consumables (for *F. vesiculosus* and *U. intestinalis*) or lease (for *C. demersum*) costs. See Fig. 3.3 for revenue structure of scenarios.

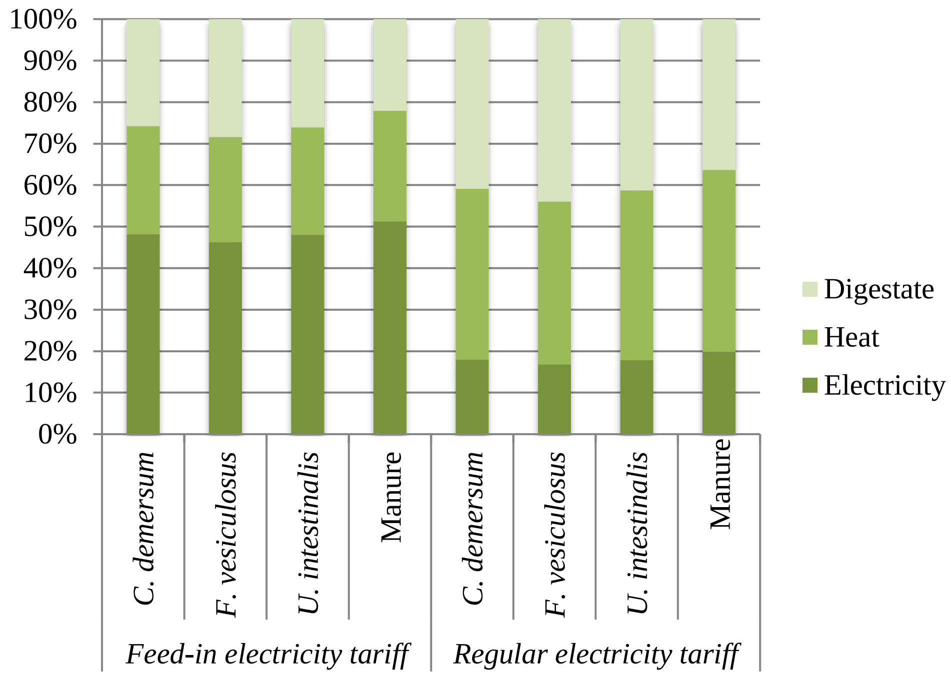

Fig. 3.3. Revenue structure of scenarios.

The revenues consist of selling electricity, heat, and digestate. The feed-in tariff for electricity selling has a major influence on revenue, changing from 46–48 % to 17–18 % (with and without the feed-in tariff, respectively). The revenues from heat and digestate make up similar amount from total revenues.

Biogas prices are in the range from 304 EUR / t. m^3 to 389 EUR / t. m^3. Recalculated as price per cubic meter of methane (65 % of biogas is methane), not considering upgrading costs, the price range is from 467 EUR / t. m^3 to 599 EUR / t. m^3. The average natural gas sale price for end-users in year 2017 was 287 EUR / t. m^3 (Central Statistical Bureau of Latvia, 2017). Without any subsidies or feed-in tariffs for biogas selling, the almost-double price is not competitive enough for a project to be viable.

3.4. Criteria Weights

The criteria weights assigned with AHP methodology have been based on author's opinion on the criterion importance. The use of criteria weights is optional, not mandatory for the final ranking of alternatives. The methodology can combine the results of multiple decision makers to lessen the subjectivity of the methodology. As long as the limitations of the AHP methodology are understood, it can be a good tool to help decision makers in choosing between similar alternatives.

See the results of weights assigned by the author using analytical hierarchy process methodology in Table 3.5.

Table 3.5

Weights Assigned by Author Using AHP Methodology

Criteria group	Sub-criterion	Weight	Criteria group weight
Energetic	BMP	21.59	28.69
	ER	7.10	
Environmental	EQ	5.13	28.39
	CC	9.83	
	HH	6.42	
	RD	7.01	
Economic	NPV	25.33	42.92
	BP	12.75	
	DPB	4.84	

As it can be seen, the highest values are assigned to net present value of a project, followed by biochemical methane potential. Even though all environmental criteria have relatively low assigned individual weights, the total criteria group weight is similar with others. Based on the assigned weights, it can be seen that the most important criteria group is economic, followed by environmental and energetic. As the selected projects have high investment costs, it is important to choose a project that can as a minimum be viable and cost-effective.

3.5. Multi-Criteria Analysis

Based on the information gathered in previous sections by performing laboratory experiments, carrying out calculations, modeling scenarios, performing life cycle analysis, performing life cycle cost analysis, and calculating weights for the chosen criteria, MCA can be carried out. The compiled results for each criterion can be seen in Table 3.6.

Table 3.6

Criteria Values and Weights for Each Scenario

	C. demersum	*F. vesiculosus*	*U. intestinalis*	Manure	Unit	Weights
BMP	0.4053	0.0811	0.0921	0.300	m^3 CH_4 / kg_{VS}	21.59
ER	0.229	0.234	0.229	0.218	–	7.10
EQ	9.97	14.15	10.46	0.31	pt.	5.13
CC	28.31	36.28	29.41	10.63	pt.	9.83
HH	38.50	46.95	37.58	12.21	pt.	6.42
RD	23.69	31.05	24.71	7.40	pt.	7.01
NPV	51 008	**–505 683**	**–219 061**	916 846	EUR	25.33
BP	355	389	373	304	EUR / t. m^3 biogas	12.75
DPB	11	20	11	2	Years	4.84

As it can be seen from the gathered data, some of the values are negative; in order to perform the MCA, data are first normalized. Even though TOPSIS methodology has a normalization step, all of the values are converted into positive ones and normalized prior to performing TOPSIS. Data are normalized on a scale of 1 to 10 (10 assigned for the highest value, 1 for lowest value with linear dispersion of everything else in between).

Based on the inputs in Table 3.6 and the weights determined by AHP methodology in Table 3.5, the ranking of alternatives were calculated with TOPSIS methodology (Fig. 3.4). The ranking shows closeness to 1, where 1 is the ideal solution that comprises the desirable values of each criterion based on the inputs.

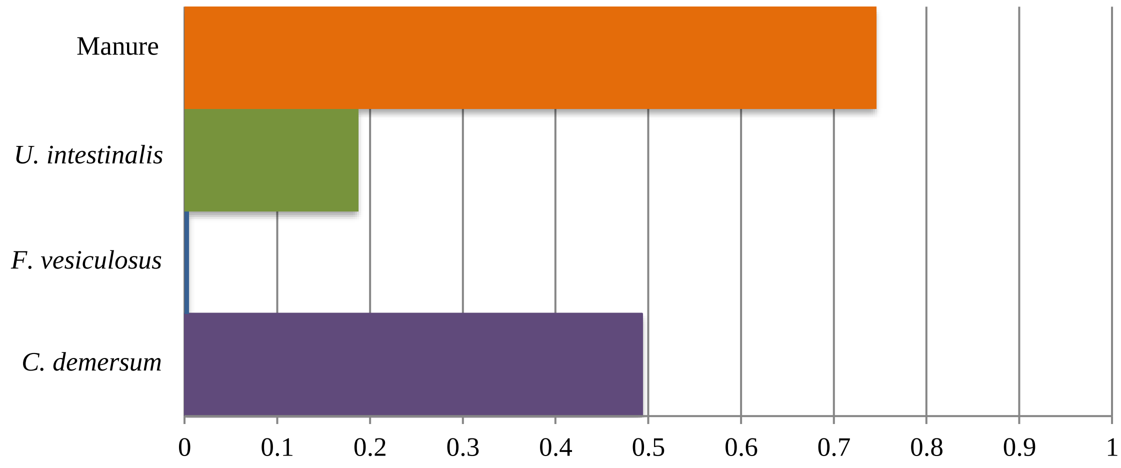

Fig. 3.4. Ranking of alternatives with TOPSIS with AHP weights.

The ranking shows a clear leader – the benchmarking alternative of just manure use for biogas production as the most suitable option. From the algae alternatives, freshwater *C. demersum* is ranked the highest, followed by *U. intestinalis* and *F. vesiculosus* as the least suitable alternative. As the ranking included the weights assigned with AHP methodology, it is also important to compare the ranking in the case of equally assigned weights for all criteria as a base of all rankings (Fig. 3.5).

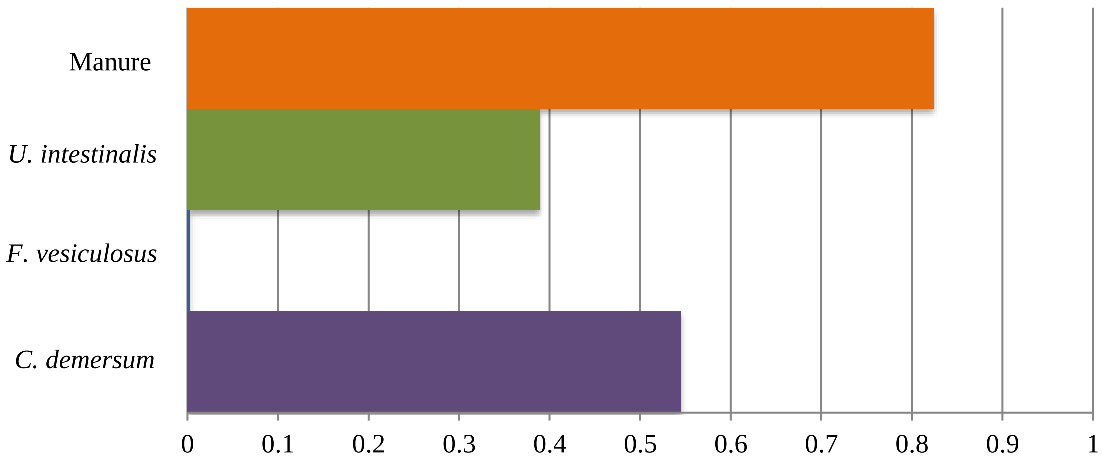

Fig. 3.5. Ranking of alternatives with TOPSIS with equal weights for criteria.

The order of ranking of alternatives with equal weights does not change, but their individual closeness to ideal solution does, for example, the ranking for *U. intestinalis* changes from 0.18 to 0.38, more than twice. As the assigned weights can have an influence on the criteria ranking it is further analyzed using sensitivity analysis.

3.6. Sensitivity Analysis

Sensitivity analysis is used to test how the methodology behaves when dependable input variables changes. Based on the known changes to variables and the response from the methodology results, it is possible to evaluate how the model behaves and whether such behavior is in line with the goal of methodology.

Sensitivity analysis of the methodology was carried out by changing all criteria weights in order to determine their impact on the alternative ranking. The weights tested were changed by several principles – each criteria group weights comprise 50 %, the rest of criteria have equal weight; each criterion has a weight of 50 %, the rest of criteria have equal weight. The results of weight impact sensitivity analysis are compiled together and averaged with standard deviation error bars in Fig. 3.6.

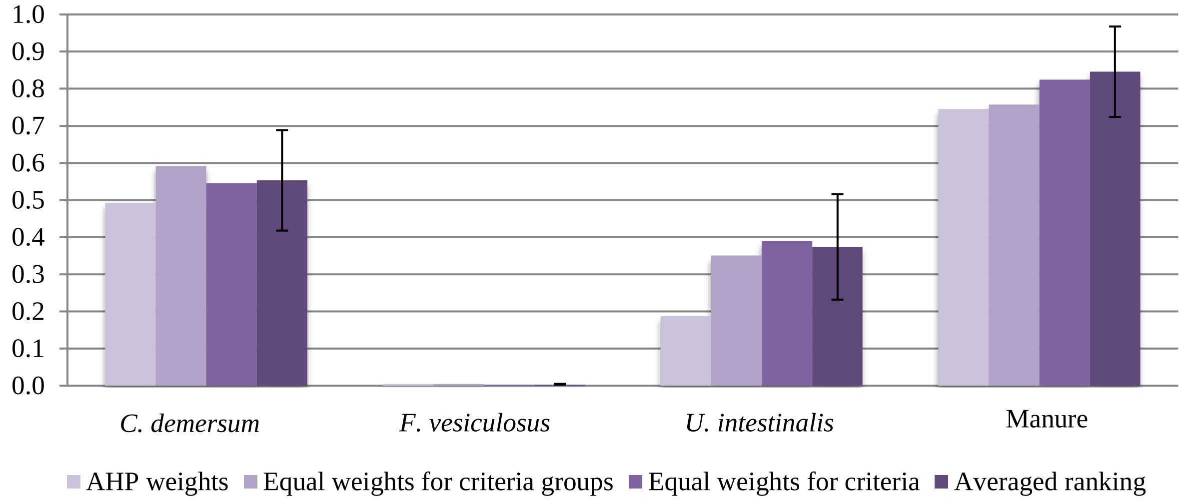

Fig. 3.6. Sensitivity analysis of criteria weights.

The standard deviation is between 14 % and 58 % of the averaged ranking value, depending on the scenario, meaning that the assigned weights have great influence on the ranking outcome. In some cases of the assigned weights, the alternatives can change the rank order. For example, when the BMP criteria weight value is 50 %, the results from TOPSIS ranking are as follows: *C. demersum* – 0.86, *F. vesiculosus* – 0.01, *U. intestinalis* – 0.12, and Manure – 0.50.

The created methodology for evaluating biogas production alternatives was tested also by changing the criteria input values and analyzing how the results change. Two criteria values were chosen to be tested – NPV and DPB as they have the highest and lowest assigned criteria weights by AHP methodology. They were tested in a *C. demersum* alternative to test how the rankings change by changing a single input data value. The two criteria values were changed one by one, from minimum to maximum value (showed as – 100 % or + 100 %, respectively) with a single step in-between the current value and the minimum or maximum value (showed as – 50 % and + 50 %. respectively). See Fig. 3.7 for the results of criteria DPB changes impact on ranking of alternatives and see Fig. 3.8. for criteria NPV changes impact on ranking of alternatives.

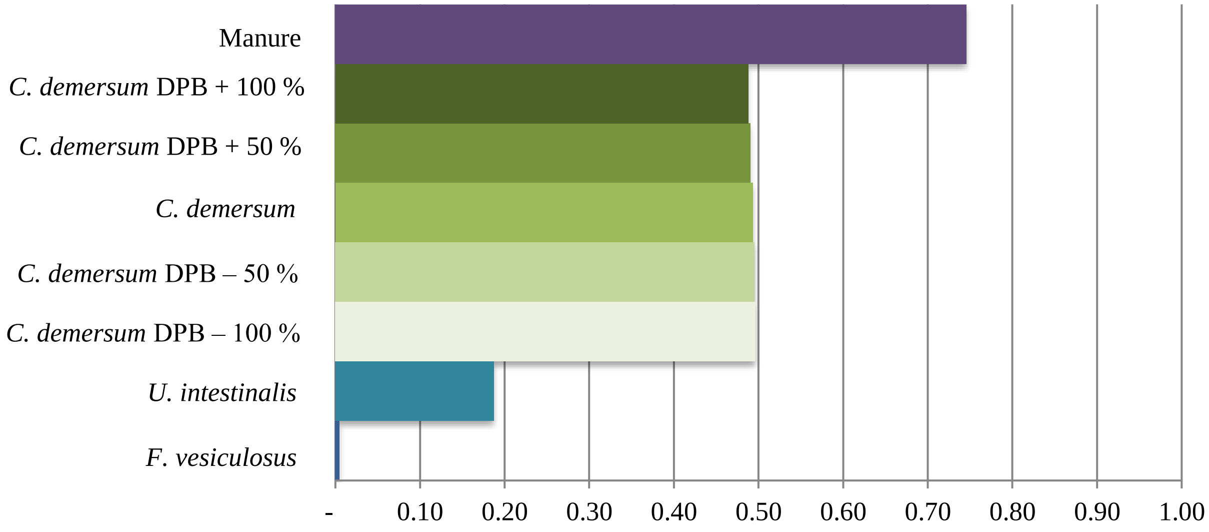

Fig. 3.7. Criteria DPB changes impact on ranking of alternatives.

As it can be seen, the final ranking changes for *C. demersum* scenarios are negligible and do not create a change of ranking order.

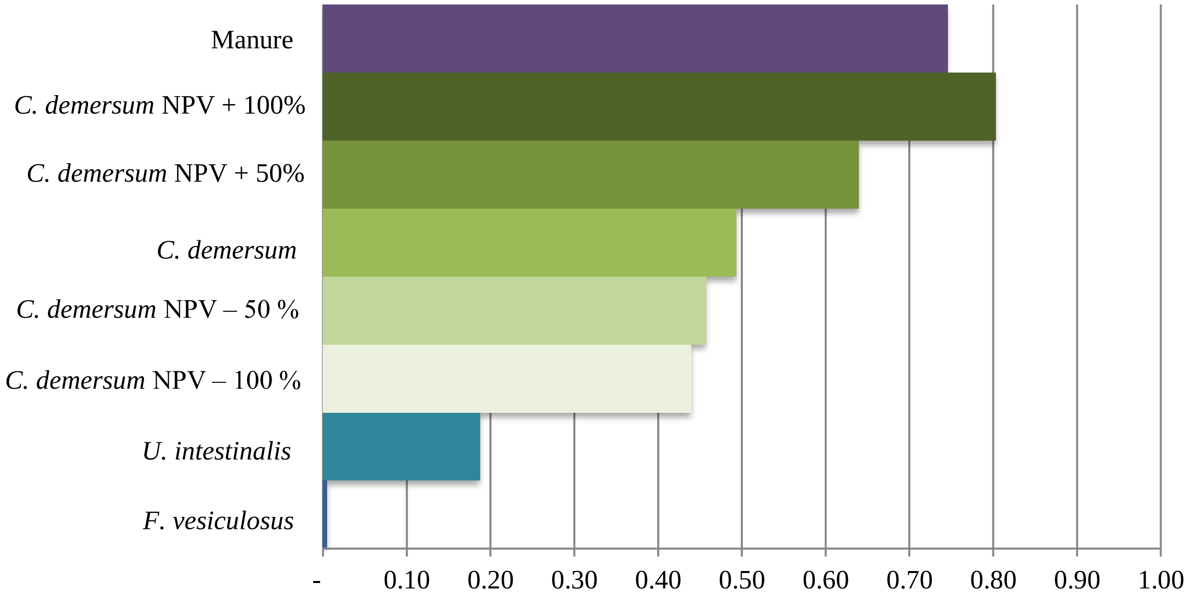

Fig. 3.8. Criteria NPV changes impact on ranking of alternatives.

As it can be seen in Fig. 3.8, criteria value NPV changes, on the other hand, can cause a change of rank order and impact the results in a major way. This sensitivity analysis showcases the importance of assigned weights and how a single data input value can change the outcome when the weights are higher for the set criteria.

The combination of criteria value changes and the assigned weight changes creates a framework that is flexible to changes of assigned weights (the subjective part of the methodology) as well as flexible to changes in criteria values (the objective part of study). As the methodology set-up allows for the weights to be determined by the stakeholders of the project to-be-evaluated, they can decide which of the criteria are of the highest importance. The AHP methodology of weight calculations also allow for more than one person to assign weights, in that way diminishing the subjectivity of the results. In the eyes of the author of the methodology such behavior is considered to be favorable as it shows that the methodology can adapt to the changes within accordingly to the expectations. If the goal of the study is to remove the subjectivity or to see the rankings of scenarios based solely on the criteria themselves, then the use of equally distributed criteria weights should be applied. It is also a good idea to always compare the results to such option just to see what the changes and possible weak points or strong points of the scenarios are.

CONCLUSIONS

1. A methodology for evaluating algae use for biogas production was created and fills the gap related to lack of comprehensive evaluation tool that considers energetic, environmental and economic aspects. The methodology provides a framework for evaluating potential algae use projects by 3 crucial aspects – energetic value determination, environmental impact, and economic efficiency. For each of the aspects several analytical and practical analysis methods are used in order to ensure data accuracy. The combination of experimental research with biogas plant life cycle modeling ensures that the main project aspects are taken into account during the whole life cycle of the project. The developed evaluation methodology and the results of study can be used at municipal, national and international policy planning levels.
2. The created evaluation methodology framework allows evaluating different scenarios of algae use for biogas production depending on the goal of study. The methodology was approbated with alternative scenarios of algae available in Latvia. Two species of washed out marine macroalgae were chosen (marine brown algae *Fucus vesiculosus* and marine green algae *Ulva intestinalis*), as well as freshwater macrophyte (*Cerathophyllum demersum*) based on literature analysis of locally available algae species. Benchmarking scenario of manure as feedstock was also tested. The study showed that the best algae alternative based on the selected criteria and their weights is *C. demersum*. As it is freshwater macrophyte, there is no need for washing as pre-treatment step, thus reducing both environmental impact and total costs. Looking at algae scenarios' one aspect at a time *C. demersum* showed the highest energetic value (more than triple than that of the other algae species). The input-output energy ratio was similar for all scenarios. The environmental impacts were lower for *C. demersum* due to lower quantities of the biomass needed, but had higher impact on human health due to carcinogens from barge use. NPV was only positive for *C. demersum* and the biogas price was in the range from 355 EUR / t. m^3 to 389 EUR / t. m^3. It must be noted that the economic feasibility for all scenarios was highly dependent on feed-in tariff use for the first 10 years of operation. For the analyzed biogas production scheme, transportation is one of the weak points in all scenarios, as it has a high impact on environment and comprises a considerable part of operational costs.
3. The use of experimental data is a crucial point in the overall evaluation of the case study and the methodology framework itself has a lot of the data calculations based on the amounts of algae needed for biogas plant operation. Finding a pre-treatment option that would increase the biochemical methane potential of the substrates can improve the overall feasibility of algae use for biogas production. As the sensitivity analysis of use of storage unit within LCA showed, the amount of algae needed for the same amount of biogas produced has impact on all of the processes increasing the impact on environment as well as costs. Another weak point of the analyzed biogas production scheme is the high investment costs, as the sensitivity analysis of LCCA data showed, even without the added costs of CHP unit, the costs for producing biogas are above the

market price and would not be a viable option. The strong points of the analyzed biogas production scheme are the fact that the used biomass is otherwise considered waste and collecting the biomass directly from shore (or water bodies) can help with eutrophication problems. The potential use of washed out algae also helps the EU to achieve its targets for next planning periods and help reduce the impact on climate change. It should be noted that legal and social aspects are not considered in the evaluation and are not included in the methodology framework.

4. Several rounds of sensitivity analysis of the methodology framework showed that the method is flexible and responsive. The changes within the criteria groups or criteria results themselves are accordingly represented in the changes of overall closeness to the ideal solution. The weights assigned with AHP have a proportional impact on the outcomes when only the input value changes. Testing of weight distribution changes among the criteria showed that there could be a significant change of closeness to the ideal solution, especially in the cases of criteria where the value for it is in the lower or upper range. For the selected scenarios, there can be a change of ranking that can be achieved with different weight distribution.
5. The methodology framework is easily adjustable and can be updated to include more stages of biogas production scheme in case it is needed. The overall structure of the developed methodology is very flexible and allows for changes according to the goal of the study. The structure of using LCA combined with LCCA based on the inputs ensures that any changes that are made in the chosen scenarios or the study itself will be reflected in the outcome accordingly. As the weight assigning with AHP methodology allows for more than one person to assign weights, this methodology is also suitable to be used when there is more than one decision maker or more than one stakeholder.

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